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Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

FAA Composite Structural Engineering Technology Safety Awareness Course

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Final report

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16. Abstract

This report documents the development of a Federal Aviation Administration (FAA) safety awareness course on composite structural engineering technology (CSET). The course is intended to promote awareness of structural engineering issues and principles for practicing aerospace engineers, as well as those relatively new to the industry, while highlighting safety implications. A practical application for professionals completing the course, such as FAA personnel, will be the ability to oversee design, production, and maintenance organizations. This was developed for a *safety awareness* education level to complement the specific skills needed for structures engineering and its relationship to maintenance and manufacturing. This includes material and process controls, design, structural substantiation, and other structural considerations essential to product safety and certification. As of 2021, 200 students have taken the course, and feedback from prior students provided the basis for improved training content.

The CSET course can be used in a variety of different teaching settings and formats. Training materials, including topic objectives, teaching points, and discussion scenarios, provide the students with opportunities to learn from each other and subject matter experts through interactive discussions, which involve practical engineering scenarios and experiences. The use of a commercially available online learning management system, Blackboard learning management system, was selected for CSET development and instruction as it allows students and instructors to participate at a time and location that is convenient for them. Blackboard enabled improvements of this course by 1 involving subject matter experts during each class, which provided valuable expertise; 2) enabling availability for a variety of students with varying backgrounds and expertise who might lack accessibility if training was confined to a specific location; and 3) accessing frequent case studies in discussions. In 2016, various improvements in the course procedures were established based on student feedback. In 2020, improvements in course content were provided to make content and organization more consistent among modules and to review for technical updates.

17. Key Words

Certification of composite structures, Structural substantiation, Integrated product development, Material and process control, Manufacturing and maintenance implementation, Design development, Flutter, Crashworthiness, Fire safety, Lightning protection

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Acronyms

Acronym	Definition
AC	Advisory Circular
AD	Airworthiness Directive
ADL	Allowable damage limit
AIR	Aerospace Information Reports (SAE)
AMM	Aircraft maintenance manual
APU	Auxiliary power unit
ASTM	American Society for Testing and Materials
ATLM	Automatic tape layup machine
BMI	Bismaleimide
BVID	Barely visible impact damage
BJSFM	Bolted joint stress field model
CDT	Critical damage threshold
CFR	Code of Federal Regulations
CFRP	Carbon fiber reinforced plastic
CLT	Classical lamination theory
CMH-17	Composite Materials Handbook-17 (formerly MIL Handbook 17)
CSET	Composite Structural Engineering Technology
CTE	Coefficient of linear thermal expansion
DR&O	Design requirements and objectives
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations (FAA)
F&DT	Fatigue and damage tolerance
FEA	Finite element analysis
GFRP	Glass-fiber-reinforced plastic
ICA	Instructions for Continued Airworthiness
IPDT	Integrated Product Development Team
K_c	Key characteristics
K_{pp}	Key process parameters
LEF	Load-enhancement factor
MMPDS	Metallic Properties Development and Standardization Handbook (formerly MIL HBK-5).
MOT	Maximum operating temperature

MPF	Melt-phase forming (Thermoplastics)
MRB	Material review board
MRO	Maintenance and repair organization
NDE	Nondestructive evaluation
NDI	Nondestructive inspection
NDT	Nondestructive testing
NASA	National Aeronautics and Space Administration
OEM	Original equipment manufacturer
PCD	Process control documents
PS	Policy statement
RDD	Readily detectable damage
RFI	Resin film infusion
RIM	Reaction injection molding
RTM	Resin transfer molding
SAE	Society of Automotive Engineers
SPC	Statistical process control
SPF	Solid-phase forming (Thermoplastics)
SRM	Structural repair manual
TCCA	Transport Canada Civil Aviation
T_g	Glass transition temperature
TMC	Transverse matrix cracking
TOS	Thermal oxidative stability
UV	Ultraviolet
VARTM	Vacuum-assisted resin transfer molding
VCCT	Virtual crack closure technique
VID	Visible impact damage

Executive summary

This report documents the development of a Federal Aviation Administration (FAA) safety awareness course on composite structural engineering technology (CSET). The course promotes awareness of structural engineering issues and principles for practicing aerospace engineers, as well as those relatively new to the industry, while highlighting safety implications. A practical application for professionals completing the course, such as FAA personnel, will be the ability to oversee design, production, and maintenance organizations. This was developed for a *safety awareness* education level to complement the specific skills needed for structures engineering and its relationship to maintenance and manufacturing. The CSET course outlines the essential concepts and safety issues associated with the certification of composite parts in commercial aviation. The course is presented in Microsoft® PowerPoint® format, and curriculum developers may customize content to suit specific organizational requirements.

CSET course development was initiated during a FAA workshop hosted at the National Center for Aviation Training, titled "Material & Process Control Workshop: Module of a Level II Structural Engineering Safety Awareness Course," September 14-16, 2010. Subject matter experts who attended the workshop presented content and shared perspectives, discussed material and process issues, and provided written feedback. Subsequently, the CSET course was developed and modified through 2020, including substantial updates to subject matter, topic sequence, and consistent formatting among all modules. The April 2020 CSET update outcome is the basis for this report.

The course is designed for a broad range of backgrounds and experience levels. Students and professionals completing the CSET course can achieve an understanding of composite structures engineering technology, including regulatory frameworks in commercial aerospace. The following student audiences will benefit:

1. FAA and other regulatory personnel seeking to improve oversight skills in production, maintenance, and engineering, with an emphasis on aircraft structures.
2. Broad engineering and/or metals background, with a goal to adapt that background into composite structural engineering practice.
3. Practical aerospace industry background, with a goal of better understanding composite technology and airplane product certification.
4. Experienced composite engineering background, with a goal of learning or refreshing knowledge of certification and substantiation frameworks.

Course content described as Introduction, or Level I, includes composite basic technology understanding and terminology. Level I also serves as prerequisites to more advanced study, Safety Awareness, or Level II. Level II provides skills needed for industry and FAA workforce supporting composite applications. Level III provides specialized skills needed in the industry and by some FAA experts, such as the use of inspection equipment or analytical software.

CSET is Level II training and includes Level I prerequisite content to bring students to a common level of understanding before advancing to Level II content. CSET emphasizes principles of composite airframe substantiation during all stages of aircraft product certification.

Two major improvements were implemented for the CSET course between 2012 and 2021. The 2016 improvements emphasized course teaching processes, followed by 2020 changes that focused on modifying the detailed content for technical updates and updating the organization and presentation format for consistency throughout the course.

1 Introduction

This document outlines the development of a safety awareness course for composite structural engineering technology (CSET). Curriculum information is detailed for training development that achieves understanding the process of composite engineering and its relationship to the certification of commercial aircraft.

CSET course content is divided into seven learning modules. A prerequisite module brings students to a common level of composites technology knowledge before continuing to the CSET modules.

The course is designed for a broad range of backgrounds and experience levels. Students and professionals completing the CSET course can achieve an understanding of composite structures engineering technology, including regulatory frameworks in commercial aerospace. The following student audiences will benefit:

- FAA and other regulatory personnel seeking to improve oversight skills in production, maintenance, and engineering, with an emphasis on aircraft structures.
- Broad engineering and/or metals background, with a goal to adapt that background into composite structural engineering practice.
- Practical aerospace industry background, with a goal of better understanding composite technology and airplane product certification.
- Experienced composite engineering background, with a goal of learning or refreshing knowledge of certification and substantiation frameworks.

Figure 1 shows the three levels of training competence for the CSET curriculum. The CSET curriculum forms the foundation for more specialized industry curriculum development applications. As training curriculum becomes more specialized, FAA involvement and investment are incrementally replaced by those of industry.

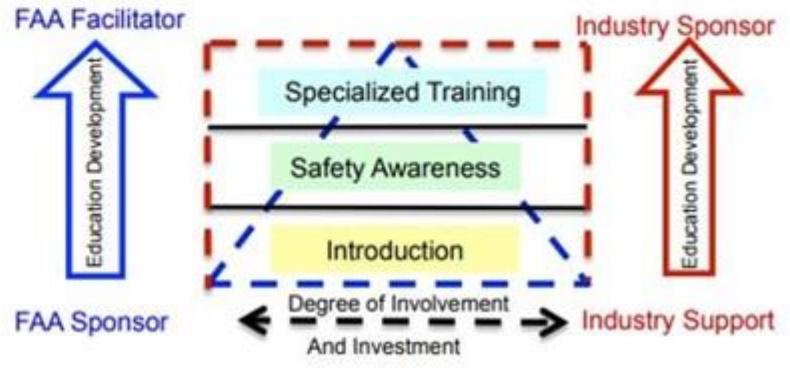

Figure 1. The FAA and industry roles in curriculum development

Each CSET module contains learning objectives, technical content, and teaching point summaries.

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CSET is Level II training and includes Level I prerequisite content to bring students to a common level of understanding before advancing to Level II content. CSET emphasizes principles of composite airframe substantiation during all stages of aircraft product certification.

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1.1 Course delivery, participation, and assessment

CSET course development required consideration for accessibility across a global network of participants from different time zones and geographic areas. As most participants were engaged in professional commitments, flexible time schedules and locations were critical. Therefore, an asynchronous online format using the Blackboard learning management system, was selected, which provided the advantages of maximum outreach independent of fixed schedules and location. Blackboard brings the added benefit of experiential education through discussions of mini-case studies, which offers improved understanding and retention. Course content is delivered through online self-study. A prerequisite module must be completed with an assessment score of 90% before additional modules can be accessed.

Discussion questions are provided that encourage learning from other students, instructors, and subject matter experts. Test assessments are provided at approximately 2-week intervals.

An optional hands-on laboratory is provided that consists of 2 to 3 days of basic composite experiences, where students, for example, could fabricate components using industry standard techniques.

1.2 Organization of CSET Course

Because of the modular organization of the CSET course, using standard formats and software tools, the course material can be easily modified for other delivery methods and venues, such as classroom instruction. The content can also be updated to keep abreast of industry advancements.

2 Overview and Outline

2.1 Overview

The CSET course provides a balanced content approach to applying basic composite technology to certification processes, safety issues, and the challenges related to engineering, manufacturing, and maintenance. Students explore topics in designing, certifying, manufacturing, and maintaining composite structures in both course content and through associated discussion topics. For example, students explore the implications of nonstandard technology associated with nonisotropic material behavior, which results in a variety of design options and opportunities; dependence on material and process controls to assure consistency and compliance with design objectives; and processes that assure technology readiness through integrated product development teams (IPDT).

The CSET course expands on content in Advisory Circular (AC) 20-107B Composite Aircraft Structure which allows students to better understand and implement the intent of the guidance. Topics are organized similarly to AC 20-107B, and include composite certification principles, material and process control, development of design, structural substantiation, interface with manufacturing and maintenance, and other related topics, such as flutter, flammability, crashworthiness, and lightning protection.

The CSET course content was attained through an iterative process involving subject matter expert involvement at various stages of development and feedback from student participants.

Throughout this process, the course has been continually updated with additional regulatory and industry guidance, such as guidance regarding major damage that has no obvious exterior indication of the extent of that damage.

Prerequisite content was developed so that students could be prepared for the more advanced topics of CSET. Instructors have the option of adapting the sequence of topics to suit organizational educational needs.

2.2 Outline

Table 1 presents an outline of the CSET course curriculum and the prerequisite content.

Table 1. Outline of CSET curriculum

CSET Course Module	**Prerequisite Content**
1.0 Composite Applications	1.1 Composites Overview
	1.2 Challenges
	1.3 Integrated Product Development Teams
2.0 Material, Processing, and Fabrication Development	2.1 Material and Process Control
	2.2 Defects and Damage
	2.3 Protection of Structure
	2.4 Manufacturing Implementation
	2.5 Maintenance Implementation
3.0 Design Development	3.1 Structural Design Details
	3.2 Design Considerations for Manufacturing and Maintenance
	3.3 Other Design Considerations
3.0 Design Development	3.4 Design Requirements, Criteria and Objectives
	3.5 Lamination Theory and Design
	3.6 Composite Analysis Methods
	3.7 Design Development
	3.8 Structural Bonding
	3.9 Structural Bonded Joints
4.0 Structural Substantiation	4.1 Regulations and Guidance
	4.2 Certification Approaches and Related Considerations
	4.3 Addressing Damage and Defects
	4.4 Building Block Testing and Analysis
5.0 Manufacturing Interface	5.1 Quality Control
	5.2 Certification Conformity Process

CSET Course Module	Prerequisite Content
	5.3 Manufacturing Defect Disposition
6.0 Maintenance Interface	6.1 Inspection and Maintenance
	6.2 Structural Repair Development and Substantiation
	6.3 Teamwork
	6.4 Repair Techniques
7.0 Other Topics	7.1 Flutter
	7.2 Crashworthiness
	7.3 Fire Safety
	7.4 Lightning Protection

3 Course summary

The CSET course expands on guidance described in AC 20-107B, Composite Aircraft Structure (2010). During the initial design of the course, an outline was developed based on AC 20-107B.

The increasing composite contact in aerospace and FAA involvement in the certification process of commercial aviation is illustrated in Figure 2 (Ilcewicz, Larry, Chief Scientific and Technical Advisor for Composite Materials, 2011).

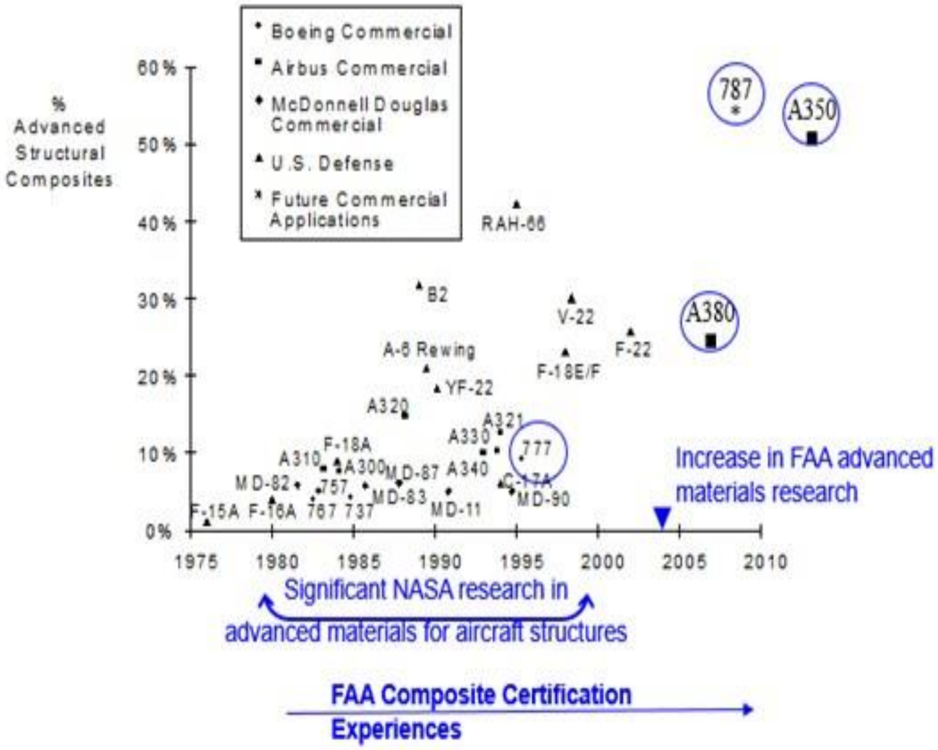


Figure 2. Increased use of composites in aerospace

This has created the need for standardized curricula, such as the CSET course. The objectives of CSET education are especially applicable to safe design and implementation practices.

By taking the CSET course, students achieve an increased understanding of composite structures engineering technology, including regulatory requirements and guidance in commercial aerospace. After completing CSET, students are able to:

1. Describe the essential safety awareness issues associated with composite structural engineering technologies important to safe applications of composites to aircraft products.
2. Describe engineering principles of substantiating composite airframe structures during all stages of aircraft product certification.
3. Apply general knowledge of the current composite technologies certified in aircraft product applications, including small airplane, rotorcraft, transport airplane, propeller, and engine components.

Appendix A provides a complete list of course objectives and outcomes for each module topic. Module objectives and corresponding content can be modified to suit the specific needs of subsequent course developers, instructors, and students.

The module summaries encapsulate the CSET course content, which complements the objectives and highlights teaching points.

3.1 Introduction, challenges, and IPDTs

3.1.1 Module 1.1: Introduction

The FAA, in partnership with industry and other regulators, conducts composite safety and certification initiatives relating to composite technology. The Composite Material Handbook 17 (CMH-17) (CMH-17, Volume 3, Chapter 4, Revision G) and other standards activities, such as American Society for Testing and Materials (ASTM) Committee D-30 on Composite Materials and the Society of Automotive Engineers (SAE) Commercial Aircraft Composite Repair Committee (CACRC), are used to document much of the identified best industry practices.

Module 1.1 describes the challenges in safety and certification efficiency, which requires a qualified workforce since many technology developments are proprietary. Challenges include a) a lack of the trained resources required to support the increased use of composites in aerospace, b) the unique technical characteristics of composites, and c) the evolving nature of composites technology. To assure that the structural parts meet design requirements, practitioners must understand and integrate the various technical characteristics of composites into the disciplines of manufacturing, maintenance, and engineering. These provide the background for CSET developments. The CSET course highlights current applications and describes the unique technical issues that distinguish composite applications from traditional metals technology that has historically dominated applications.

The CSET course expands on topics covered in the guidance of AC 20-107B Composite Aircraft Structure. Topics include material and process control, development of design, structural substantiation, interface with manufacturing and maintenance, and other related subjects.

3.1.2 Module 1.2: Challenges

Composites technology can offer performance advantages over traditional metals, but also have significant challenges when used in aerospace applications. In addition to technical considerations, adapting composites into aerospace applications must address the cost structure of composites. For example, composite product development, implementation, and knowledge transfer issues often result in high nonrecurring costs, which may be mitigated by industry standards and best practices.

Evolving composite technologies with increased choices in structural design and certification methods have reduced standardization and made the creation of industry-accepted training standards more difficult. Liquid resin molding, co-cured complex structures, and thermoplastic structures are all examples of new composite technologies that challenge standardization efforts that have been underway for thermoset prepreg materials. Other examples include recent technology advances for improving thermal uniformity by reducing temperature cure variations during fabrication, which may affect repair design. Advances include 1) use of inductive heating elements in silicone heat blankets that adjusts heat application within a part during cure to accommodate heat deviations and 2) increased use of thermal surveys to identify heat sinks.

The potential lack of adequately trained resources is an important topic in composites technology, and the lack of documented training standards has motivated industry partners, including the FAA, to improve the consistency and content of composites knowledge in engineering, manufacturing, and maintenance.

3.1.3 Module 1.3: Integrated product development teams

The focus of this module is the role of IPDTs and material review boards (MRBs) in the CSET lifecycle. Involving disciplines associated with procurement, project management, product design, analysis, manufacturing, certification, and customer support throughout the design process enhances product technical and cost performance. Much of the cost structure is defined in the early stages of development, which further supports the need for an interdisciplinary approach to design.

IPDTs are assembled and utilized to assure technology readiness before committing to production during early phases of development. The IPDT also provides support for scaling activities and assures that development and implementation of advanced composite technology is properly applied to the large transport aircraft structure.

Throughout the design and manufacturing phases, IPDT disciplines require specialized knowledge of composite technology. A permanent IPDT, for example, supports disposition of rejected parts during production. As part of the IPDT, the MRB dispositions rejected parts. The MRB review includes design, structural integrity, materials and processes, and other expertise as required. The MRB typically falls under the responsibility of the quality department. IPDT responsibilities are depicted in Figure 3 (Ilcewicz L. C., 2012).

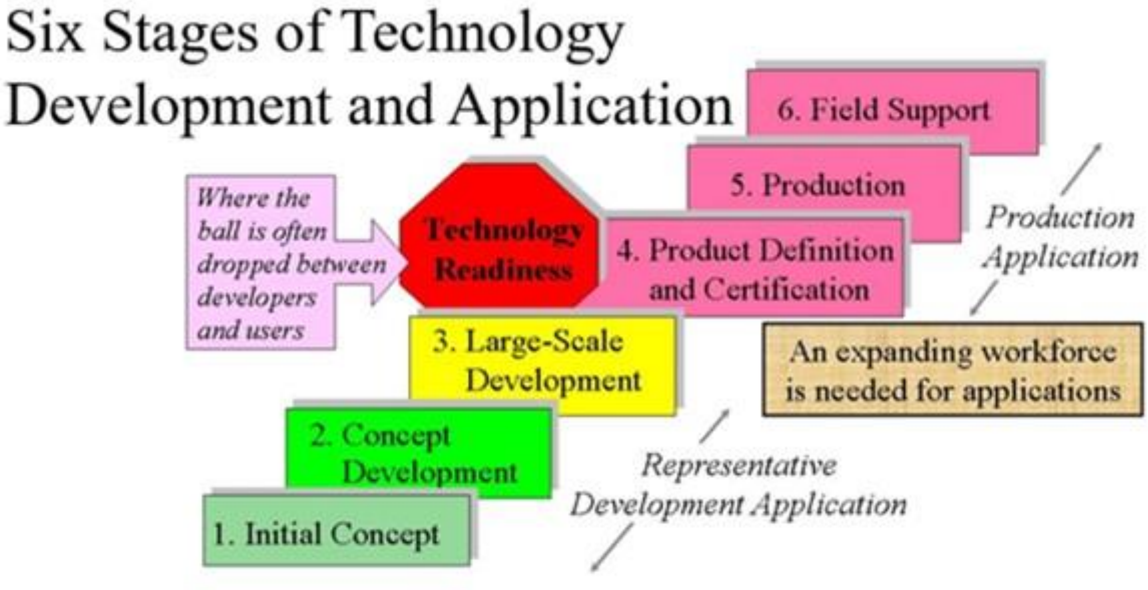


Figure 3. Integrated product development team responsibilities

3.2 Material, processing, and fabrication development

3.2.1 Module 2.1: Material and process control

This module focuses on the regulations and controls associated with composite materials. Aviation regulations are generally the same for both metallic and composite construction, but different materials require different methods to demonstrate compliance to the regulations. The FAA and industry publish guidance and guidelines with acceptable means or methods of compliance. Additionally, detailed background information is often provided within the guidance to assist applicants in understanding regulatory intent and to provide industry best practices and concepts behind various compliance methodologies.

Module 2.1 addresses issues related to the relationships between regulatory control, characterization and certification of composite materials, design and process controls, structural substantiation, manufacturing processes and material properties, specifications, and process qualification, as described below. The various linkages provided by material and process specifications are depicted in Figure 4.

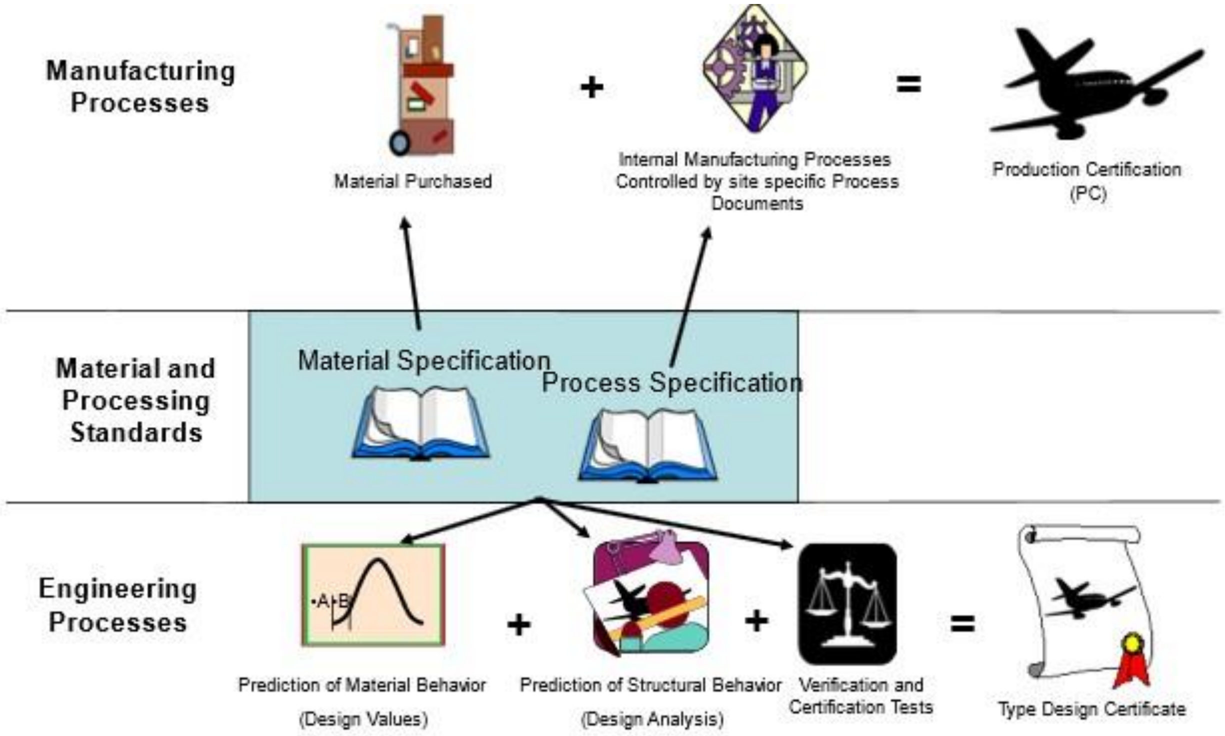


Figure 4. Material and process specifications link engineering and manufacturing

Regulations require applicants to define the configuration and the design features of the product. In the case of composites, this includes material definition and process instructions. Regulations also require that strength and design values minimize the probability of structural failure due to variability of material and the manufacturing processes. Unlike traditional metals, a composite part manufacturer is also the material manufacturer, and they are ultimately responsible for ensuring consistent structural properties.

Characterizing and certifying composites are a challenge due to the considerable number of fiber and matrix combinations with specific anisotropic properties, and unique characteristics of composites, which include environmental sensitivity, statistical variability, and notch sensitivity and fatigue behavior.

Design allowables and material and process controls are directly linked. Traditional metallic materials have published databases of bulk structural properties that the FAA accepts, which can be used with standardized analytical tools to predict structural behavior. Composites, on the other hand, have unique material databases that are tied to the raw material, the fabrication process, and design details such as laminate configuration.

Structural substantiation depends upon material and process control due to the linkage between structural performance, raw materials, and fabrication processes.

Stable manufacturing processes and material properties are required for structural substantiation and form the base of the building block approach. This is achieved through rigorous material and process control, consisting of controls for raw or uncured materials as well as the process used to convert them to the final form. Procured materials must be stable and combined with a repeatable process to produce consistent performance in the final part. Furthermore, many characteristics of composite structures cannot be evaluated nondestructively after fabrication, making process control critical to ensure quality and consistency.

Material specifications, or similar documentation, must govern both the procurement of uncured materials and the properties of final cured material since the part manufacturer is also the material manufacturer. Process specifications define the steps required to convert the uncured material to the cured part.

Process qualification is expected for each manufacturing facility and each manufacturing process. Material and process specification expectations as well as quality system controls are provided in numerous FAA and industry publications and summarized in the CSET course material.

3.2.2 Module 2.2: Defects and damage

Module 2.2 of the CSET course addresses how defects and damage are detected and resolved. Attention is given to the in-process requirements aimed at detecting anomalies.

Part validation depends on adherence to process requirements. Without this adherence, inspection and testing of a cured part will fail to validate that a good part was produced. For example, weak adhesive bonds cannot be reliably inspected after cure is completed and may escape detection. Therefore, in-process controls are an essential part of composite manufacturing and repair.

The inspection process typically involves visual detection accompanied by nondestructive testing (NDT), destructive coupon testing, and/or process record review. Nonconforming parts, referred to as anomalies and other discontinuities, discovered during inspection are classified as either acceptable or nonconforming. Acceptable anomalies are considered in the design and substantiated as part of certification, removing requirements for rework or repair. Unacceptable anomalies are defects and must be reviewed and dispositioned as use-as-is, rework/repair, or scrap. Inspection methods do not characterize anomalies consistently, resulting in the requirement to uniquely define inspection methodology for each structure to properly identify and characterize defects for accurate disposition. Disposition of rejected parts is a function of the specific anomaly location, loads, and configuration, including form, fit and function.

3.2.3 Module 2.3: Protection of structure

This module addresses the structure protection methods that are in place to protect against environmental variables.

Regulations require protection from:

- Environmental conditions, such as temperature and humidity, expected in service
- Deterioration or loss of strength due to any cause, including weathering, corrosion, and abrasion
- Effects of lightning

In practice for composites, protection methods must address moisture absorption, lightning strikes, galvanic corrosion, ultraviolet radiation, and erosion due to sand and rain, in addition to other threats. Protection of structure begins with the careful selection of materials to avoid many damage threats. Even so, composite materials typically require protective treatments with unique processing instructions, such as protective layers or painting.

Polymer matrix composites are vulnerable to moisture absorption and heat, which can lower matrix dominant properties, but are less subject to corrosion when compared to aluminum or steel. Note that galvanic corrosion is still a concern, particularly between mating surfaces of aluminum and carbon. Epoxy resins are sensitive to ultraviolet (UV) radiation and will become brittle and degrade if unprotected. Epoxy resins are also susceptible to erosion from sand and rain, which may expose the fibers of a composite laminate. Engine environments, where many ceramic matrix composite (CMC) materials are used, are particularly harsh, necessitating environmental barrier coatings.

Conductive material is commonly added for lightning strike protection and other electrical considerations since composite structure is typically not electrically conductive. Composite part temperature relates to paint reflectivity, and material must be stable at maximum operating temperature (MOT) and not used near high temperatures approaching the glass transition temperature where material properties will irreversibly degrade.

3.2.4 Module 2.4: Manufacturing implementation

All composite production follows similar steps, regardless of material or process. Module 2.4 provides instruction on the following topics:

- Raw Material Manufacture
- Transport, Incoming QC and Storage
- Tool Prep, Cutting, Layup, and Bagging
- Cure and Solidification
- Trim and Drill
- Inspection
- Bonding and Part Assembly
- Paint and Finish
- Handling and Storage
- Defect Disposition

While quality system requirements are the same whether manufacturing metallic or composite parts and assemblies, composite manufacturing generally requires a higher level of in-process inspections, as many anomalies cannot be identified after fabrication. Inspection must also assure that manufacturing complies with material and process specification requirements during production since deviations from those requirements will affect performance of the fabricated part. For example, one of the most challenging processes, structural bonding, requires stringent process controls and a thorough substantiation of structural integrity.

Quality management systems may implement a variety of tools to ensure consistent composite production, such as supplier testing, receiving inspection tests, in-process testing, NDT, or destructive test sampling. The type and number of inspections are typically related to the criticality of the part. Changes to materials and processes, which are common in manufacturing environments, require recertification.

3.2.5 Module 2.5: Maintenance implementation

Module 2.5 focuses on the challenges and importance of maintenance and repair considerations in CSET. Maintenance should be considered during the development of composite structures. At the time of entry into service, guidance must be provided to operators, and Instructions for Continued Airworthiness (ICA) should be provided as part of initial type certification. Although not required, most manufacturers publish a structural repair manual (SRM) with approved repair information. Structural substantiation should integrate damage tolerance, inspection, and repair.

Few standard practices exist for repair designers or technicians. Repair of Composite aircraft structure lacks maturity compared to metal structure repair, and materials and processes vary among manufacturers. Repair technician training is not standardized, and there are limited reliable competency assessment measures for those involved in composite structural repair.

Inadequate knowledge of base structure materials, processes and design philosophy, less-controlled repair environments, and significant structural damage that is not visually apparent are among some of the most prevalent challenges of composite structural repair. Additionally, bonded repairs have size limitations due to limited confidence in detecting understrength bonds

Repair designs must meet the same performance requirements as the original aircraft structure, relying on adherence to approved materials and processes to restore the original part strength and stiffness. Repair procedures should be sufficiently detailed to account for the lack of standard techniques, and often require significant knowledge transfer among design approval holders and maintenance facilities.

3.3 Design development

3.3.1 Module 3.1: Structural design details

The focus of module 3.1 is to examine various assembly and structural component designs, which are classified by application and function. Examples of assembly designs include the pressurized transport fuselage, light gauge monocoque design, and the main torque box of wing or stabilizer. Generic component designs include tubes, beams, sandwich panels, stiffened panels, stiffeners and stringers, ribs and frames, and lugs/fittings. Generic component designs may be used in commercial, general aviation, and helicopter applications and functions. For example, the generic sandwich panel component may find application in control surfaces by supporting multiaxial in-plane, flexural, and pressure loads.

Challenges to structural design are also presented in this module, in which include choosing among design and manufacturing alternatives when weighing manufacturing costs, structural design challenges, systems interface, and nonrecurring development costs. Stiffened skin panels, spar and beams, frames and fittings, and sandwich components are structural categories that have differing fabrication issues, as well as unique composite structural design challenges. Examples of critical issues in design may include in-plane stress concentrations (cutouts, attachments), out-of-plane failure mechanisms (ply drops, structural terminations), and delamination or disbonding in typical angle bracket bolted joint fittings, sandwich panels, and tubular components.

3.3.2 Module 3.2: Design considerations for manufacturing and maintenance

Module 3.2 provides the student with an understanding of the design considerations and their variables and relationships. Material properties are affected by the linkage among fabrication processes, potential defects, and structural configurations. An example of the effect of damage size and defect type on compression strength is shown in Figure 5 (Whitehead, 1991), which illustrates the effect of how different linkages to be considered in design.

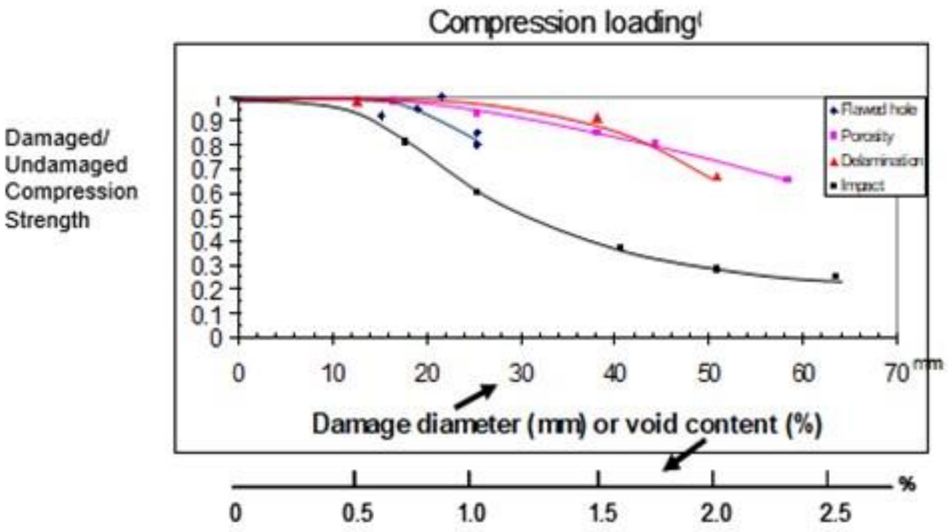


Figure 5. Compression strength due to defect size and type

Tool and tolerance requirements determine the manufacturing and tooling processes selection and cost. Material properties, part strength, and stiffness are reduced by flaws induced by processing, including issues associated with material handling, material layup methods, lack of adequate laminate compaction, tooling, and cure cycle. Other potential issues include heat exothermic reactions, matrix cracking of thick parts cured by autoclave, and the creation of resin pockets. Many of these issues are important in composite repair, especially in field maintenance locations, which do not have the capabilities of a dedicated factory.

Following design guidelines associated with different fabrication and assembly methods can support lower part costs and consistency in meeting design and part performance, while reducing nonconformance and the related production delays and rework costs.

Design criteria, materials, and structural configurations may affect both manufacturing and maintenance. Composite structural components should include inspection methods available to both manufacturer and customer, minimize the need for more costly nondestructive inspection (NDI) and should allow for easy backside/internal visual inspection, ensure that metal fittings or interfaces with metal parts can be visually inspected for corrosion and/or fatigue cracking, and ensure visual accessibility of both external and internal surfaces.

3.3.3 Module 3.3: Other design considerations

Module 3.3 explains other design considerations that affect structural design. Flutter, crashworthiness, fire safety, and lightning protection are additional considerations during structural design. Flutter is a structural oscillation, which occurs at certain frequencies and mode shapes. Flutter is self-exciting, and its characteristics are affected by design changes. Each aircraft product type has unique regulations governing the crashworthiness of aircraft structures, and composites display different failure mechanisms providing different levels of energy absorption. Lightning protection design features are required for composite aircraft structures, and lightning protection design features are generally required for composite aircraft structures.

Composites are more vulnerable than metallic structures to moisture absorption and heat, UV radiation, lightning damage, and erosion, adding requirements for protection and material selection. In addition, damage protection methods must be incorporated in design. Carbon composite parts must be isolated from adjacent aluminum structures to prevent galvanic corrosion.

3.3.4 Module 3.4: Design requirements, criteria and objectives

Differing composite failure modes and propagation mechanisms that combine to affect structural failure which must be accommodated in design requirements, criteria, and objectives. Certain design practices are incorporated to address prevention and management of potential structural failure, such as the use of laminate layup and ply drop rules to avoid delamination and test criteria for allowable impact damage. Failure may be fiber- or matrix-dominated. Composite notch sensitivity, illustrated in Figure 6, is a design driver for static strength (both tension and compression), and damage zones that relate to design details can relieve stress concentration in fiber dominated laminates.

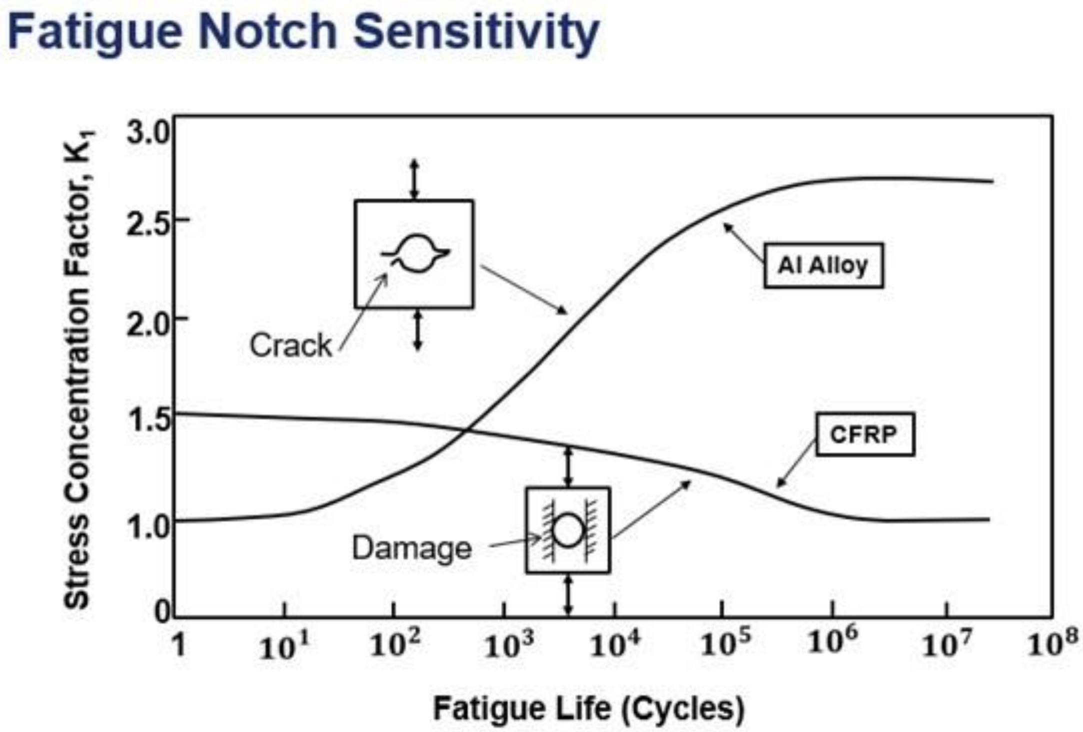


Figure 6. Composite stress concentration under fatigue compared to metal behavior

Local failure modes often combine in the failure of composite structures, with the likely dominant failure mode originating at a stress concentration. Composite design details, manufacturing defects or field damage, which causes stress concentrations, will result in lower static strengths under most loading conditions.

Temperature, moisture, and exposure to environment affect composite properties. Composite properties are influenced by environmental factors and must be accounted for in design and proof of structure substantiation. Examples of These environmental considerations are aircraft ground and in-fight temperatures, thermal analysis parameters, moisture absorption, and UV exposure. Design criteria and other design constraints are often used to establish consistent practices for a given product type based on the application and environmental exposures.

Design criteria and related documentation guides should demonstrate a disciplined process for design, material and processing selections, analysis, linkage to fabrication processes, and repair design and processes. Design documents can facilitate more effective IPDTs, by defining consistent design practices that meet customer requirements while minimizing cost and weight, thereby increasing product value.

3.3.5 Module 3.5: Lamination theory and design

Composite laminated plate stiffness characteristics, microstructural scaling issues, and other composite theories can facilitate efficient design. Composite materials are non-isotropic, and consistent terminology must describe the properties in each direction since strength properties vary with direction and orientation of loading.

The mechanics-based approach to classical laminated plate theory includes extensional and bending stiffness predictions as related to laminate layup, as well as related coupling phenomena and the effect of stacking sequence on laminate bending and torsional properties. Analyses to evaluate free-edge stress conditions, including concentrated out-of-plane normal and shear stresses, provide insights on the effects of finite specimen geometry on apparent strength. In this context, Figure 7 (Humphries, E.A. and Rosen, B.W. Materials Science Corporation, 1993) shows as a separate document. General guidelines are available for the selection of durable, damage tolerant laminate layups in structural design.

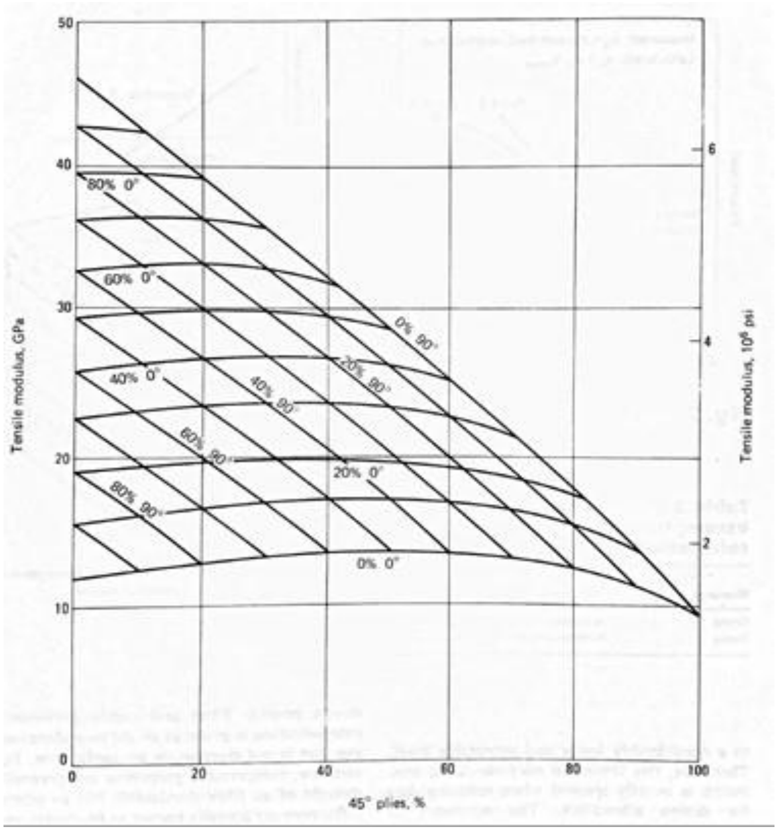


Figure 7. Properties affected by fiber orientation

3.3.6 Module 3.6: Composite analysis methods

This module addresses the methods and challenges involved in analyzing the stress components in composite structures. Typical stress analysis checks are described for a variety of configurations. Analysis challenges include defining appropriate design assumptions, criteria and limitations, experimental data needs, and analytical modeling. Most design sizing strength checks account for in-plane and out-of-plane stress concentrations and require semi-empirical failure criteria and simplifying conservative assumptions. The effects of different-sized holes can change with structural geometry, including finite width and other size effects, laminate layup, stacking sequence, load conditions, laminate thickness, and specific material types.

Composite finite element analyses are essential tools for predicting the load paths in built-up and assembled composite structures. Structural internal load path predictions support the primary means of composite certification; analyses supported by tests are essential when semi-empirically deriving composite design values from mid-pyramid building block tests. The results of analysis might, for example, identify accurate load path predictions and potential progressive damage mechanisms.

Progressive damage modeling is currently limited in accuracy and requires significant material-dependent input properties and large-scale test data to cover a range of real-world problems. The difficulty of simulating an impact damage in structural models is due to the combined effects of delamination, matrix cracking, and fiber failure occurring during impact damage, particularly with structural details that involve bonded or co-cured stiffening elements. Therefore, impact damage assumptions for a given structural design rely on impact test surveys and conservative design criteria applied in scaled test data collection for post-impact residual strength.

3.3.7 Module 3.7: Design development

Module 3.7 explains how design values impact the development of composite structures. Design values must link to the specific materials and processes used to fabricate parts, the analytical methods that will utilize the values, and the design details. They must also account for the variability introduced by both the materials and the fabrication methods used to produce the final product. Any values derived prior to controlling processes for a stable and repeatable product may not reflect the actual capacities of the product, adding to increased cost and schedule requirements.

Material allowables, typically developed at the lower levels of the building block, control the raw materials and provides the basis in the simplest design properties with statistically significant numbers of tests. The confidence of derived material variables must account for variability in testing results, which is typically higher for composites (B_c) than for metals (B_m) in Figure 8 (Spendley, 2012).

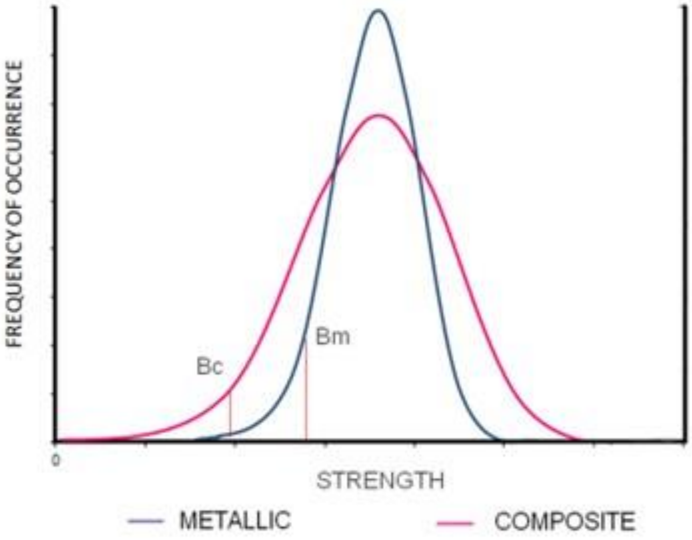


Figure 8. Comparison of composite and metal variance

While design values derived at higher levels must account for variations in material and fabrication processes, repetitive testing is usually impractical. Typically, larger-scale tests include structural details with stress concentrations, such as holes, attached stiffening elements, and structural joints. Allowable damage and manufacturing defects apply conservative design criteria or design features to reduce scatter. Knockdown factors, based on empirical and analytical evidence, are additional assumptions used to obtain the design values used for calculating safety margins.

Statistical process control (SPC) provides a means for monitoring the consistency of any process parameter that is measurable. Control charts for key process parameters are tools used to determine whether a process is in a state of statistical control. The data used to establish material and process controls come from qualification efforts and manufacturing scaling trials.

3.3.8 Module 3.8: Structural bonding

Adhesive bonding, co-bonding, and co-curing transfer loads through shear. The three methods for joining composite or composite-to-metal parts may use configurations that include single or double overlap, simple lap, step-lap, and scarf joints. Sandwich panels involve another type of joining in which the face sheets attach to honeycomb or foam core materials. All joints formed with adhesive, or matrix materials, may have the same manufacturing defects that exist for composite lamination, including porosity, disbonds, delamination and inclusions, creating unique challenges.

One objective for the design of any bonded joint is to design for failure to occur in the adherends, or substrates, or within the bulk adhesive, which is primarily under shear loads. Shear load capability is also affected by structural design details, such as adhesive thickness in Figure 9 (Ruffner, 2020).

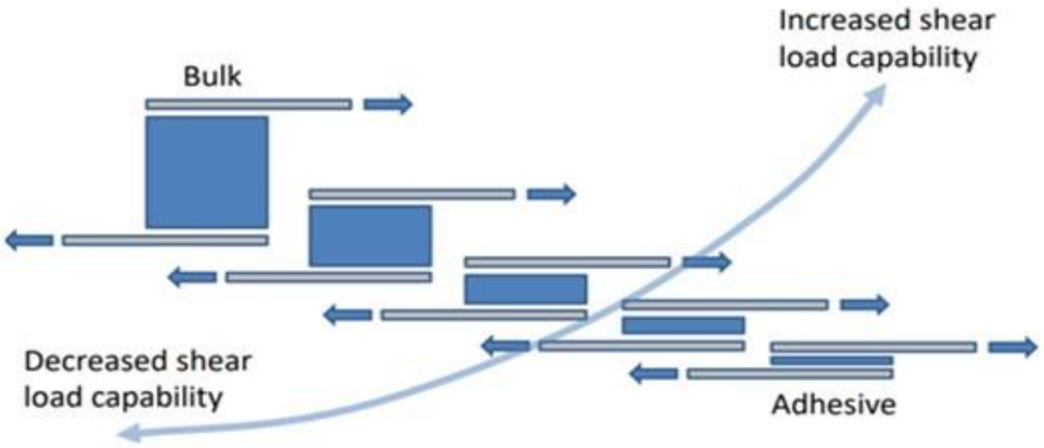


Figure 9. Shear load capability

In addition to production bond defects, bonded joints may fail by adhesion failure along interfaces. Adhesion failure is an unacceptable failure mode since it is unpredictable and implies understrength or weak bonds caused by contamination or poor processing, such as faulty surface preparation. Cohesion failure of the adhesive or substrate are both acceptable failure modes but a mixed failure mode that is a mix between adhesion and cohesion failure requires added focus if significant evidence of adhesion failures is present.

Adhesives behave elastically at lower shear stresses but can exhibit plastic and other nonlinear behavior at higher shear stress levels at the ends of a joint. Adhesive bonded joints and repairs therefore must have adequate overlap length to provide an elastic behavior, where the shear stress trough is zero in the middle of the joint. This often also provides creep and fatigue resistance of bonded adhesive joints.

3.3.9 Module 3.9: Structural bolted joints

This module examines joint configuration and the resulting effects on fastener load distribution, which defines bolted joint selection and the mechanical joint test verification program. Failures at fastener hole locations may be one or a combination of several basic failure modes, and general guidelines for preliminary design exist for edge and side distances and fastener spacing. Each failure mode typically relies on semi-empirical strength predictions that depend on many design variables that affect test matrices defined for structural development and verification. Higher strengths are obtained using fastener types specifically developed for composite materials.

A balance in the stiffness of individual joint elements should minimize peaking of bolt shear loads. Load sharing between fasteners is influenced by step thickness, fastener material and diameter, and clamp-up pressure. Transition or close tolerance hole fits are not acceptable due to the potential for hole damage during fastener installation, especially in thick laminates. This damage includes various combinations of broken fibers, delamination, and matrix cracking. Common laminate layups strive for near quasi-isotropic stiffnesses, with some allowed variations depending on load levels.

A simplified finite element analysis (FEA) model, utilized to predict load share in the form of bearing/by-pass loading obtained for various fastener flexibilities, will base failure predictions on specified checks around the circumference of the bolt hole. Design rules apply the sizing checks to evaluate different failure modes around the hole, conservatively addressing the effects of structural geometry and joint element finite widths. The semi-empirical nature of such analyses leads to reasonably accurate predictions, with some conservatism for joint process variations.

3.4 Structural substantiation

3.4.1 Module 4.1: Regulations and guidance

This module addresses regulations and guidance for proof of structures, including aspects of each major regulation for airframe structural compliance and the related implications. These aspects include a focus on static strength and deformation and fatigue and damage tolerance (F&DT) for three different product types, including small airplanes, transport airplanes and rotorcraft. Small rule differences regarding F&DT exist among the different product types, but structural compliance requirements, objectives, and damage category requirements retain overall similarity. As further noted in AC 20-107B (AC20-107B, 2010), compliance procedures and related technical issues yield many of the same considerations for static strength and damage tolerance requirements, often facilitating combined tests and analyses for structure particularly at the larger scales of study.

As damage severity increases, milestone load levels are defined as allowable damage limit (ADL) and critical damage threshold (CDT) , resulting in damage categories. Each category has specific guidance as described in AC 20-107B (AC20-107B, 2010), as shown in Figure 10, which also provides a framework for placement of damage threats in categories.

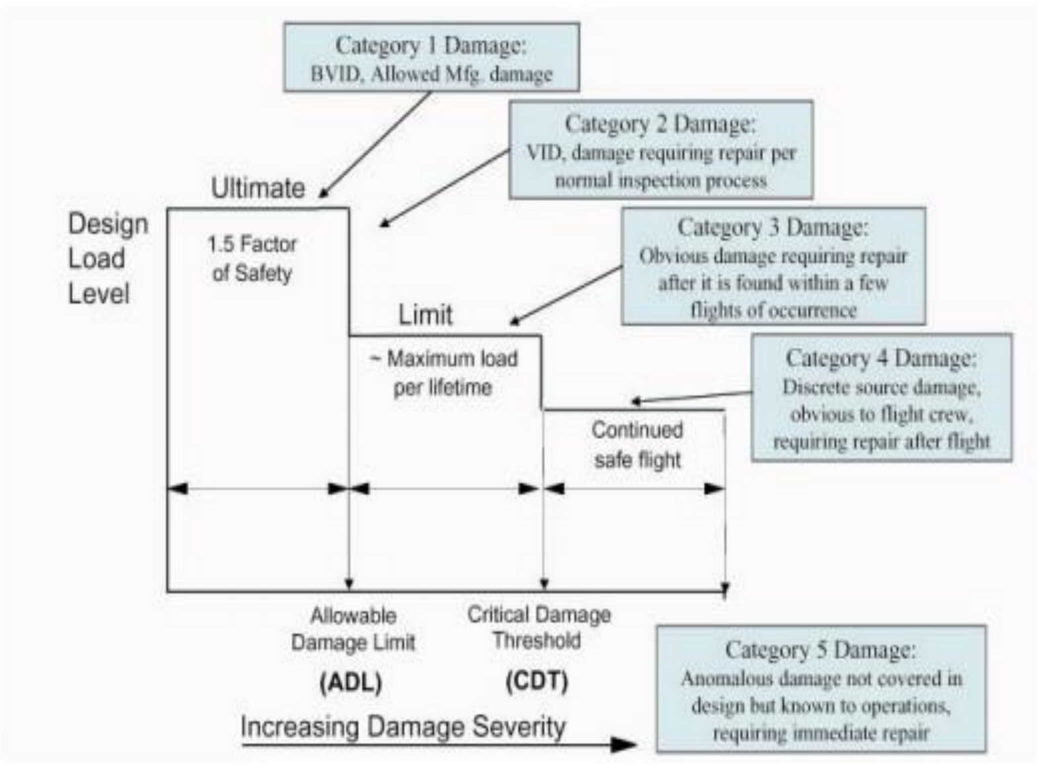


Figure 10. Damage categories and design load levels

For composites, damage, manufacturing defects, and stress concentrations are important for static strength, deformation, and F&DT. Assessing allowable damage and defects often merges with substantiating fatigue and static strength since relatively small flaws typically do not grow with repeated operating loads. These small flaws in composites can be retained in structure for life without loss of static strength. As a result, fatigue is often not a design driver for composite structures, and it is common to couple fatigue and static strength substantiation from coupons through large-scale tests. This substantiation methodology is typically not possible for metals, and those transport airplane regulations for F&DT oriented to metals applications have often required composite guidance interpretation.

3.4.2 Module 4.2: Certification approaches and related considerations

For this module, two primary certification approaches are examined: 1) certification by analysis supported by test, and 2) certification substantiated by test only. A third alternative, certification primarily by analysis, is rare and only allowed under certain circumstances. Most transport airplane and rotorcraft certification programs utilize the certification by analysis supported by test methodology. However, this approach has typically required more testing compared to metallic structure, which increases certification costs. Some small airplane certification programs find the certification substantiated by test only method more cost efficient, but those programs can experience some weight penalties due to structural overloads that are common with this approach.

Deterministic and probabilistic approaches for damage tolerance, used individually or in combination, support certification of composite aircraft structure. Both deterministic and probabilistic approaches can support static strength, fatigue, and damage tolerance for composite aircraft structure, supported by appropriate design criteria, structural tests, and analyses.

Impact damage growth, delaminations, and disbonds typically involve compression and shear loads, or out-of-plane loads, and sensitivity of the structure to damage growth must be assessed by applying no growth, slow growth, and/or arrested growth approaches. Most composite applications use a no growth approach for structural substantiation. Avoiding composite damage growth is desirable, including customer satisfaction by reducing the need for NDI procedures to detect damage growth.

Close coordination with the regulatory authorities is required to approve a certification test plan, and several iterations may be necessary. Substantiation documents normally include design allowables, analysis methods, static strength analysis, fatigue analysis, damage tolerance analysis, SRM allowable damage limits, SRM repair strength analysis, and repair damage tolerance analysis. Despite the terminology reference to analysis, most efforts, including those using certification by analysis supported by tests, are strongly dependent on the use of semi-empirical design values, with analysis relating to load path predictions. This methodology is due to the difficulty of assigning damage metrics to many accidental damage types and complex damage accumulation affecting local stress concentrations and load redistribution prior to structural failure.

3.4.3 Module 4.3: Addressing damage and defects

The goal of a damage threat assessment is to determine damage and defect types, with locations and severity levels that may possibly occur in the structure during manufacturing and service.

Strength also depends on material attributes and construction, as shown in Figure 11 (CMH-17, Volume 3, Chapter 12, Revision G).

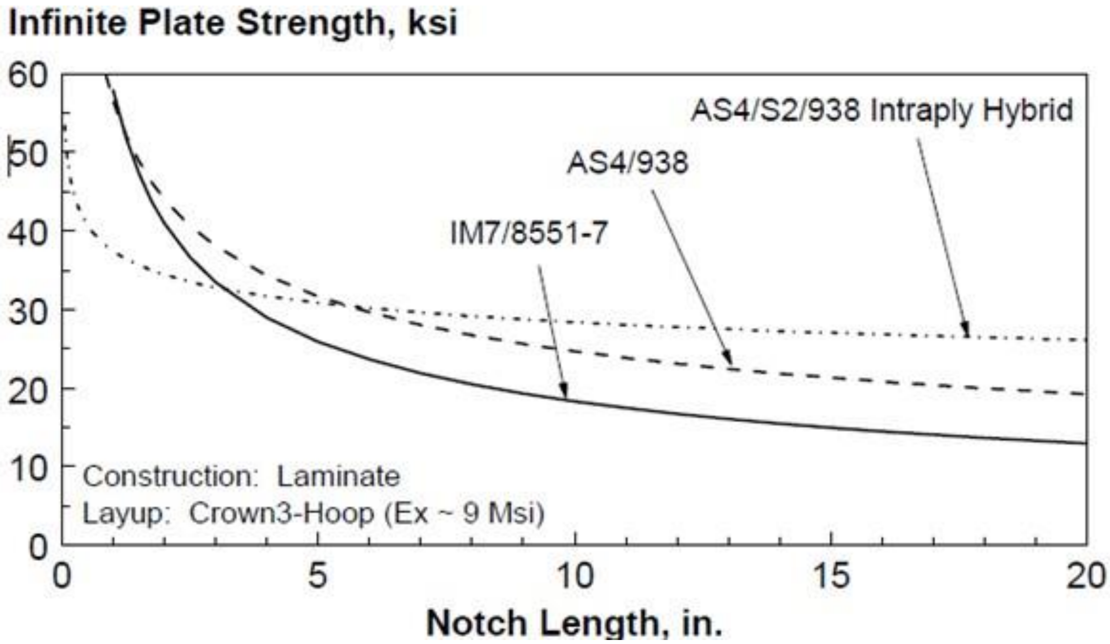


Figure 11. Material effects on tension-fracture strength

Damage-related design criteria are selected to address many of the identified threats and ensures coverage of the least detectable but most serious damage of a particular type in design and structural substantiation. As a result, the design criteria should 1) specify representative and conservative damage and defect types, locations, and severity levels used for each category of damage identified by the damage threat, and 2) link selected damage and defect types, locations, and severity levels to the probability of detection for production and service inspection methods.

Structural impact damage includes matrix damage, consisting of delamination and matrix cracks, in addition to disbonding, fiber breakage, and sandwich core crush or fracture. Remote damage can occur away from the impact location. Details of the impact damage are strongly dependent on many impact variables and structural details. Internal impact damage spans an area greater than visual indications, and visible damage on one side of a composite may not reveal the full extent of damage. Design criteria that cover a range of damage scenarios, while allowing practical design and affordable structural substantiation, will generally be conservative.

Factors affecting the placement of damage threats in categories include design requirements, objectives and criteria, inspection methods, and other factors such as service experience, costs, customer acceptance and workforce considerations. Categories of damage provides a means of compliance for many complex damage types. Assigning a damage metric such as crack length when analytically addressing potential composite growth and residual strength is an example of this complexity. Impact surveys are used to determine impact events to define damage detectability for each detail, including various impactor geometries. Impact damage threats require sufficient structural assessments to identify impact damage severity, critical impact locations, and the corresponding damage detectability for design and maintenance.

Typically, aircraft structures are loaded in more than one direction and, in some cases, need to be designed as fail-safe structures. Multiple load path structure designs that demonstrate structural damage capability can present a high level of robustness. Secondary loadings can also occur because of aircraft environments and structural loading conditions. These load types require special attention in the design of many composite structural components such as laminated composites as the loads are often in the weak direction of many composite material forms.

3.4.4 Module 4.4: Building block testing and analysis

Module 4.4 explains the building block approach, illustrated in Figure 12 (CMH-17, Volume 3, Chapter 4, Revision G), as an essential element in the development of composite structural substantiation due to the multiplicity of failure modes and the need for risk reduction and cost control.

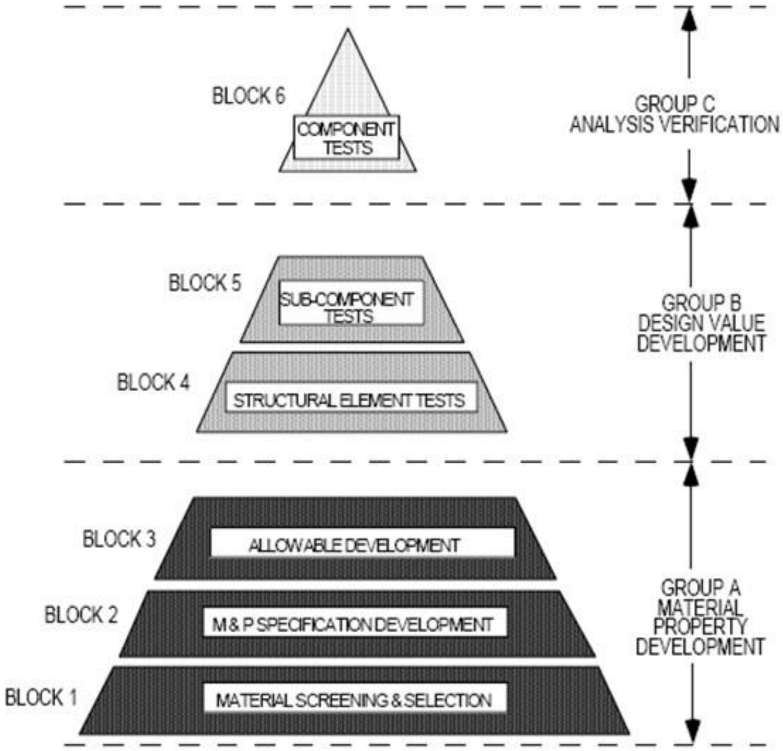


Figure 12. Building block approach

Testing aligns with design criteria, structural design details, and the certification approach. Design optimization often occurs well before detailed design development since building block costs, manufacturing development, and maintenance considerations require design constraints to control both recurring and nonrecurring costs. Substantiation of composite structural performance and durability consists of a complex mix of testing and rationale analyses, which often have semi-empirical relationships with larger-scale design detail tests. This is particularly true for static strength, damage tolerance, and fatigue assessments.

Design values must account for variability in materials and processes. Whereas material and process variabilities are assessed at the coupon levels of the building block, element and detail levels address the variability associated with part fabrication and assembly steps. Mid-pyramid tests also address complex failure modes, whereby nonlinear buckling and local failures lead to load redistribution prior to failure of the structural detail. Metal and composite structural behaviors often are similar, especially under high-tensile loading conditions. The compression and shear behavior of composites may start in a manner similarly to metal structures but, due to sensitivity to stress concentrations, final structural collapse is likely different. In addition, the in-service environment can affect structural performance, and details on how to account for the environment needs attention during larger-scale testing and overall structural substantiation.

Determining the average life for aircraft structures must account for uncertainties associated with a) factors, such as materials, failure modes, and interaction of design features, and b) the design spectrum versus actual aircraft loads and usage environments. Fatigue testing for composite material uncertainties may alternatively utilize two methodologies, entailing a) the life factor involving additional fatigue cycles, or b) the load-enhancement factor utilizing increased loads. Although highly fatigue resistant, composites are generally notch sensitive, including strength-dependent stress concentrations coming from structural details, accidental damage, and manufacturing defects. Fatigue testing for composites usually demonstrates “no growth” of damages and defects, whether it is associated with structural details, such as bolt holes, accidental damage from foreign object impact, or manufacturing defects. For relatively small damages, no growth demonstration provides a basis for allowable damage or defects. For large damages requiring repair, fatigue testing supports maintenance procedures similarly to metals. Fatigue test costs can be high and may require design constraints to minimize nonrecurring development and certification costs. Conservative design criteria for both small and large damage directly relates to lower test costs but may add weight penalties.

Composite structural substantiation involves the prediction of structural load paths through predictive analysis. Substantiation of structural performance and durability of composite components consists of a complex mix of testing and analysis. Validating analysis methods with test results should consider major load paths, secondary loading, damage state, and failure modes. Many other composite analyses include semi-empirical design values, collected at coupon, element, or subcomponent test levels. Material and/or process changes must be managed, and new data will be necessary to cover significant changes. Certification by analysis supported by tests methodology, while more expensive during development, is more cost-effective for evaluating changes later during the life of the structure, compared to certification primarily by test.

3.4.5 Module 4.5: Large-scale testing

Module 4.5 examines the benefits and challenges associated with large-scale testing approaches for composites. Environmental effects of large-scale structural tests are frequently conducted at ambient rather than critical environmental conditions. This approach is particularly effective due to difficulties in achieving long-term equilibrium moisture content in larger representative structures. Full-scale test article quality must be representative of production parts to capture nondetectable characteristics and material architecture. Failure mode correlation across environmental conditions is necessary to conservatively cover all environmental conditions through environmental overload factors at ambient testing. In addition, interactions between the environment and internal loads are important for composite/metal hybrid structures, and environment-induced internal loading caused by thermal expansion mismatch must evaluated.

Structural test setups and loading conditions depend on the application, including tests for aircraft wing, unpressurized and pressurized fuselage, discrete attachment points, such as jackscrew and pivots for the horizontal stabilizer, and the vertical stabilizer. Full-scale test objectives will vary depending on the integration methodology, and the certification approach selection, *analysis supported by test* or *primarily by test*, defines the number of load cases to be demonstrated for a large-scale test article. Large-scale tests are an important part of the analysis validation for both composites and metals and require evidence of accurate load path simulation for use of design values for structural details in predicting strength. This includes the secondary load conditions best simulated in built-up structural assemblies.

Development of an integrated large-scale test program must consider the unique responses of composite and metallic structures, when both are present in aircraft structures, and require proper coverage in substantiation. Large-scale composite tests often include acceptable manufacturing defects and allowable service damage. Separate metal and composite fatigue tests are difficult due to the differences in critically repeated load spectrum. In addition, there is often a difference in overall fatigue test goals, with metals emphasizing sites of crack initiation and with composites demonstrating of no-growth for acceptable manufacturing defects and damage.

3.5 Manufacturing interface

3.5.1 Module 5.1: Quality control

Module 5.1 of the CSET course explains the role of quality control in all phases of composite structure development. Manufactured part quality depends on the control of critical factors during the manufacturing process. Critical factors include tooling design and practice, assuring proper inspection of manufacturing steps, and adherence to specifications as part of type design. Laminated thermoset fabrication processes contain quality control steps to address these factors for composites. Identifying and monitoring key characteristics and process parameters must be a part of an effective quality assurance plan, which has both in-process and post-process quality assessments. Adequate quality control tools include a post-process records review of in-process measurements, physical testing of materials and parts, and NDIs.

3.5.2 Module 5.2: Certification conformity process

Module 5.2 of the CSET course explains the certification conformity process. Conformity defines inspections to ensure that test articles used in certification are manufactured in accordance with documented procedures. The conformity process used during certification ensures that manufacturing processes are followed when building test articles and is required at all levels of building block testing. Many composite part requirements cannot be nondestructively inspected after fabrication or assembly, and conformity inspections should begin before part production and continue through in-process steps.

Static strength and F&DT test articles need to include intentional flaws and damage, which is subjected to conformity checks. In addition, any changes to the type design after test articles have been conformed requires substantiation.

3.5.3 Module 5.3: Manufacturing defect disposition

This module explains how defects and anomalies are characterized and handled throughout the composite structure process. Anomalies are present in all composite parts, but only become a defect when the part no longer meets its design property requirements. Terminologies associated with anomalies include flaws, damages, and defects. Sources of anomalies can originate from manufacturing operations, assembly-related handling, and service environments. Bondline integrity issues closely relate to bondline thickness, improper cure process, and weak bonds.

A part or assembly rejected with an anomaly determined to be a defect must be identified, segregated, and dispositioned through the MRB, which typically consists of representatives from engineering, quality, manufacturing, and other functions as required. Disposition of rejected parts may be use-as-is, rework, repair, or scrap, taking into consideration part criticality, specific structural locations, and performance requirements (see Figure 13 (Corrective Action Board Overview, 2016)). The MRB is also engaged in trend analysis and corrective action efforts.

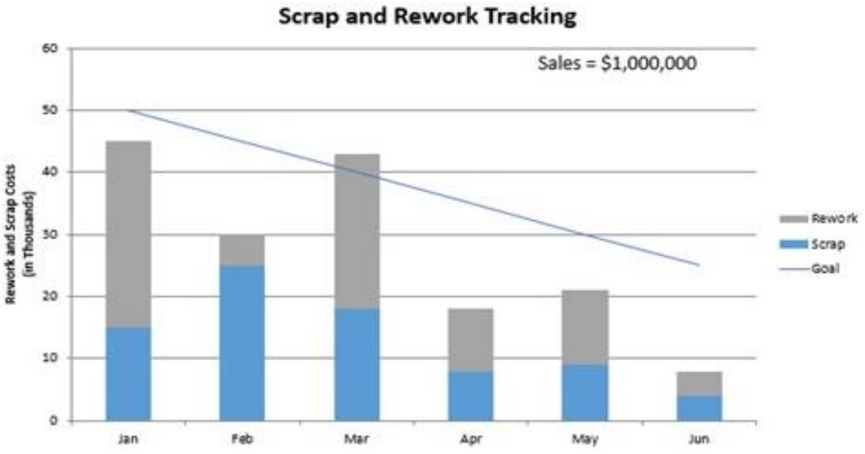


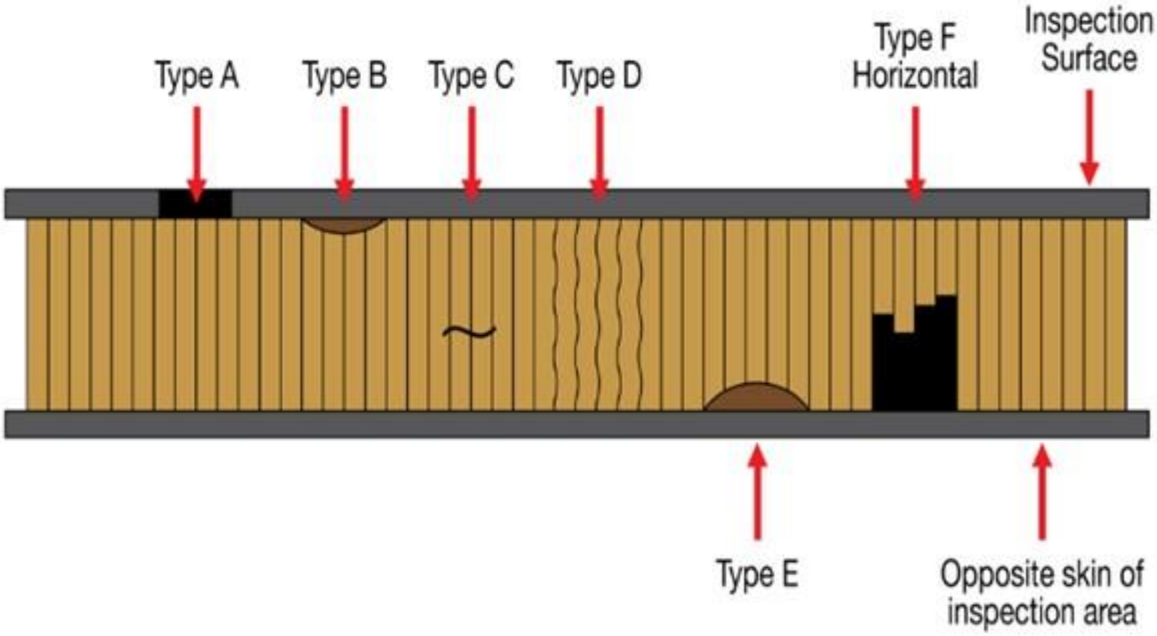
Figure 13. Corrective action board overview

3.6 Maintenance interface

3.6.1 Module 6.1: Inspection and maintenance

Module 6.1 of the CSET course describes the inspection and maintenance process for composites. Nonconforming parts are characterized by a variety of NDT techniques prior to disposition. While production environments frequently rely on through transmission ultrasonic techniques, in-service environments typically utilize tap testing and pulse echo ultrasonic methods. Visual inspection is the first line of defense, and additional NDI techniques are required to fully assess the extent of visually detected damages. Damage scenarios which are not fully characterized using traditional inspection methods include fiber failure, delamination, sandwich core damage detection, and weak bonds.

The range of potential damage events in a sandwich structure is depicted in Figure 14 (Nondestructive Bond Testing for Aircraft Composites). The damage characterization of each event will vary depending on inspection methodology.



Type A — delamination between plies of outer carbon fiber-reinforced plastic (CFRP) skin, parallel to the surface
Type B — disbonding between the outer skin and the honeycomb core
Type C — cracked honeycomb core parallel to the inspection surface
Type D — crushed honeycomb core in parallel area
Type E — disbonding between inner skin and honeycomb core
Type F — fluid ingress in honeycomb core

Figure 14. Sandwich damage events

Damage types are categorized from 1 to 5 for increased severity. Structure should be designed such that ultimate load can be carried with barely visible impact damage (BVID) to compensate for impact damages that may go undetected whenever visual methods are used for damage detection. For visible impact damage (VID) ranging from small to larger damage, structure should carry limit load. NDI procedures must detect damages prior to load degradation and be able to accurately quantify the extent of the damage so that effective repairs can be performed.

Damage tolerant design is closely associated with a wide range of maintenance capabilities and practices and integrated into structural substantiation efforts. Probability of detection studies for Category 1 damage use deterministic and probabilistic approaches, and those studies should validate that Category 2 through 4 damages will be detected through defined inspection intervals.

3.6.2 Module 6.2: Structural repair development and substantiation

Structural repair substantiation as an important component of commercial transport certification. Various strategies should be defined early in the design process, as shown in Figure 15 (Ilcewicz L. , 2000).

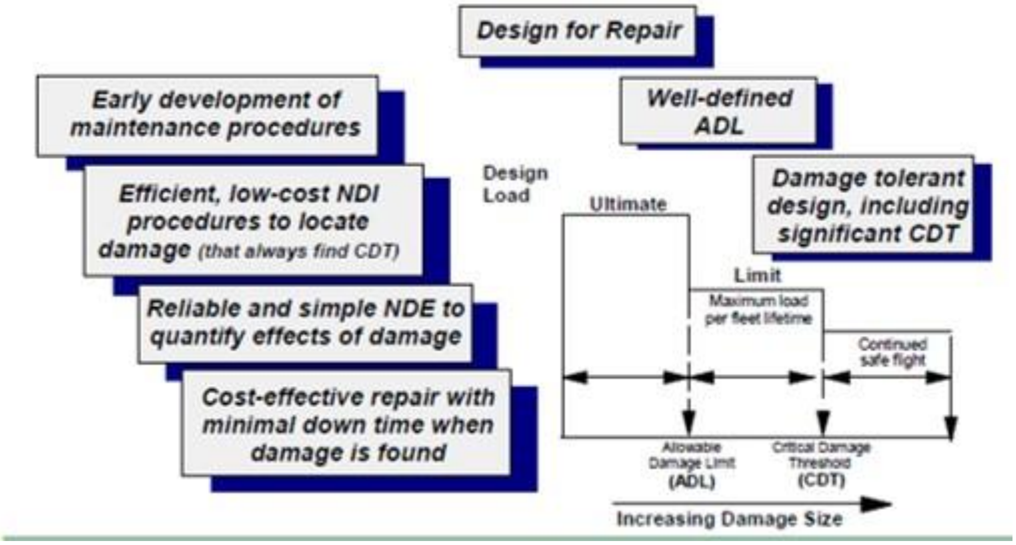


Figure 15. Strategies for composite maintenance technology development

Damage configurations are affected by various factors, including energy and velocity of the source of damage, composite part configuration and material properties, and susceptibility to cyclical loading over time. Viewing damage on one side of a composite normally does not reveal the full extent of damage, and nonvisible damage resulting from large high-energy blunt impacts may hide large damages that are difficult to characterize.

Flaws or defects that occur in manufacturing or maintenance, and which are undetected by the selected inspection schemes, must retain ultimate load and residual strength load requirements when subjected to repeated load cycles over the part lifetime. Primary composite structural components design must accommodate impact damages that may go undetected by having the capability of carrying ultimate loads, described as BVID. Damage to a composite component beyond the limits of BVID requires more rigorous NDI inspections and is considered VID. VID may be serious enough to reduce structural capability below that required to carry regulatory loads.

Repair designs must meet the same airworthiness requirements as the base aircraft structure, and composite inspection techniques and repair design, materials, and processes must be substantiated to meet airworthiness regulations. All composite inspection techniques and repair design, materials, and processes must be substantiated to meet airworthiness regulations. Repairs require validation upon completion, and process control through authorized procedures and proper equipment in a controlled environment is required, including repair process documentation.

3.6.3 Module 6.3: Teamwork

Teamwork is essential to accommodate the unique characteristics of composite materials, processes, and design details. Team participants should include a diverse base of skills, including those of repair technicians, inspectors, engineers, management, and original equipment manufacturer (OEM) support personnel. Required education, knowledge, and skills should be identified, and acquired skills should be continually demonstrated after initial training.

Effective maintenance and repair include structural inspection and damage detection, disposition of damage, repair fabrication, and resource knowledge when questions arise. The OEM utilizes many disciplines to ensure that the source documentation, such as the SRM, which contains guidance to perform accurate dispositions of damage, with instructions for performing approved repairs by operators, and maintenance, repair, and overhaul organizations (MROs).

3.6.4 Module 6.4: Repair techniques

Module 6.4 defines the various repair techniques used in CSET and explains the selection process for choosing the best method. Bolted and bonded repair techniques have advantages and disadvantages, and selection depends on geometry, configuration, and design objectives. Both bolted and bonded repairs require the restoration of any protective coatings such as paint and lightning strike protection. On-aircraft repairs under challenging environmental conditions require that permanent bonded and bolted repairs adhere to substantiated data, materials, and processes. Temporary bonded repairs, utilizing lower temperature cure materials, require inspection at prescribed intervals.

Repair depends on an understanding of the part geometry and other unique characteristics to assure thermal uniformity during cure. With this understanding, repair mechanics can utilize techniques and equipment to mitigate the potential for under- or over-heating of the part and its repair. The effect of heat sinks due to the higher masses of a frame and a longeron using a single zone heat blanket is illustrated in Figure 16 (Davis, 2004).

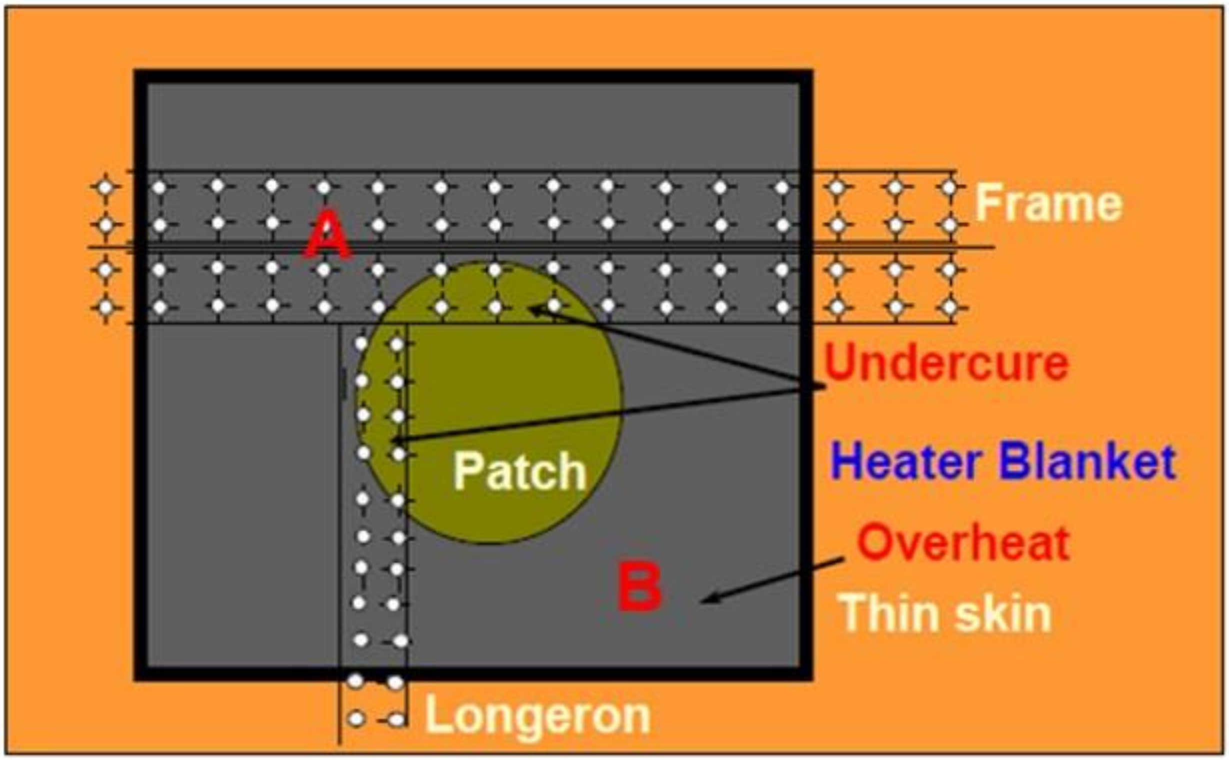


Figure 16. Zones A and B cure temperatures exhibit nonuniform heating

Nonuniform heating risks are higher with the increased use, size, and complexity of composites in commercial transports and can cause an improper cure outside of material specifications, requiring special processes and equipment. Mitigating heat sink issues to reduce heat gradients during cure may be addressed by a variety of process practices, heat sources, and controllers available or under development. Major contributors to non-uniform heating include heat sinks, complex heating environments, non-uniform heat sources, and high ply count composite laminates.

Proper repair techniques require skills and knowledge of the mechanic, but a deficiency in either can require repair, rework, or part scrappage. The following descriptions of repair activities and important issues lists common repair activities and important issues related to those activities. Table 2 lists the common repair techniques and the issues they address.

Table 2. Common repair activities and issues

REPAIR ACTIVITIES	IMPORTANT ISSUES
Damage removal	• Damage-mapping inspection techniques • Removal of damaged material
Bonded repair preparation	• Surface cleaning and preparation • Moisture removal and drying cycle • Ambient air humidity • Surface contamination including foreign objects
Bonded repair: ply collation	• Ply wrinkling, orientation, and location in the layup • Process cycles including pressure, temperature, and time schedule
Bonded repair: curing	• Uniform application of heat and pressure according to prescribed cure cycles • Pressure and heat source application alternatives • Porosity and voids • Matrix microcracking • Warpage, spring back, and delaminations
Bonded repair: process and procedure	• Patch selection • Resin and adhesive selection • Improper bondline thicknesses • Foreign objects • Under or over-cured adhesives
Bolted repair: patches, drilling, and machining	• Tolerances between repair patches and the base structures, including coefficients of thermal expansion compatibility • Shimming • Delaminations during drilling • Matched holes • Fastener selection • Patch orientation on base structure • Load path balance in repair design
Inspection	• Full damage characterization • Application and interpretation of inspection techniques

3.7 Other topics

3.7.1 Module 7.1: Flutter

This module describes the characteristics of flutter and its effects on composite structures. The module provides instruction on how to compensate for it within composite structures. Aeroelasticity is the interaction between inertial, elastic, and aerodynamic forces. Wing divergence occurs when aerodynamic load creates deflection or twist of the wing potentially leading to failure, known as flutter. As an example, aileron reversal may result in loss of lift on the wing due to aileron deflection.

Flutter is a structural oscillation that is self-exciting or self-sustaining and can occur at certain frequencies and mode shapes, extracting energy from the airstream due to motion of structure. Flutter vibration modes are determined by the mass distribution, stiffness distribution, geometry, and damping of structure and are excited by external forces that are independent of motion of structure. Design changes may affect flutter characteristics, including mass and mass distribution, airframe stiffness and stiffness distribution, and profile changes of aerodynamic shapes.

Large category 3 and 4 damages can alter flutter characteristics. Large damage can cause significant changes in structural stiffness, including different loading types that combine to cause dangerous flutter conditions. Any repair to a flight control panel must also consider mass or mass distribution effects on flutter characteristics even with retention of adequate residual strength margin.

3.7.2 Module 7.2: Crashworthiness

Crashworthiness is the ability of a vehicle to protect its occupants or cargo during a crash and includes concept development to limit crash loads transmitted to aircraft occupants. Crashworthiness is a systems approach with aircraft lay-out and design defining crash behavior, including structure, seats, seatbelts, cabin environment. Crashworthiness emphasis includes injury criteria and overall aircraft systems design to allow for survivability and emergency egress.

Crashworthiness regulations focus on occupant protection during the testing of seating systems and assumes a level of energy absorption from the airframe and certification requirements include peak-load pulse magnitude, direction, and duration. Special conditions are issued for new model airplanes with novel or unusual design features, such as the Boeing 787-8, due to carbon-fiber-reinforced plastic (CFRP) used in the fuselage construction.

The main failure mechanisms associated with crash energy absorption are flexural deformation, axial crushing, and bolted joint failure. Composites can fail in tensile-fiber fracture, compressive compressive-fiber kinking, matrix cracking, shearing, or delamination. Various loading conditions, loading speeds, and geometric features will promote or inhibit different failure mechanisms, thereby providing different levels of energy absorption. Structural element designs that have failure processes which absorb significant energy over large areas are of particular interest.

Certification by test is empirical and often used with seats and other applicable components and assemblies. The certification-by-analysis-supported-with-test-evidence approach relies on concurrent development of analysis methods and testing. The building block approach applied in such cases is also semi-empirical for translating complex failure modes, particularly for elements that absorb energy, into modeling simulations. This calibration is key to analytical validation for crash simulation. ‘Certification by analysis alone’ is not a viable approach for composites due to complex failure modes of key elements absorbing energy. Figure 17 (CMH-17, Volume 3, Chapter 16, Revision G) compares measured and predicted energy absorption for different configurations.

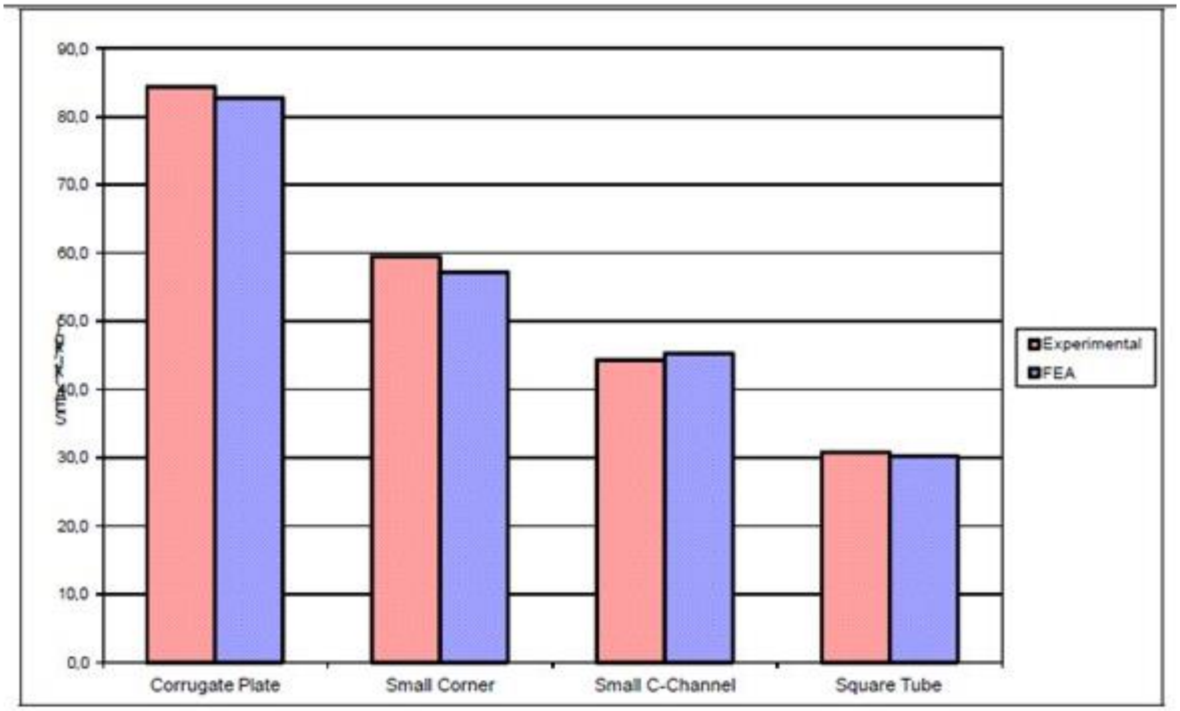


Figure 17. Crashworthiness energy absorption: analysis vs test

3.7.3 Module 7.3: Fire safety

Module 7.3 addresses the issue of fire safety in CSET and the regulations that must be considered. Fire threat concerns include in-flight fires, post-crash fires, and fuel tank flammability. In-flight fires occur within the pressurized area of the cabin during flight, and the safety objective for in-flight fires is to mitigate flame propagation in inaccessible areas. Survivability during a post-crash fire depends on successful occupant egress before flashover by prolonging a) fire penetration, and b) flashover by limiting cabin materials through enhanced certification fire testing. Composites in early transport fuselage applications have exhibited excellent burn-through protection compared to the melting of conventional aluminum structure. The safety objective for fuel tank flammability is to reduce vapor flammability levels of fuel tanks during all phases of taxi, takeoff, and landing.

Flammability regulations address cabin interior materials, and fuel tank flammability reduction and prevention of ignition sources. Each regulation must be reviewed to determine if modifying the structure and skin material will change the severity of the fire threat. Standard tests have been established to evaluate flammability for potential threats.

3.7.4 Module 7.4: Lightning protection

Lightning is a complex event that involves high current resulting from two areas in the atmosphere with opposite charge concentrations. Carbon fiber composites are susceptible to lightning damage, requiring specific lightning protection features. The lightning effect on carbon fiber composites includes resin vaporization and delamination at lightning attachment points, sparking and hot gas ejection at fasteners, and high induced current and voltage on wiring and tubes.

Lightning attachment zones define locations on the aircraft where lightning is likely to attach, and lightning zone definitions are required to support fuel system, structure, and system lightning protection. Protection concepts can prevent lightning puncture by adding metal to outside surfaces by using aluminum, copper or bronze mesh or foil, and selecting suitable fastener and fastener installation processes.

Lightning protection regulations address structure, fuel system, and aircraft systems. Lightning protection features required in showing compliance to regulations need special attention when carbon fiber composites are used for aircraft structure, particularly in composite fuel tank applications.

4 Prerequisite

The purpose of the prerequisite course material is to provide students with a basic understanding of composites technology and an overview of composites engineering prior to taking CSET. Students with composite technology backgrounds assess their knowledge by taking an exam to avoid studying the prerequisite material. Prerequisite content is presented in appendix E of this document.

5 Discussion boards

Discussion boards stimulate interactive discussions among students and instructors and are a critical part of the CSET course. Instructors facilitate the process utilizing their technical expertise as well as implementing a teaching methodology that follows a Socratic questioning technique, whereby students deduce the teaching points through their interactions with their instructors.

Discussion topics, also referred to as mini case studies during conduct of classes, provide experiential learning by considered real-world challenges to a) improve understanding of the content and its relation to safety management, b) enhance retention of the subject matter by engaging all participants in the course, and c) gain the perspective that issues often do not have a single answer but involve design and economic trade-offs during development of composite structures.

The discussions reinforce the concept that there is rarely one right answer, and that judgment and trade-offs, which include both economic and technical considerations, greatly influence design. This concept also is a major contributor towards the challenges of composite technology in establishing standard composite industry training and practice. In addition, discussion boards support the improvement of CSET content during development by identifying potential gaps in understanding.

The following are examples of topics, with the complete list provided in appendix D.

- Technical Characteristics for Composite Airframe Structures: How would you modify the list of top ten “Key Technical Characteristics for Composite Airframe Structures” described in module 1.0 in terms of a) additions or deletions, and b) order of importance? Alternatively, if you agree with the list without any changes as described in the reading material, how would you justify that conclusion?
- Material Specification Equivalency: A statement is made … “it is assumed by many applicants that all materials purchased per a material specification are the same.” Provide

your perspective on this statement, through actual or hypothetical examples and include your opinion as to how prevalent this assumption is in aerospace at present.

- Background note: As recently as the 1990s, a materials specification often included alternate materials, and the specification requirements were often minimum values since it was believed that an increase in base strength would improve all structural properties, with little to no links with material qualification tests. Current composite guidance does not accept such practice for material control.
- Material Suppliers: You are responsible for designing a secondary structure composite part. Purchasing has identified three suppliers that provide material to the same specification and is beginning a competitive bid. Selection is to be based on lowest price. From an engineering standpoint, you identify potential issues, and advise Purchasing as follows: (list one issue and expand on it).
- Values: There exist qualification values, design values, and acceptance values (the values that the incoming material must exceed to be accepted for use in the factory). Explain the relationship among the various values, including comparing the relative sizes of the values in a specific application
- Flutter: How can a repair affect the flutter characteristics of a composite sandwich flight control panel such as rudder?

The discussion board topics were developed as a key part of the education platform for CSET instruction and involve experiential training. Instructors may choose other topics to suit the needs of the student audience. The discussion forum also provides feedback to the training organization on further improvements in the content of the course.

In addition, students were given the option of providing essay discussions based on CSET content.

All discussion board entries are available for comment and discussion by the instructors and students. One outcome is that individual education organizations may continuously update and improve the discussion forum training content.

6 Course design and development

Following its first delivery in 2012, CSET was continuously improved through participant feedback

6.1 Learning venue alternatives

Three venues are described in term of advantages and limitations in Table 3 below in order to describe various methods for student outreach, with comments on advantages and limitations. For the CSET development, the asynchronous remote online format, Blackboard, was particularly well-suited due to the opportunity to involve global participant feedback among students and subject matter experts for continuous improvement.

Table 3. Alternative teaching formats and venues

VENUE	**ADVANTAGES**	**LIMITATIONS**
Classroom	• Fixed schedule • Little distraction from work • Face-to-face interaction with instructor • Short courses can be combined with other business trip agendas • Can combine with hands-on laboratory	• Teacher-centered, with quality of instruction highly dependent on instructor • Classroom learning experience is determined by instructor availability and student schedules • Costs associated with classroom environment • Experienced instructor pool available for classroom with fixed schedule is limited • Active discussion topics often focused on instructor experience and interests
Asynchronous Remote and On-Line	• Student-centered, with sharing of student and instructor experiences improving learning retention without location restrictions • Flexible time schedule • Discussion boards engage all students through online interactions in a non-threatening environment, compared to classroom learning • Experienced instructor pool, with instructors having a variety of backgrounds, is available through remote interactions • Cost effectiveness	• Insufficient allowance for student participation during work hours may occur, with study in those instances often performed off-hours • Certain organizations will not support concept due to work loads and requirements • Use of computers and software may require additional training for students
Self-Paced On-Line Tutorial	• Student-centered whereby students learn on an individual basis in the absence of instructor • Flexible time schedule	• Little or no instructor interaction • Little or no instructor sharing of content based on experience

VENUE	ADVANTAGES	LIMITATIONS
	• Ease of completion • Cost effectiveness • Continuous assessment of student progress	• Learning retention highly variable: Potential for passing assessment exams without learning material • Additional limitations similar to those in Asynchronous Remote and On-Line Venue

6.2 Learning theory: Asynchronous remote

Asynchronous online education methodologies provide students with an experiential learning approach, providing course content and utilizing discussion threads whereby students learn through interactions with student and instructor experiences and perspectives. It is distinguished from traditional classroom teaching methodology by emphasizing the involvement of students in learning interactively with experts in various fields and other students.

Asynchronous learning enables global education and involvement of the students, independent of time-zone and without location constraints.

1. Asynchronous learning usually appeals to a broader section of the professional student population due to its ease of access, schedule flexibility and cost effectiveness
2. Asynchronous learning utilizes the Socratic questioning learning methodology, described below, which is highly effective for comprehension and retention

Asynchronous discussions, made possible by digital technology offered by various learning management systems, are conducted based on Socratic questioning by the students, monitored by a subject matter expert and facilitator, with the goal of encouraging the students to discover specific teaching points through their course interactions. This effective learning process in an online educational environment includes the interaction among students, the interactions between faculty and students, and the collaborative learning that results from these interactions.

Assessment is based on exams and frequency and quality of student involvement in the discussions.

6.3 Student background based on prior CSET course deliveries (2016)

As part of the review process supporting CSET improvements, a detailed assessment of background, participation and feedback from students was conducted in 2016. This included students from CSET courses delivered between 2013 through 2015. Significant conclusions included:

1. 50% of students had experience in Composites Engineering; 90% were practicing engineers.
2. 25% of students had Aerospace Engineering and, by their own stated objectives, wanted to extend their knowledge into further Composites Technology and Certification practices.
3. Approximately two thirds of students came from the military, industry or National Aeronautics and Space Administration (NASA); the balance was primarily FAA and other regulatory agencies.

6.4 Process of development of CSET course content

CSET development began in 2011, with a detailed outline created in accordance with AC 20-107B and identification of primary contractors. The first course was taught in 2012. The following subjects were addressed:

1. Prerequisite
2. Challenges of composite applications
3. Design, material, and fabrication development
4. Proof of structure
5. Quality control
6. Maintenance interface
7. Additional considerations (flutter, crashworthiness, fire safety, lightning protection and structural coatings and paint)

Following a pilot course in 2012 and two courses in 2013, the following improvements were noted from student and participant feedback:

1. Prerequisite content established a common-knowledge baseline prior to entering the main CSET course.
2. Syllabus adequately described the course and its expectations from the students.
3. Students felt breadth of content also had practical application.
4. Asynchronous online education was convenient and accommodated work schedule and time zones.
5. Classroom mix of student and instructor backgrounds enhanced the learning experience; the student population included both regulators and industry representatives.

Areas of improvement were identified as follows:

1. Course scheduling over 10 weeks (online) was too aggressive for content expected of the students, suggesting an additional week to be added.
2. Discussion boards were too often design-specific and were only appropriate for practicing engineers. This suggested broadening the discussion topics to accommodate those students with less experience.
3. Tests were too infrequent and addressed too much content, suggesting an exam given in two-week intervals rather than one mid-term and one final.
4. The file structure for course content utilizing Adobe pdf files which accommodated PowerPoint slide notes were difficult to read and comprehend by many students.
5. The flow and format of the course content was uneven, inconsistent and did not have the proper emphasis in certain subject areas. In addition, duplication due to the input of many authors added volume to the content.
6. Students informally suggested that the prerequisite material was too detailed, and the perception of many students was that the content included more depth than the main course in areas such as composite design.

6.5 Improvements based on student feedback (2016 and 2020)

Two major improvements were implemented for CSET. The 2016 improvements emphasized course teaching processes, followed by 2020 changes which focused on modifying the detailed content in the CSET course.

Evaluations of the courses taught through 2015 through statistics and questionnaires to prior students, are exhibited in appendix B. These evaluations provided guidance for subsequent improvements in the course in both 2016 and 2020.

The following improvements were implemented in 2016 and 2020, with positive student feedback from subsequent courses:

1. Online course schedule was increased from 10 weeks to 12 weeks (including the Prerequisite), easing the weekly student reading and content assimilation burden.
2. Discussion topics were broadened to accommodate less experienced students.
3. Tests were provided in two-week intervals.

4. Adobe pdf files were replaced by Microsoft® PowerPoint® slides.
5. Course flow, content and format were implemented during 2017-2020.
6. CSET is nominally a 12-week learning experience when taught online. This length of time prohibited some potential students from taking the course. Therefore, beginning in 2021 students can take CSET in two 6-week modules for schedule flexibility.
7. Initial modifications to the prerequisite removed advanced (Level III) content. Additional changes to the prerequisite material are subject to further evaluation and development.

Improvements have been implemented during 2016-2021, with consistently positive student feedback for the three improved courses. In addition, CSET content received a major update in 2020, and appendix C correlates the earlier CSET modules with those in the updated course. Final improvements which include updated course flow, content and format were incorporated into courses beginning in 2020.

7 Conclusions

7.1 Summary

CSET provides an awareness of structural engineering issues and principles for practicing aerospace engineers as well as those new to the industry while highlighting safety implications. For professionals completing the course, such as FAA personnel, a practical application is the ability to oversee design, production, and maintenance organizations. The course content is at a 'safety awareness' level of education, Level II, with specific skills within these disciplines typically developed by industry and considered beyond the scope of CSET. As of December 2021, over 200 students have taken the course in an online format. Student feedback has been the basis for continuously improving content and delivery.

The development of CSET reflects the guidance and topic sequence of AC 20-107B. Additionally, subject matter experts in the various engineering disciplines were critical in developing the initial and revised content, and participating in as the course was being taught. CSET assumes some knowledge of composite basics and aircraft certification applications, as available in other base educational studies for these subjects or the course prerequisite module. The course starts with a summary of essential technical themes for composite aircraft applications, including a historical context on the related challenges in moving away from the predominant use of metals technology in critical structures to having composites in much of the flight vehicles surface area such as rotor blades, control surfaces, empennage, wings, and fuselage. The course is then organized to cover composite material and process control as an essential component of integrated product development before addressing design, manufacturing, and maintenance product development and certification. The above subjects consume the first half of CSET. The remaining course covers structural substantiation, including static strength and F&DT, followed by manufacturing and maintenance implementation. Flutter, crashworthiness, fire safety, and lightning strike protection are addressed as special considerations.

Essential to the continuous improvement of the CSET development process was the outreach to students through a learning management system which enabled collaboration and interactions on a global basis. This delivery method was also selected for both development and teaching which emphasized the following educational elements to achieve understanding and gain retention:

1. Content accessibility
2. Exam assessments
3. Interactions among all participants on real-life engineering design issues, often unique to composites technology (experiential education)

Interaction among participants with students and other experts broadens student understanding and improves retention of educational material. It provides the students with opportunities to learn from each other and subject matter experts through the use of discussion boards based on practical engineering scenarios and experiences. During these interactions, students realize that production and service challenges frequently involve design trade-offs, and that there is often not ‘one best answer’ or solution depending on details relating to a given problem.

While selection of venue for teaching students CSET is the choice of the educator, the course described in this report was developed and improved over time primarily using the Blackboard education platform, especially adaptable for asynchronous online training. Some experiences in using CSET for classroom style tutorials and short courses were also successful.

A detailed summary of CSET content is also provided in this report which can be utilized a) for student aids and b) for establishing a basis for an industry training standard for composite materials structural engineering.

7.2 Improvements

Prerequisite content was not assessed for its effectiveness in preparing students for CSET Level II training. Feedback from course participants indicated that in many instances, prerequisite content exceeded expectations for Level I, with detailed design discussions which more appropriately should be reserved for the primary CSET course. Although considered a benefit by more experienced students, future efforts in CSET updates should consider reassessment of the prerequisite material based on the necessary level of knowledge required of students at the beginning of CSET.

CSET content should be assessed periodically to assure that the latest technology advances and FAA guidance and regulations are incorporated into the course.

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A Course objectives and teaching points

Table A1. Composite Structural Engineering Technology Course Objectives

Section/Subsection		Terminal Course Objectives
1.0 Composite Applications	1.1 Composites Overview	1. Describe the course objectives which include principles of substantiating composite airframe structures during certification and composite safety and certification initiatives by regulators. 2. Provide motivations for adopting composites from an owner and passenger perspective. 3. Provide examples of composite applications Describe the key technical characteristics of composite airframe structures. 4. Describe composite safety and certification initiatives by the FAA relating to composite technology.
	1.2 Challenges	1. Illustrate by example how costs, lack of standardization, lack of trained resources, and evolving composite technologies have presented challenges in promoting safety awareness and incorporating composites into aircraft design. 2. Describe the role of standards organizations in addressing the consequences of those challenges in aircraft composite structural design and certification.
	1.3 Integrated Product Development Teams	1. Identify benefits of concurrent engineering and historical evolution of the IPT concept. 2. Describe various objectives of IPT during the design. 3. Describe the disciplines, including responsibilities and knowledge within those disciplines, that comprise an IPT.
2.0 Material, Processing, and Fabrication Development	2.1 Material and Process Control	1. Identify FAA regulations and guidance materials that are relevant to controlling composite materials and processes and deriving associated design values. 2. Describe technical challenges associated with composite material control, highlighting differences with metallic materials. 3. Describe the importance of achieving stable materials and mature manufacturing processes before finalizing specifications and developing design values. 4. Describe the content and purpose of material specifications. 5. Describe methods to control manufacturing and information contained in process specifications.

Section/Subsection		**Terminal Course Objectives**
		6. Describe the purpose and guidance for qualification testing. 7. Identify roles and responsibilities.
	2.2 Defects and Damage	1. Provide an overview of common processing defects and damage.
	2.3 Protection of Structure	1. Identify composite structure damage protection requirements and methods.
	2.4 Manufacturing Implementation	1. Identify aspects of composite manufacturing that are common to all processes. 2. Describe the balance between type design and quality system manufacturing controls. 3. Describe procedures for changes to materials and processes.
	2.5 Maintenance Implementation	1. Describe why maintenance is considered during the development of composite structures. 2. Describe challenges and regulations related to substantiating service damage.
3.0 Design Development	3.1 Structural Design Details	1. Describe the classifications of various assembly and structural component designs. 2. Discuss design and manufacturing challenges associated with various assembly and structural component designs.
	3.2 Design Considerations for Manufacturing and Maintenance	1. Discuss the links between fabrication processes and structural configurations, including how fabrication processes and defects may affect material properties. 2. Describe how following design guidelines can support consistency, while minimizing surprises, rework, and repair. 3. Describe how design criteria, materials, and structural configurations may affect maintenance, e.g., inspection and repair.
	3.3 Other Design Considerations	1. Describe an overview of structural design approaches for addressing flutter, crashworthiness, fire safety and lightning protection. 2. Compare composite structure coatings with those for metallic structure, and describe why protection is important relative to material selection for composites. 3. Identify composite structure damage protection methods.
	3.4 Design Requirements, Criteria and Objectives	1. Describe composite failure modes, propagation mechanisms and how they may combine to affect structural failure.

Section/Subsection		Terminal Course Objectives
		2. Discuss the effects of environmental factors on properties and various composite materials, including an assessment of the structural significance. 3. Describe the content of design documents that includes criteria, requirements, and objectives, including typical examples of structural significance.
	3.5 Lamination Theory and Design	1. Describe composite laminate characteristics, microstructural scaling issues and early composite theories as related to failure. 2. Discuss a mechanics-based approach to classical laminated plate theory, including coupling phenomena and the implications of changes of stacking sequence on laminate properties and free edge stress conditions. 3. Describe general guidelines for the selection of durable, damage tolerant laminate layups currently used by industry for structural designs.
	3.6 Composite Analysis Methods	1. Describe typical stress analysis checks for laminates, tubes, and simple beams. 2. Discuss typical stress analysis checks for skin/stiffened panels, shear beams, and sandwich panels. 3. Introduce typical load share analysis methods for bolted joints and describe stress analysis checks for lug and fittings. 4. Discuss stress analysis unique to braided composite structures. 5. Introduce analysis challenges and solutions, including structural design assumptions, criteria and limits, and any semi-empirical experimental data needs, as well as the associated conservative analytical or experimental bases. 6. Discuss required stiffness properties for static, buckling, and interlaminar analyses. 7. Describe laminate and sandwich structure post-processing for strength analysis. 8. Discuss special finite element modeling approaches and issues for a) bolted joints, b) non-linear analyses needed to properly model composite structural buckling, c) interlaminar cracks and delaminations, and d) thru-thickness notches and cracks. 9. Explain the challenge in trying to assign a damage metric to realistic impact damage or other manufacturing defects/damage types found in composite structure.

Section/Subsection		Terminal Course Objectives
	3.7 Design Development	1. Describe the differences between an “allowable” value and a “design” value as related to structural strength properties. 2. Discuss the concept of a statistically based “allowable” strength value and differences between “generic” and “point design” values, including any possible links with selected analysis methods. 3. Explain the statistical basis of “knockdown factors”, including conservative assumptions applied as needed 4. Discuss regulatory issues and list FAA accepted sources of allowables. 5. Define the regulatory statistical requirements and key statistical parameters needed to derive design values 6. Provide overview of statistical tools for applicants using “shared” databases. 7. Describe some of the basics of statistical process control, noting the physical relationships with design data and proof-of-structure.
	3.8 Structural Bonding	1. Describe different types of bonded joints and the process for selecting joint configurations. 2. Describe typical fabrication processes for each type of joint. 3. Describe typical defects and joint failure modes in bonded joints. 4. Describe the adhesive properties required for the design of bonded joints and bonded repairs, including the structural details that affect stresses in the joint. 5. Describe typical stress analysis checks for bonded joints and bonded repairs, including the effects of design variables, environment, and key process variables (e.g., surface preparation).
	3.9 Structural Bolted Joints	1. Describe different types of bolted joints in composite structures Discuss the process for selecting joint configurations. 2. Describe different bolted joint failure modes, including the effects of laminate layups and bearing bypass issues for composite bolted joints. 3. Discuss the effects of geometrical parameters on joint strength as related to typical stress analysis checks for bolted joints. 4. Discuss the need for metal reinforcements for critical joints.

Section/Subsection		Terminal Course Objectives
		5. Describe issues associated with composite bolted joints and installations. 6. Describe different fastener systems and installation methods for composites.
4.0 Structural Substantiation	4.1 Regulations and Guidance	1. Identify and describe key regulations and guidance for proof of structures. 2. Identify the aspects of each major regulation for structural compliance and the related implications. 3. Identify and describe objectives and requirements for structural compliance. 4. Describe the categories of damage for composites and how the related requirements differ by structural category. 5. Describe the issues that must be addressed in demonstrating compliance with static strength requirements. 6. Describe the issues that must be addressed in demonstrating compliance with fatigue and damage tolerance requirements.
	4.2 Certification Approaches and Related Considerations	1. Describe the two main compliance approaches used. 2. Discuss the usage and limitations of these compliance approaches. 3. Describe the key concepts and issues associated with the use of deterministic and probabilistic approaches for damage when certifying composite aircraft structure. 4. Discuss the three approaches (no growth, slow growth, arrested growth) to the substantiation of damage tolerance of composite structures. 5. Describe the key considerations related to technical issues, schedules, facilities, and human resources in developing an overall aircraft structures development and certification plan. 6. Describe the key contents of test-related certification documents for composite structure. 7. Discuss the key contents of substantiation documents for composite structure.
	4.3 Addressing Damage and Defects	1. Describe key aspects associated with the relationship between the damage threat assessment, the design criteria and testing. 2. Describe key aspects associated with the complexities of structural impact damage. 3. Describe key aspects associated with the damage threat assessment.

Section/Subsection		Terminal Course Objectives
		4. Describe key aspects associated with the role of damage- and defect-related design criteria in achieving composite aircraft structural safety. 5. Describe key aspects associated with design considerations for fatigue and damage tolerance of composite structures.
	4.4 Building Block Testing and Analysis	1. List differences with metallic structures and overall goals of building-block testing. 2. Describe the necessity of aligning testing with design criteria and certification approach. 3. Describe typical types of tests at each building block level. 4. Compare building block testing associated with static and with fatigue and damage tolerance (F&DT). 5. Describe how analysis links results from different levels. 6. Compare testing associated with static, and F&DT substantiation. 7. Describe key aspects associated with accounting for material and process variability in the design values (Raw materials, processes, assembly, testing, etc.) 8. Describe the types of tests needed to assess variability. 9. Describe the degrees to which coupon/element test articles must be representative of production structure 10. Explain how the in-service environment can affect. structural performance and how environment is accounted for during testing and substantiation. 11. Describe key aspects associated with the types of tests used to characterize environments, defects, large disbonds, BVID, VID, large notches, discrete source damage, bolted/bonded repairs. 12. Describe examples of typical building-block tests addressing static strength, fatigue, and damage tolerance. 13. Describe key aspects associated with repeated load reliability and load-enhancement factor (LEF). 14. Describe key aspects associated with analysis correlation with tests. 15. Describe key aspects associated with materials and process changes.

Section/Subsection		Terminal Course Objectives
	4.5 Large Scale Testing	1. Describe key aspects associated with addressing effects of environment in large-scale structural tests. 2. Describe key aspects associated with addressing effects of non-detectable and detectable defects and damage in full-scale structural tests. 3. Describe typical test setup and loading for aircraft wing test, fuselage test (unpressurized and pressurized), horizontal stabilizer test, and vertical stabilizer test. 4. Describe key aspects associated with structural test plans for large-scale structural tests. 5. Describe key aspects associated with test program integration for large-scale structural tests.
5.0 Manufacturing Interface	5.1 Quality Control	1. Identify critical factors during the manufacturing process which may affect quality. 2. Describe the quality inspection process and identify different in-process and post-process inspection techniques.
	5.2 Certification Conformity Process	1. Describe conformity process used during certification to ensure manufacturing processes are followed when building test articles.
	5.3 Manufacturing Defect Disposition	1. Describe how nonconforming production parts and material are discovered through inspection processes and dispositioned. 2. Describe the role of the MRB in the disposition of nonconforming production parts and material.
6.0 Maintenance Interface	6.1 Inspection and Maintenance	1. Describe the capabilities and limitations of inspection techniques used in the development, production, and service environments and their effect on damage strength assessments. 2. Define approaches for defining and substantiating inspection programs for assessing damage to composite structure.
	6.2 Structural Repair Development and Substantiation	1. Discuss composite damage types, detection, and characterization. 2. Describe repair design and process substantiation related to repairs, including challenges, regulations/guidance, and source documentation.
	6.3 Teamwork	1. Discuss the need for teamwork and the individual roles.

Section/Subsection		Terminal Course Objectives
	6.4 Repair Techniques	1. Describe bonded and bolted repair processes and coating maintenance. 2. Describe issues and equipment solutions related to achieving thermal and pressure uniformity during the field repair of composites. 3. Describe trends in maintenance practice which may respond to the increasing composite content in commercial aircraft.
7.0 Other Topics	7.1 Flutter	1. Define aeroelasticity and aeroelastic instabilities. 2. Identify regulations, guidance materials and compliance methodologies related to flutter. 3. Describe how structural properties may change during operations and maintenance.
	7.2 Crashworthiness	1. Describe terms and basic principles of crashworthiness. 2. Describe FAA requirements, including the special condition for transport aircraft crashworthiness. 3. Explain the general concepts of energy absorption, and relative behavior of metals vs. composites. 4. Discuss test and analysis considerations to show compliance to the transport aircraft special condition.
	7.3 Fire Safety	1. Describe fire threats in civil aviation. 2. Describe relevant regulations to prevent and/or mitigate hazards. 3. Describe FAA fire safety research on composite structures.
	7.4 Lightning Protection	1. Provide an overview of lightning protection and lightning characteristics, including examples of lightning damage. 2. Describe lightning attachment zones and their significance. 3. Identify lightning design goals, protection concepts and verification tests. 4. List FAA regulations related to lightning protection .

Table A2. The CSET teaching points

Chapter/Section	Teaching Points
1.1 Composites Overview	• The objectives of CSET include a) describing essential safety awareness issues, b) describing engineering principles of substantiating composite structures, and c) gaining general knowledge of current composite technologies.

Chapter/Section	Teaching Points
	- Composites will be increasingly used in a variety of applications. - Composites are a non-standard material presenting unique challenges. - A list of ten key technical characteristics is described relating to various unique attributes of composites. - Part manufacturing and repair have a significant effect on the performance of certified aircraft parts made from composites. - Composites are notch sensitive but should not be considered “brittle”. - Out-of-plane loads are important to composite materials, even when relatively small. - Anisotropic properties must be characterized for composites. - Composites are dimensionally stable in-plane. - Composite airframe structures will generally have competing failure modes to consider. - Composites are generally more sensitive to environmental effects and overheating than metals. - Analysis of composite strength is typically derived from semi-empirical relations with tests involving structural details. - The analysis, design, fabrication, tooling, and repair technologies used for composite airframe applications are generally proprietary and, hence, “non-standard technology”. - The most experienced composite personnel still learn something new about composites with each “advanced application”. - The FAA has been actively involved in composite safety and certification initiatives relating to composite technology.
1.2 Challenges	- A general understanding of the unique cost structure of composites will influence decision processes during certification compared to metals. - Coping with the high composite structure has resulted in various management strategies, and two case studies illustrate product decisions related to composite cost structure. - Lack of composite standardization has resulted in a wide range of approaches in aircraft composite structural design and certification. - Lack of trained resources has resulted in strategies and related FAA initiatives which have been adopted to help improve the composite knowledge in the industry. - Evolving composite technologies are increasing composite design and process options. - Standards organizations exist to help develop more composite standards, engineering guidelines and other shared data as the technology evolves in the future.

Chapter/Section	Teaching Points
1.3 Integrated Product Development Teams	- Integrated product teams usually include all the disciplines required for product design, analysis, manufacturing, and project support. - The team composition may vary with the functionality, materials and construction of the product or component. - Large projects may have individuals or groups for each discipline. - In smaller projects or companies, individuals may cover more than one discipline.
2.1 Material and Process Control	- 2x.601, 2x.603, 2x.605, 2x.6039, and 2x.613, 31.33, 31.35, 33.15, and 35.17 describe regulatory requirements associated with material and process procedures and are the basis for controlling materials and processes. In addition, Advisory Circulars, Policy Statements, and Policy Memorandums are available guidance materials. - Regulations are the same for both metallic and composite constructions, but the means of compliance can differ. - Among the unique technical challenges presented by composite materials are the anisotropic property behavior of composites, the unlimited variety of materials available through different combinations of materials and processes, and the creation of material properties during the fabrication of composite parts. - Differences between metallic and composite parts include environmental sensitivity and statistical variability, notch sensitivity, and fatigue behavior. - Designers utilizing published composite design allowables must demonstrate equivalence which addresses statistically equivalent design values for minor material or process changes and manufacturing facility changes. Accepted sources of design allowables for composites include CMH-17 and the National Center for Advanced Materials Performance. - Stable manufacturing processes and material properties are required for structural substantiation. - Stable manufacturing processes and material properties are required for structural substantiation. - Base materials and processing must be stable for tests conducted at the coupon level for the higher structure levels to be valid. - Controlling the purchase and processing of composites is required for repeatable composite structures and assuring conformance to part approved design. - Design values are unique for each material, process, and design detail, and any change in these features requires re-evaluation of design values and substantiation if necessary. - Assuming all materials purchased under a given material specification are equivalent may result in numerous challenges since several materials may differ significantly but still meet specification requirements.

Chapter/Section	Teaching Points
	• Final properties and quality of composite parts depend on processing because the material is made the same time as the part. • Composite processing is controlled through a variety of documents, including material and process specifications, process control documents and manufacturing plans which reflect the unique requirements of processes and material characteristics. • Structural bonding includes two types of bonding: Co-bonding (components bonded together during cure of one of the components, requiring adhesive), and secondary bonding (two cured components bonded together with a separate bonding operation, requiring adhesive). Surface preparation is critical since no reliable NDI methods detect "understrength bonds" exist. • Co-curing differs from structural bonding since chemical bonds are created during initial cure, requiring no surface preparation. • Material specifications typically relate to a specific manufacturing process, but any given composite material, bought per a single material specification, may be used by multiple process specifications. • Although the exact parameters may vary among different composite manufacturing methods, resin cure requirements of time, temperature, and pressure must be defined. • Inspections must be performed throughout the composite lay-up, cure and assembly process, with attention to potential inaccessibility for inspection after closeout or assembly bonding. • Certified composite material requirements require material specifications, process specifications, and statistical design allowables. • Material qualification is the process where materials are shown to meet the requirements in an existing material specification by demonstrating that material purchased under that specification performs as expected and validates long-term stability through multiple batches. • Process qualification demonstrates that a given set of fabrication instructions will generate material properties that meet the requirements in the material specification. Process qualification is required for each manufacturing facility and each manufacturing process. • Any given composite material, bought per a single material specification, may be used by multiple process specifications. • Material maturity refers to the stability of the material. Qualifying materials before properties have stabilized may affect design values. • The design approval holder is responsible for all design aspects of the certified product and the production approval holder is responsible for manufacturing control. Material suppliers, part suppliers, test labs, and regulatory agencies have specific roles and responsibilities. All entities are interdependent.

Chapter/Section	**Teaching Points**
2.2 Defects and Damage	• Deviations from the approved design also referred to as “deviations” or “anomalies” and are considered in the design. • Deviations must first be fully characterized for accurate disposition, including visual detection accompanied by nondestructive testing (NDT) and/or process record review. • Inspection and testing will not validate good parts; weak adhesive bonding cannot be reliably inspected. • Adhering to process conformance and controls is the basis for good parts validation. • Inspection methods are typically different between manufacturing facilities and service organizations. • Testing and inspection will not validate good parts and can only detect certain flaws. • Typical defects related to processing include vacuum bagging, during scaling from material testing at the coupon level to assemblies, and dimensional control.
2.3 Protection of Structure	• Protection of structure requires carefully selecting material and developing processing instructions. • Polymer matrix composites are more vulnerable than metals to moisture absorption and heat which will degrade the properties of the matrix. • Polymer matrix composites are not subject to corrosion like aluminum or steel, but some composite materials must be isolated from certain metals to prevent galvanic corrosion of the adjacent metallic part. • Epoxy resins are sensitive to UV and will become brittle and may eventually disintegrate if unprotected. • Epoxy resins are susceptible to erosion from sand and rain which may expose the outer fibers of a composite laminate. • Conductive material must be added for lightning strike protection and other electrical considerations since composite structure is typically not electrically conductive. • Composite part temperature is related to paint reflectivity. • Material must be stable at the maximum operating temperature (MOT) and not be used near the temperature where the material properties will degrade, and one option is to select a material with a glass transition temperature, Tg, that is 50ºF greater than the MOT. • Protection methods must typically address moisture absorption, lightning strikes, galvanic corrosion, ultraviolet radiation, and corrosion due to sand and rain.
2.4 Manufacturing Implementation	• All composite production follows similar steps, regardless of material or process.

Chapter/Section	Teaching Points
	• Inspection should be included for any process step that will result in earlier production efforts difficult or impossible to inspect. • NDT procedures exist will not detect “understrength bonds” in production. • All composite parts have some level of flaws inherent in their manufacture (e.g., porosity). More complex structures have greater likelihood of additional manufacturing flaws, such as wrinkling or bridging. • If a flaw or damage is outside the allowable limits, then the part is dispositioned (use-as-is, repair, rework, or scrap) by the MRB. • Quality system requirements are the same whether manufacturing metallic or composite parts and assemblies, although composite manufacturing generally requires a higher level of in-process inspections as product quality from prior operations often cannot be checked. • The production approval holder quality system is responsible for assuring supplier quality control. • Each combination of material and curing process may yield products with unique mechanical properties. • Specifications control materials and processes, including detailed process parameters for a specific manufacturing method. For example, a prepreg hand-layup specification typically contains an approved material list, standard practices for cutting and layup, approved cure cycles, standard process tolerances, and acceptance criteria. • To save development and certification time and money, manufacturers may only certify single source materials. However, the effects can be a high risk to a program if a prepreg manufacturer stops producing a product or the material. • Reducing qualification efforts during the design phase will likely result in higher costs and work in support of future changes in processes. • Structural bonding requires stringent process controls and a thorough substantiation of structural integrity. Best practice for qualifying structural bonds includes both qualitative and quantitative measurements. • If cured component dimensions are different from its corresponding room temperature tooling, the importance of this difference depends on the magnitude of dimensional change and tolerances specified for the component. • Types of manufacturing controls will normally differ among different manufacturers and part characteristics. • Guidance on the level of qualification required for the changes of materials or processes is given in FAA Tech Center Report DOT/FAA/AR-03/19 and in CMH-17.

Chapter/Section	Teaching Points
	• Two options when qualifying a second material system include 1) preparing a new material database and qualifying all parts that are made with it independent of the existing certification, and 2) demonstrating that the new material is equivalent to the existing material system involves coupon testing and some testing of parts at higher levels of the building block pyramid.
2.5 Maintenance Implementation	• Maintenance should be considered during the development of composite structures and must be provided to operators at the time of entry into service. • Type certificate / Supplemental type certificate holders define instructions for ICA as part of initial type certification. Although not required, most also publish a SRM with approved repair information. • An SRM, or equivalent document, is often the most complete maintenance document for providing instructions for damage inspection, disposition, and repair. SRMs or AMMs should provide operators with multiple repair options for a given damage situation. • Structural substantiation should integrate damage tolerance, inspection, and repair. • Few standard practices exist for repair designers or repair technicians. Repair of composite aircraft structure lacks maturity compared to metal structure repair, particularly regarding factors affected by aging. Materials and processes vary among manufacturers. • Repair technician training is not standardized and there are no reliable competency assessment measures for those involved in composite structural repair. • Repair challenges include inadequate knowledge of base structure materials, processes and design philosophy, less-controlled repair environments, and significant structural damage that is not visually apparent. Approved repairs depend on adherence to approved materials and processes. • Repair designs must meet the same performance requirements as the base aircraft structure. Substantiation is subject to damage characterization (size, location, and effect on structural performance), and the repair environment. • Repairs should restore the original part strength and stiffness, and repair procedures should be sufficiently detailed to account for the lack of standard techniques. • Repair substantiation should include inspection procedures to characterize damage, perform inspection during the repair procedure, and describe instructions for continued maintenance after the repair.

Chapter/Section	Teaching Points
	• Bonded repairs have size limitations due to limited confidence in detecting understrength bonds Reference: FAA Policy Statement (PS-AIR-20-130-01, 2014). • Reverse engineering practices are not mature and are not recommended. • Structural integrity of repairs is linked to material and process control. • Repair designs must meet the same performance requirements as the base aircraft structure.
3.1 Structural Design Details	• Structural design requirements for a pressurized transport fuselage include considerations for frame spacing requirements, stringer spacing and stress concentrations. • Light gauge monocoque design is commonly used on fixed-wing aircraft and helicopters in lightly loaded shell structure applications. • Generic components and their applications and functions include tubes, beams, sandwich panels, stiffened (laminate) panels, stiffeners and stringers, ribs and frames, and lugs/fittings. • Beams are typically used for spars, ribs, and floor beams. J- or I- section beams are often used for wing and stabilizer torque box spars, loaded in bending and shear. • Stiffened panels applications include wing, empennage, and fuselage skin panels. • Stiffener and stringer fabrication provide options for single or multi-step manufacturing. • Structural categories requiring fabrication option considerations include stiffened skin panels, spars and beams, frames, and fittings (lugs), and sandwich components. • Out-of-plane failure mechanisms may limit structural performance due to brittle behavior, and this issue may represent the most critical issue in composites design. • Delamination in typical angle bracket bolted joint fittings may occur in tightly curved transition geometries, and the design should avoid significant loads in curved laminates.
3.2 Design Considerations for Manufacturing and Maintenance	• Part geometry, cured part quality, ply orientation, and stacking sequence are impacted by tooling and fabrication processes. • Tooling provides dimensional rigidity necessary to meet required tolerances. • Tolerance requirements affect manufacturing and tooling processes selection and cost. Different processes produce varying tolerance control. • Material properties are affected by fabrication processes and potential defects.

Chapter/Section	Teaching Points
	• Part strength and stiffness are reduced by flaws induced by processing, including issues associated with material handling, material lay down methods, lack of adequate laminate compaction, tooling, and cure cycle. • Autoclave cured thick parts may exotherm with fast heat-up rate, or result in matrix cracking with fast cool-down rate, since thermal stresses are not relieved. • Creation of resin pockets may result in resin-poor regions near resin pockets, and may cause matrix cracking at the resin pockets under fatigue loading, potentially resulting in delaminations or disbonds. • For resin transfer molding, the lack of process control of fiber preform assembly and/or resin infusion steps may cause incomplete wet-out of the fibers, creating voids and porosity, and non-uniform distribution of resin. • Limitations and issues are unique to various processes, including automated tow placement, fiber placement and pultrusion. • Impact damage has a greater effect on compression strength than void content due to the combination of different damage types associated with impact events, including broken fibers, delaminations and matrix cracking. • Use of design guidelines associated with different fabrication methods can assure consistency in meeting design and part performance, while reducing nonconformances. • Design considerations which may affect maintenance, such as strength, structural configurations, and durability, typically result in design criteria which are often contained in PART 25 OEMs' design requirements and objectives DR&O documents. • Composite structural components should include inspection methods available to both manufacturer and customer, minimize the need for NDI and should allow for easy backside/internal visual inspection, ensure that metal fittings or interfaces with metal parts can be visually inspected for corrosion and/or fatigue cracking, and ensure visual accessibility of both external and internal surfaces. • Sandwich configurations can result in inspection challenges, such as potted area assessment, fluid detection, disbonds, and bondlines of stiffeners or frames bonded to internal face sheets. • Designing for maintainability and repair is essential during the development of composite aircraft structures. • Supportability is the collection of attributes of a structure affecting ease or difficulty in providing maintenance or support. Consideration of supportability issues during design minimizes maintenance costs. • Optimum performance design may restrict allowable damage limits (ADLs) to very small sizes, resulting in repair requirements for small damages.

Chapter/Section	Teaching Points
	• The back side of some components that exhibit visible exterior damage may be difficult to either inspect or gain access for repair. • Industry shared databases, standard repair materials, with associated material procurement and process specifications facilitates ability of airlines and maintenance repair organizations to manage inventory of perishable and accepted materials. • Trade-offs exist between designing for minimum maintenance costs and designing for minimum production costs and weight.
3.3 Other Design Considerations	• Flutter is a structural oscillation which occur at certain frequencies and mode shapes, and is self-exciting which can result in dynamic instability. • Design changes may affect flutter characteristics, including mass, airframe stiffness and aerodynamic shapes of lifting surfaces. • Airframe design should assure that occupants have every reasonable chance of escaping serious injury under realistic and survivable crash impact conditions. • Energy absorption is typically implemented in the area below the passenger cabin. • While in most conditions many metals only fail by yielding, composites can fail in tensile fiber fracture, compressive fiber kinking, matrix cracking, shearing, or delamination, different loading conditions, loading speeds, and geometric features which will promote or inhibit different failure mechanisms with varying levels of energy absorption. • Each aircraft product type (i.e., transport, small airplane, rotorcraft) has unique regulations governing the crashworthiness of aircraft structures. Compliance may be demonstrated by certification by test or by certification by analysis supported by test. • Composites display different failure mechanisms, and different loading conditions and geometric features will promote or inhibit different failure mechanisms providing different levels of energy absorption. • Three concerns for aircraft fire safety include in-flight fires, post-crash fires, and fuel tank flammability (in-flight or on the ground). • Lightning protection design features are required for composite aircraft structures, and lightning protection design features are required for composite aircraft structures. • Carbon, glass, composite resins and adhesives, and aramid fibers composites are much less conductive than metallic materials which must be accommodated in the design. • Proper electrical bonding must be incorporated between structural parts. • Electrical bonding features must be sized to conduct lightning current. • Special consideration must be given to fuel system lightning protection for aircraft with integral fuel tanks in a composite structure.

Chapter/Section	Teaching Points
	• Composites are more vulnerable than metals to moisture uptake and heat, UV radiation, lightning damage, and erosion, requiring considerations for protection and material selection. • Composite parts are not subject to galvanic corrosion like aluminum or steel, but must be isolated from aluminum to prevent galvanic corrosion of the adjacent aluminum part. • Composite part temperature is related to paint reflectivity. • Composite structure damage protection methods include paint, outer fiberglass plies, Teflon®, Tedlar® film and bonded metal strips/sheet. • Damage threat assessment identifies required levels of impact damage resistance which must be accommodated in the design.
3.4 Design Requirements, Criteria and Objectives	• Local failure modes often combine in the failure of composite structures, with the likely dominant failure mode originating at a stress concentration. Failure may be fiber-dominated or matrix-dominated. • Foreign object impact damage must be addressed due to the related stress concentrations and competing failure modes. • Composite notch sensitivity is a design driver for static strength, and design details, manufacturing defects or field damage which causes stress concentrations will result in lower static strengths. • Damage zones can relieve stress concentration in fiber dominated laminates. • Impact to composite laminates can cause multiple types of damage, including broken fibers, matrix cracks, multiple delaminations, disbonds and holes. Fiber breakage tends to be the most serious effect of impact damage. • Typically, compression, shear strength, and stiffness may be more affected by impact damage than tension properties. • Matrix cracking may be the least critical damage caused by an impact and damage may be undetected over an extended time; matrix cracks may increase in size or join other cracks, forming larger delaminations under cyclical loading. • Without data from testing of multiple specimens with differing layups and thicknesses, variable boundary conditions and impactor parameters, predicting failure of laminates is difficult due to the multiplicity of failure mechanisms resulting from impact. • Design criteria and guidelines established for product value, maintenance or manufacturing purposes may avoid aging mechanisms that are complex and have synergistic relations with environment, secondary loading, and structural permeability. • Design constraints, guidelines, criteria, and multi-load paths are essential to avoid undesirable failure modes.

Chapter/Section	Teaching Points
	• Temperature and moisture affect polymer matrix composite properties and is addressed in design. • Environmental effects may be accommodated either through material selection, using protection schemes, or by evaluation and substantiation in a test program and the resulting design properties. • AC 20-107B contains guidance for substantiating structure for aircraft environments, considering both short- and long-term effects and determining critical environments at each location on the structure. • Aircraft ground and in-fight temperatures must be established for each unique aircraft structural component, considering the operational conditions, structural configurations, and exterior surface coatings. • Many parameters are required for the thermal analysis, including environmental conditions, composite properties, surface finish properties, and conduction/convection/radiation/reflection evaluations. • Absorbed moisture reduces some composite material properties over extended time periods. • Intra and interplay residual stresses result from different thermal expansion properties of fiber and matrix materials. • Thermal and/or moisture cycling and long-term exposure to high temperatures can result in matrix/interface degradation and matrix cracking. • Increasing or decreasing temperatures may cause modified properties for typical epoxy matrix materials. • Temperature and moisture cycling can cause matrix cracking and can increase intra/interplay residual stresses. • Transverse matrix cracking (TMC can affect most composite material forms where fibers are aligned in multiple directions and can occur due to thermal cycling. TMC typically does not degrade the strength of the part initially but fluid ingression through a network of cracks can further degrade the structural integrity. • TOS is a surface phenomenon that can be affected by the additional surface area due to matrix cracking. • MOT is the material design temperature upper limit. The MOT for a material should be used as a guide for material selection for an application. • Direct exposure to UV light can cause mass loss and degradation of polymers. • Design criteria documentation guides and demonstrates a disciplined process for design, material and processing selections, analysis, linkage to fabrication processes, and repair design and processes. • Design criteria documentation describes damage threat assessments and demonstrates an understanding of regulation compliance approaches.

Chapter/Section	**Teaching Points**
	• Design criteria can establish company-specific expectations within degrees of freedom allowed by aviation regulations. • Design documents are used to provide this information to integrated product teams.
3.5 Lamination Theory and Design	• When creating designs that include composite materials which are non-isotropic, terminology should be used to describe the properties in each direction, and some strength properties may vary with direction and orientation of loading. • Plies may be oriented in any direction, making the potential design of a laminate limitless. To simplify the design and manufacturing process most designs are limited to varying proportions of 0°, 90°, and ±45° plies. • Classical lamination theory primarily involves the determination of laminate elastic properties such as modulus, Poisson's ratios, coefficients of thermal and moisture expansion, etc., for generic laminates. • Classical lamination theory may be used to predict the strength of the laminate, but test confirmation is generally needed, particularly when considering damage, manufacturing defects and stress concentrations. • Material properties are often determined at the lamina level by mechanical testing and combine them using classical lamination theory to determine laminate properties. • A mechanics-based approach to classical laminated plate theory addresses coupling phenomena and the implications of changes of stacking sequence on laminate properties and free edge stress conditions. • Classical lamination theory concepts include transformations, stress and strain profiles, integration of each ply contributions, coupling phenomena, and free edge effects from multi-angle laminates. • Composites are “notch sensitive” and design must account for all stress concentrations. • Ply orientation affects damage tolerance characteristics; laminates with a higher percentage of plies with orientation parallel to load typically have higher load capacity, and laminates with a lower percentage of plies with orientation parallel to load and are typically more damage-tolerant. • Carpet plots may be used for convenience when showing laminate properties for designs with various amounts of 0°, 45°, and 90° plies.
3.6 Composite Analysis Methods	• Classical laminate plate theory can be used to calculate lamina strains and stresses based on applied loads and moments, assuming an appropriate failure theory. • Stiffened panel stress checks include issues related to laminate strength, buckling, out-of-plane effects. Failure or buckling load of each segment of a stiffened panel is determined by the minimum segment failure load. • Stiffened shear beam stress checks require buckling and strength assessments at design ultimate and limit load scenarios.

Chapter/Section	Teaching Points
	• Sandwich panel buckling analysis should include stiffness effects of edge bands, core ramps, and facesheet ply additions and drops in the panel. Geometric characteristics include cell size, core depth, facesheet thickness, panel width and panel depth. A variety of sandwich beam failure modes must be assessed. • Composite bolted joints tend to be bearing critical for typical layups (e.g., quasi-isotropic which is usually chosen for critical bolted joints) rather than net-section critical. • Lugs loaded in compression laminates tend to delaminate under constant loadings. Bushings are used for wear surfaces since laminate construction is not suitable for the high contact loads typical of lugs. • Composite lug analysis checks should assess bearing, shear-out, net-tension, and fatigue strengths. Building block test programs may be used to validate analyses of composite lugs. • Changing the braid angle in braided composite tapered structure affects the fiber volume fraction and layer thickness, influencing mechanical properties. • Control of laminate layup and other manufacturing tolerances can minimize stiffened panel “imperfections” that affect part stability. • Composites are notch sensitive and will have some strength knockdowns relating to design details that concentrate stress. • Composites will have complex strength knockdowns related to manufacturing defects, environmental effects, and accidental damage. • Complex strength dependencies are solved through semi-empirical relations with experimental data and conservative design criteria. • Lamina based failure theories related to in-plane strength analysis are generally not fully accurate, and empirical approaches use maximum strain from laminate level tests over a range of layups. • Stress based analyses can provide acceptable results for simple cases such as curved laminates. • Fracture mechanics approaches used for interlaminar strength analysis can provide accurate predictions of interlaminar crack onset and growth. • Two fracture mechanics approaches are virtual crack closure technique and cohesive zone model. Virtual crack closure technique calculates energy-release rate. Cohesive zone model relates interfacial tractions to displacement discontinuities. • Bonded joint strength analysis can use simple stress-based approaches if calibrated to representative test data, but commonly occurring failures are not addressed and must rely on empirical test data. • Bolted joint analysis must consider interaction between bypass and bearing loads. Bearing strength is typically covered by empirical test data over range of joint configurations.

Chapter/Section	Teaching Points
	• Composite material stiffness properties can utilize FEA based on external laminate codes which are based on external or internal laminate codes. Internal laminate codes are built into the pre-processor. • Special finite element modeling approaches exist for a) bolted joints b) non-linear analyses needed to properly model composite structural buckling c) interlaminar cracks and delaminations, and d) thru-thickness notches and cracks. • Progressive damage modelling is currently limited in accuracy and requires significant large-scale test data to “calibrate” the related damage simulations, particularly if trying to extrapolate outside available structural test data for similar design details. • Assigning a damage metric to impact damage or other manufacturing defects/damage types found in composite structure can be a challenge. • Impact damage assumptions for a given structural design relies on impact surveys and conservative design criteria applied in test data collection for post-impact residual strength.
3.7 Design Development	• Design values must be linked to the specific materials and processes used to fabricate parts, and analytical methods used in design determine the specific material properties for which allowables must be developed. • No single generally accepted industry approach exists for composite design/analysis. • An allowable is a lower bound on the distribution of strength for a particular property, and is applicable to a defined material and fabrication process, and geometric and layup parameters. • Allowables, typically developed from data at the coupon and element levels of the building block, form the basis of design values. • Design values must account for variability introduced by both the materials and the fabrication methods used to produce the final product. Values derived prior to controlling processes to provide a stable and repeatable product may not reflect the actual capacities of the product. • Design values must be linked to the specific materials and processes used to fabricate parts; allowables derived for lamina properties may not meet the requirements for developing design values as the variability of processing is not fully captured in various lamina-based tests. • A and B-basis defines the lower bound level (99%, 90% respectively) with a statistical confidence (95%) that the calculated value from a sample of strength data is equal or lower than the true population lower bound level as required by the regulations. B-basis values are used for redundant structure, whereas non-redundant structure uses A-basis values. • Generic design values are valid for a range of design and fabrication conditions. Point design values are linked to fabrication process. Composite design values and allowables are point design values.

Chapter/Section	Teaching Points
	• Knockdown factors are assumptions applied to obtain the design values used to calculate safety margins and are based on empirical and analytical evidence. • Knockdown factors should be conservative for design applications and take into consideration limitations of those assumptions. • Allowables are typically developed at the lower levels of the building block, and statistically significant numbers of tests at higher levels is usually not practical. • Demonstrating compliance to material related regulations is more complicated for composite materials compared to metallic materials due to greater design flexibility, more fabrication process options, greater environmental sensitivity, and susceptibility to accidental impact damage. • Users of published material properties and allowables must demonstrate that produced laminates and structures have equivalent properties to those published. • Statistical requirements defined in the regulations do not mandate specific statistical tools, but define the statistical relevance needed in design values for specific capabilities of the structure to be analyzed. • Data being used must account for the variability of the material and the fabrication process the data is intended to represent. • Compliance with the statistical requirements of the regulations includes an adequate sampling of the population from which the sample was taken and the identification of the distribution which fits the data. • Factors which influence the derived design values include sample size, combinability of data from different material batches and production runs, and the selection of an appropriate distribution of data set. • To evaluate whether samples are representative of the overall population and capture variability, statistical tools can be used to test whether design values can be based on the combination of data from different material batches and production runs. CMH-17 uses the k-sample Anderson-Darling test to assess batch-to-batch variability. • A material specification must define material qualification, material acceptance, and material equivalency including the definition of statistical methodologies. • SPC provides a means of continuing to monitor the consistency of any process parameter that is measurable. Control charts are tools used to determine whether a process is in a state of statistical control. • SPC can be a valuable tool for not only ensuring that process is in control, but can alert that a process is trending to an unacceptable control condition.

Chapter/Section	Teaching Points
	• SPC is needed to ensure design data remains valid, particularly those structural properties that depend on manufacturing processes (e.g., damage tolerance and energy absorption for crashworthiness).
▪ 3.8 Structural Bonding	• Adhesive bonding is defined as two parent parts (adherends) joined by a comparatively weak adhesive, compared the strength of the adherends. • Load is transferred by shear of the adhesive, rather than by tensile loads. • Bonded joint configurations include single or double overlap, simple lap, step-cut, and scarf. • Selection of adhesive joint type is based on load transfer requirements, available overlap length, and aesthetic/ aerodynamic considerations. • Three methods for forming composite or composite-to-metal bonds include secondary bonding and co-curing. • Production bond defects include voids, porosity, disbonds, delaminations or disbonds, and bondline defects; service bond defects include cohesion and adhesion failures. • The objective for a bonded joint is for the adherends to fail outside of the joint and joints must be designed for shear loads. • Bonded joints may fail by adhesion failure along interfaces, cohesion failure of the adhesive, a mix between adhesion or cohesion, or failure outside the joint at or above ultimate load. • Structural considerations that affect stresses in the bonded joint include load path eccentricity, out-of-plane bending, and tapering. • Adhesive shear strains are not uniform along the adhesive bond joint. • Adhesives behave elastically at lower shear stresses which can be as high as 80% of load capacity, but can exhibit plastic behavior at higher shear stress levels at the ends of a joint. • In performing stress checks for bonded joints, the joint strength would be limited by the strength of the surrounding structure because if that condition is satisfied the joint should never fail. • Adhesive bonded joints and repairs must have adequate overlap length to provide an elastic behavior, whereby the shear stress trough is zero in the middle of the joint, which provides creep and fatigue resistance. • In short overlap joints, adhesive can rapidly become plastic, exceeding elastic limits, and thereby increasing susceptibility to creep and premature failure. • Once the elastic trough is developed, there is no change in strength when additional overlap length is added. • Design data derived from the Thick Adherend Test ASTM D5656 represents the properties of the adhesive, not the adherends.

Chapter/Section	Teaching Points
	• Adhesive properties are affected by service temperature, any differences in stiffness in the adherends, and any differences in coefficient of thermal expansion.
3.9 Structural Bolted Joints	• Joint configuration effects on fastener load distribution define bolted joint selection and the mechanical joint test verification program during design. • Isotropic fracture mechanics techniques can be applied directly to advanced composite materials but under certain conditions. • Failures at fastener hole locations may be one or a combination of several basic failure modes. • General guidelines for preliminary design exist for edge and side distances, and fastener spacing. • Reinforcement of highly unidirectional laminates with additional ±45o and 90o plies can influence failure modes around bolt holes. • Under static loading the strength analysis of composite bolted joints must account for bearing-bypass interaction at each fastener location. • Far-field stress state (bypass stresses) at the hole, affects the ultimate bearing strength of the composite material under loading. • IBOLT performs a fracture-mechanics-based static strength prediction for a rectangular composite joint element, and provides excellent correlation between predictions and measured damaged initiation for several complex composite systems. • The stiffness of individual joint elements should be balanced to minimize ‘peaking’ of bolt shear loads. • Load sharing between fasteners can be accomplished by variation in step thickness, fastener material and diameter, and clamp-up pressure. • A simplified FEA model can be utilized to predict load share in the form of bearing/by-pass loading obtained for various fastener flexibilities. • Critical joints can be reinforced with metal plates to limit bearing/by-pass strength of composite laminates and the potential for bolt bending to damage the outside plies in a composite fastened joint. • Typical fasteners used in critical aircraft structural bolted joints are HI-LOKs and Lockbolts. • Transition or close tolerance hole fits are not acceptable in composite joints interference due to the potential for hole damage during fastener installation, especially in thick laminates, through combinations of broken fibers, delaminations, and matrix cracking. • Flush fasteners are less efficient than fasteners with protruding heads due to lower bearing stress capability. • Protruding head fasteners are superior flush fasteners in all respects except for satisfying aerodynamic requirements.

Chapter/Section	Teaching Points
4.1 Regulations and Guidance	• Regulations for composite aircraft structure are generally no different than those for metallic. However, the paragraphs containing regulations governing Proof of Structure, Static and Proof of Structure, and F&DT vary somewhat by aircraft type. • Structural regulations are very broad, and provide little guidance for how to comply. • Several advisory circulars (ACs) are relevant to composite structure, including AC 20-107B, AC 23-19A, AC 25.571-1D, AC 29-2C MG8, AC 43-214, and AC 25.307-1. • Several policy statements (PSs) are relevant to composite structure, including PS-ACE100-2001-006, PS-ACE100-2004-10030, PS-ACE100-2005-10038, PS-ANM-25-20, PS-AIR-100-120-07, and PS-ACE100-2-18-1999. • Other guidelines are in CMH-17, chapters 3, 12, 13, and 14. • The building block approach is used for structural substantiation and has become the most efficient way to deal with composite certification. • Large-scale tests are an essential part of static strength substantiation for new design and manufacturing concepts. • Static substantiation for composites addresses strength at ultimate load with the most severe acceptable defects in the process specification and/or with damage up to the threshold of detectability (or allowable damage limits), including a lifetime of cyclic loading. • In most cases, fatigue and damage tolerance for composites focuses on demonstrating no growth from these acceptable defects and barely detectible and/or allowable damages. Slow or arrested growth options are available but are more challenging for composites. • AC 20-107B is the primary composite guidance material used for small airplanes, rotorcraft, and transport airplane applications. • Categories of damage link damage threats with regulations and industry requirements. • All damage that lowers strength below ultimate load must be repaired, and repaired components must be able to withstand ultimate load. • Factors for Proof of Structure – Static includes a) an approach for integrating composite design and manufacturing processes, b) time-related degradation mechanisms that yield undetectable flaws, and c) accounting for allowed or undetected manufacturing defects and service damages • Time-related composite degradation mechanisms involve considerations for moisture, repeated loading, and matrix failure. • Composites are “notch sensitive”, and ultimate allowable strengths have knockdowns related to non-detectable damage or other common design details such as cutouts.

Chapter/Section	Teaching Points
	• Metals “yield”, while composites are said to “strain soften”. While yielding may result in “notch insensitivity”, strain softening will tend to cause local failures, whereby stress concentrations can become a function of hole or damage size. • Building block test and analysis should recognize the need for “effects of defects”. • AC 20-107B Paragraph 8: Proof of Structure – Fatigue/Damage Tolerance addresses a) damage tolerance evaluation, b) fatigue evaluation, and c) combined damage tolerance and fatigue evaluation. • Non-detectable damage and other damage levels which can exist for the life of the airplane must be able to sustain repeated loads and ultimate load capability without a need for repair. • Damage tolerance no-growth option includes inspection intervals which depend on damage size. Damage tolerance slow and arrested growth options define inspection methods and intervals to detect growth before criticality. • Like metals, composite damage tolerance practices address the rare cases where ultimate load capability is lost for a time period, while safety is covered by sufficient residual strength and maintenance inspection methods. • Cycles for fatigue testing should be statistically significant, and may be determined by load and/or life considerations; LEFs can be used to adjust the number of fatigue cycles to reduce the duration of the testing.
4.2 Certification Approaches and Related Considerations	• Three certification approaches include a) certification by analysis supported by test, b) certification substantiated by test only, and c) certification primarily by analysis. • Certification primarily by analysis is typically allowed only under certain circumstances, such as derivative aircraft programs when an initial aircraft program used certification by analysis supported by tests, including minor material/process changes and minor aircraft modifications. • Deterministic models are based on a set of input parameters to yield a single result or set of results. • Probabilistic models account for randomness, and variable states are described by probability distributions, usually developed by using many iterations. • Both deterministic and probabilistic approaches can support static strength, fatigue, and damage tolerance for composite aircraft structure, leading, during certification, to design criteria, structural tests, and analyses used. • Development can benefit from a combination of deterministic and probabilistic approaches.

Chapter/Section	Teaching Points
	• Deterministic tests and analyses establish relationships among a) residual strength and damage size, b) damage detection, sizes and inspection intervals, and c) damage limits design criteria and requirements. • Deterministic damage criteria concepts include BVID, ADL, maximum design damage (MDD), CDT, and readily detectable damage (RDD). • Probability approaches for damage tolerance assessments must demonstrate that the occurrence of an unsafe event or damage state is extremely improbable, and the goal is to ensure that the length of time with lost ultimate load capability is very short if the damage is large, or long if the damage is smaller. • Pure probabilistic approaches have limited applications to composite proof of structure due to significant data needs for variables and the complexity of combining statistics with structural analyses. • Semi-probabilistic approaches often integrate deterministic methods but are challenged by acquiring needed data and the education of engineers in using probabilistic methods for design and/or structural substantiation. • Primary reasons for limiting service exposure with large damage that may occur in accidental damaging events are the statistics driving includes loads expected in service, and the extent of damage coming from accidental events. • Damage source and inspection considerations for both deterministic and probabilistic approaches include source of damage as the result of in-flight discrete event, damage which is readily detectable, damage which is detected during planned inspections, and damage which is undetectable, but which may or may not grow. • Damage tolerant structure must have adequate residual strength and stiffness to continue safely in service until it can be detected by scheduled maintenance inspection and repaired, or until the demonstrated life is reached. • Growth of impact damage, delaminations, and disbonds is generally driven by compression and shear loads, or by out-of-plane loads, and sensitivity of the structure to damage growth must be assessed. • No growth, slow growth, and arrested growth approaches: Once damage is detected, the structure is either repaired to restore ultimate strength or replaced. • The no-growth approach establishes that damage may not grow for a significant number of cycles. • The slow-growth approach describes slow, stable, and predictable growth within inspection intervals. • The arrested-growth approach establishes that damage growth is terminated before residual strength drops below a critical threshold such as limit load.

Chapter/Section	Teaching Points
	• Arrested damage growth must be slow, stable, and predictable within inspection intervals. • Aircraft development program must include a schedule of event sequences and linkages, manpower requirements, required facilities, cost, and technical performance. • A certification plan should be developed and agreed with the certifying agency early in the airplane development program. • Material qualification and allowables and structures test schedules must be linked to establish and validate stable materials and processes. • Materials and fabrication processes for test parts must be representative of the actual airplane components. • Final composite material is created during part fabrication, and design properties are dependent on the fabrication process used to produce the part. • Material batches must be representative of the production material population. • Close coordination with the regulatory authorities is required to get approval of a certification test plan, and several iterations of submittal for review and comment may be necessary. • Substantiation documents include allowables, analysis methods, static strength analysis, fatigue analysis, damage tolerance analysis, SRM allowable damage limits, SRM repair strength analysis, and SRM repair damage tolerance analysis.
4.3 Addressing Damage and Defects	• Goal of damage threat assessment is to determine damage and defect types, with locations and severity levels that may possibly occur in the structure during manufacturing and service. • Goals of damage-related design criteria are 1) to specify representative/conservative damage and defect types, locations, and severity levels used for each category of damage identified by the damage threat, and 2) link selected damage and defect types, locations, and severity levels to the probability of detection for production and service inspection methods. • An inspection program should be developed consisting of frequency, extent, and methods of inspection for inclusion in the maintenance plan. • Only standardized, representative, reasonable, or conservative damage types are typically tested and considered in structural analysis • Damage standards may be established for each damage type defined in the design criteria and used in testing. • Impact damage types include matrix damage, fiber breakage, and sandwich core crush or fracture. • Remote damage can occur away from the impact location.

Chapter/Section	Teaching Points
	• Impact damage to sandwich structure may allow 1) moisture or fluids to penetrate the core in sandwich panels with thin face sheets, 2) core crushing, and/or 3) delamination in facesheets and disbonds with core. • Internal impact damage spans an area greater than visual indications, and visible damage on one side of a composite may not reveal the full extent of damage. • During the development of composite structures, experiments should be performed to establish relationships between inspection methods, damage, and the prediction of residual strength. • A thorough assessment should be made of all potential damage scenarios based on both manufacturing and service environments. • An impact damage threat assessment is necessary to identify impact damage severity and detectability for design and maintenance. • Impact surveys assist in determining appropriate impact events to create desired damage detectability for each detail, including various impactor geometries. • Impact surveys assist in the development of a database linking actual damage to in-service metrics, and should consider a wide range of conceivable impacts possible in the manufacturing and service environments. • Most defects resulting from process failures that occur during manufacture and escape factory quality control can be expected to be detected by the factory inspection programs or if occurring during handling or storage following factory inspection, during a scheduled maintenance inspection. • The weak or “kissing” bond is a very serious issue due to the lack of current NDI capability to either detect or assess the strength of these process defects. • Events resulting in damage beyond that covered in the damage tolerance evaluation or structural substantiation procedures (i.e., Category 5 damage) can occur in aircraft service environments. • Not all damaging events (e.g., severe vehicle collisions) can be covered in design and scheduled maintenance, requiring conditional inspections defined by engineers familiar with the structure after knowledge of the event is collected and shared. • The goals of design for damage and defects ensures application of practical maintenance for damage detection and inspection. • BVID damage severity levels should not reduce component strength or stiffness deteriorating below ultimate load capability. • VID damage severity levels should not reduce component strength or stiffness deteriorating below limit load capability. • Five damage categories are associated with different design load levels.

Chapter/Section	Teaching Points
	• Factors affecting the placement of damage threats in categories include design requirements, objectives and criteria, inspection methods, and other factors including service experience, costs, and workforce considerations. • Impactor geometry and structural design details play a role in converting a damage threat assessment into the placement of different damage types into categories of damage. • Effects of real-time aging and long-term environmental degradation could lead to life limits lower than substantiated using repeated load tests. • Failsafe design considerations may be needed to place large hidden damage into Category 2. • A missed manufacturing defect may go undetected through the component's service life and therefore is included in Category 1 damage or defects. • Category 3, 4 and 5 damages generally require special inspections of structural elements near obvious damage. • Material resin types can affect damage tolerance performance of through-notched carbon composite structures. • Typical aircraft structures are loaded in more than one direction and, in some cases, need to be designed as fail-safe structures. • Multiple load path structure designs that demonstrate structural damage capability present a high level of robustness. • Secondary loadings can occur because of typical aircraft environments and must be considered in the design of composite structural components. • Airbus and other industry studies revealed that a disbond can propagate due to the ground-air-ground cycle and can lead to a significant reduction of the structural capability; the study showed that thermal cycling without pressure differential does not propagate damage. • Hybrids such as composite/metal joints have inherent advantages due to their simplicity and ease of disassembly, but must have additional considerations such as metal fatigue, thermal effects, moisture absorption, etc. • Residual curing stresses and strains have limited direct effect on fiber-dominated laminate properties, but may be high enough that resin microcracking and delamination may occur before any mechanical load is applied.
4.4 Building Block Testing and Analysis	• The building block approach is essential in the development of composite structural substantiation due to the multiplicity of failure modes, the need for risk reduction, and cost control. • Testing must be aligned with the design criteria and certification approach, and substantiation of composite structural performance and durability consists of a complex mix of testing and analysis.

Chapter/Section	Teaching Points
	• Obtaining design allowables late in the development phase introduces program risks. • Analytical methods predicting stiffness, as-fabricated strength, fatigue performance and residual strength should be selected prior to preparing the building block test plan. • Building block characteristics: 1) Coupon and element tests provide basic data for first iteration design and analysis 2) At the subcomponent level more complex static and fatigue loadings are analyzed and verified at the subcomponent level 3) The numbers of test specimens are reduced at higher test levels in the pyramid. • Building block testing is applicable to a) static and b) fatigue and damage tolerance substantiation. • Sources of structural performance variability include a) materials and fabrication processes and b) assembly, test specimen preparation, and test procedures. • Coupon levels of the building block pyramid assess and quantify base material and process variability. • Element and detail levels address the variability associated with part fabrication and assembly steps. • Variability should be evaluated for each failure mode. • Coupon/element test articles must be representative of production structure. • Exposure to temperature, moisture, and other fluids may degrade or otherwise may affect the strength and stiffness of the structure. • Static strength related to manufacturing defects is typically assessed with tests at coupon and element level. • Fatigue related to manufacturing defects is typically demonstrated with tests at coupon through subcomponent levels. • Effects of large disbonds are typically assessed with large element or subcomponent tests. The test specimen width should be at least 5 times the size of the disbond, and the length should be 4 times the specimen width to provide for adequate load redistribution. • BVID is typically assessed with tests at coupon through large-scale levels. • VID is typically assessed with tests at subcomponent and component levels. • Coupon tests include a) material screening, pre-qualification and qualification, b) baseline statistical allowables and design values, c) fatigue, d) effects of defects, and e) repair. • Element tests, which require some design detail definition, include a) design value development, b) effects of defects, c) fabrication process sensitivities, and d) environment.

Chapter/Section	Teaching Points
	• Subcomponent tests include a) evaluation of the effect of structural complexity and scale-up, b) effect of damage on static strength, c) validation of no-growth (or predicted growth) of category 1 and 2 damages, d) large damage category 3, and e) VID residual strength and large notches. • Component tests include verification of a) internal loads modelling and resulting stress, strain, and deflection predictions, b) large-scale verification of design and analysis methodology, c) of no-growth and residual strength of structures with various levels of damage, and d) large structural repairs. • Fatigue design life or the design service goal identifies the average life to be expected under average aircraft utilization and environments. • Determining the average life for aircraft structures must account for uncertainties associated with a) factors such as materials, failure modes, and interaction of design features, and b) the design spectrum versus actual aircraft loads and usage environments. • Fatigue testing for composite material uncertainties may alternatively utilize life factor (additional fatigue cycles) or LEF (increased load factor) methodologies. • The life factor may require an excessive test duration, and the load enhancement factor approach can be of a shorter duration test by increasing the applied loads in the fatigue tests to achieve the same level of reliability. • Full-scale test substantiation is performed for conditions that are beyond aircraft experience during the design service goal to account for the uncertainties in design spectrum versus actual aircraft loads and usage environments. • Substantiation of structural performance and durability of composite components generally consists of a complex mix of testing and analysis. • Validating analysis methods with test results should consider major load paths, secondary loading, damage state, and failure modes. • Substantiation testing should focus on validating load paths, damage initiation, damage propagation, and maximum load capability and failure mode. • Any material and/or process changes must be managed to maintain the certification basis of a product over the life of the product, and new data will be necessary to cover significant changes. • For equivalency testing, a test matrix must be tailored by all process stakeholders to investigate the proposed change to ensure that potential adverse effects are identified.

Chapter/Section	**Teaching Points**
4.5 Large Scale Testing	• Large-scale tests are frequently conducted at ambient rather than critical environmental conditions. • For cases with a wider than normal range of environments for fatigue loading (such as structures near heat sources), the environment may need to be included if thought to affect fatigue performance. • When demonstrating ultimate strength capability through large-scale tests at ambient environment two methods for accounting for environmental effects are 1) certification by analysis supported by test and 2) certification by test. • Overload factors are typically derived from coupon / element level test data, and different overload factors may be used for different load cases, depending on the associated critical failure modes. • Factors are applied to both limit and ultimate static loads. • Failure mode correlation across environmental conditions is necessary to conservatively cover all environmental conditions through environmental overload factors at ambient testing. • The interactions between environments and internal loads are important for composite/metal hybrid structure. • It is necessary to account for environmentally induced internal loading caused by thermal expansion mismatch in composite/metal structures and which must be evaluated. • Full-scale test article quality must be representative of production parts to capture non-detectable “characteristics” and material architecture. • Unintentional defects/damage in the full-scale article can result from the nominal fabrication process, a process anomaly, or accidental damage. • Defects and/or damage intentionally incorporated in the full-scale test article to adequately cover design criteria may include fabrication defects and damage. • Key considerations for selecting defect/damage locations for full-scale test article include high-stress and/or low-margin locations, critical load paths, detectability of damage relative to the extent of the internal damage state, and guidance in AC 20-107B and AC 25-571D (Section 6.g). • For the aircraft wing test, all applied loads on wing are reacted by loads on fuselage hard points. • The body bending and torsion loads for both the pressurized and unpressurized fuselage test are applied at the landing gear, vertical fin, horizontal stabilizer, and wing. • Body bending and torsion loads for the unpressurized fuselage test are applied to the landing gear, vertical fin, horizontal stabilizer, and wing loads, using either point loads at interface locations or distributed loads on the components.

Chapter/Section	Teaching Points
	• Body bending and torsion loads for the unpressurized fuselage test are applied to the fuselage, using distributed loads on the fuselage, representing payload mass inertia loads. • Pressure loads for the pressurized fuselage test require adequate sealing of test article and are applied using air or water pressure. • Reactions at discrete attachment points (jackscrew, pivots) for the horizontal stabilizer test allows off-aircraft tests. • The vertical stabilizer test typically takes place as part of the fuselage test, and distributed pressure loads are simulated by discrete fixtures or pressure pads. • Testing remotely from the fuselage requires a reaction test fixture that simulates the stiffness of the fuselage in the connection area. • Full scale test objectives will vary depending on the integration approach. • Example objectives for a given approach include validations for load distribution and stiffness, no-growth of defects and damages, ultimate load capability with defects, category 1 damages and repairs, regulatory load capability with category 2 – 4 damages, and critical ultimate load case failure load, mode, and location. • A typical instrumentation plan includes deflection transducers. crack wires, instrumented fasteners, strain gages, and acoustic emission sensors. • The certification approach (analysis supported by test or certification by test only) defines the number of load cases to be demonstrated on a given large-scale test article. • For test sequencing, testing details will be dependent on the application and experience. • Aircraft structures containing composite materials often include, in addition, metallic components (e.g., frames, ribs, fittings, splice plates), and development of an integrated large-scale test program must therefore consider the unique responses of each material to substantiate the metallic and composite structure. • Multiple requirements are often addressed with each test article to minimize costs associated with large-scale testing. • Combined composite-metal hybrid structures pose additional challenges for full scale tests. • If the OEM has significant prior experience with the material and/or the structural configuration, less testing may be required for mature applications.
5.1 Quality Control	• Composite quality control depends on continuous control of key process steps. • The same controls exist, regardless of the composite manufacturing method.

Chapter/Section	Teaching Points
	• Tool design should be controlled and approved, and tool maintenance procedures should be defined, including revision control of any changes to the tools. • Production tools may be used to ensure the parts and assemblies meet type design. • The layup process requires close control and frequent inspection throughout the process. • Features that cannot be nondestructively inspected after cure include proper handling of refrigerated materials, ply placement and orientation, and environmental controls and cleanliness during layup. • Cure cycle control depends on measurement locations. • Critical features that must be controlled through process for structural bonding include tool proofing and prebond assembly checks for secondary bonding, surface preparation, elimination of moisture and other contaminants, and adhesive application. • Features that are difficult or impossible to inspect and which must be controlled by process include material shelf life and out time, handling and debulking processes, and environmental controls during layup and bonding. • Inspections should be performed on prior operations if subsequent process steps result in difficult or impossible NDT on those prior operations. • Examples include ply orientation and sequence, and features hidden after assembly, especially without an access panel. • Type design includes specifications which define the configuration of the part, thereby ensuring the part meets airworthiness requirements. Specifications include the processes necessary to be followed for part production, and provide pass/fail criteria for inspection of the final part. • Key characteristics (Kc) include features of part or assembly whereby Kc variation directly affects final form, fit, or function. Examples of Kc include geometric features, strength, and stiffness. • Key process parameters (Kpp), includes those parameters of the production process whereby Kpp variation directly impacts a Kc feature. Examples of Kpp include cure time/temperature/pressure, and material tack. • Quality assurance programs define Kpp that must be monitored to ensure achievement of Kc. • Quality control tools include post-process records review, physical testing of materials and parts, and nondestructive inspections. • Records review is used to ensure critical process steps were followed when other physical inspection methods are ineffective. Examples include cure cycle parameters, environmental conditions during layup or bonding,

Chapter/Section	Teaching Points
	ply placement, uncured material out life and shelf life, and surface preparation technique prior to bonding. • Anomalies or defects detected by visual inspection or tap testing typically require additional inspections to verify and characterize the extent of damage.
5.2 Certification Conformity Process	• "Conformity" is an official term used to define inspections performed by the FAA or their designee to ensure the test articles used in certification were manufactured per documented procedures. • As many composite part requirements cannot be nondestructively inspected after production, conformity inspections should begin before part production. • Conformity is required at all levels of building block testing. • Test articles at each level of the building block pyramid must be representative of the structure being certified. • Tools are an integral part of the manufacturing cycle and design, and tooling should be included in the conformity process. • The static strength and fatigue and damage tolerance test articles need to include intentional flaws and damage. • Any changes to the type design (including materials and processes) after test articles have been conformed requires substantiation.
5.3 Manufacturing Defect Disposition	• Anomalies, flaws, damages, and defects are terms often used interchangeably as synonymous expressions but are defined uniquely. • Anomalies are present in all composite parts, but only become a defect when the part no longer meets its requirement for strength, stiffness, etc. • Type design should define pass/fail inspection criteria, and criteria based on level of defects is substantiated during certification. • Common production anomalies include cosmetic defects, cracks, disbonds and delaminations, voids, and inclusions. • Potential sources of anomalies originate from manufacturing operations, assembly-related handling, and service. • Bondline integrity issues are related to bondline thickness and weak bonds due to poor surface preparation. • Numerous NDI Methods exist, but not all are suitable for every type of structure and defects. • A part or assembly rejected with an anomaly determined to be a defect must be identified, segregated, and evaluated ("dispositioned") through MRB. • MRB typically consists of representatives from Engineering, Quality, and Manufacturing. Other functions may include Purchasing and customer representatives as required.

Chapter/Section	Teaching Points
	• Trend analysis of anomalies may be conducted by a corrective action board often chaired by program management which may utilize trend analysis to assess corrective actions. • Some defects, even though they are beyond the limits in type design, may be substantiated to use-as-is. • Rework returns a part to a conforming configuration, such as an undersized hole that is further drilled to correct size. • Repair changes the configuration of the part to something other than original type design, but is acceptable through substantiation.
6.1 Inspection and Maintenance	• NDI techniques are not reliable for detecting all damage to laminate and sandwich structure, and NDI cannot reliably detect damage to substructure. • Production environments frequently rely on through transmission ultrasonic technique. In-service environments rely primarily on tap testing and pulse echo ultrasonic. • Damage scenarios which are not fully characterized using typical inspection methods include fiber failure, delamination, sandwich core damage detection, and weak bonds. • Inspection programs must be defined and substantiated for assessing damage to composite structure when defining an inspection program. • Visual inspection is the first line of defense, and additional NDI techniques are required to fully assess the extent of visually detected damages. • Damage types are categorized from 1 to 5 for increased severity. • Structure should be designed such that ultimate load can be carried with BVID to compensate for impact damages that may go undetected. • Structure should be able to carry limit load with damage ranging from small VID to larger VID. • NDI procedures must detect damages prior to load degradation and be able to accurately quantify the extent of the damage so that effective repairs can be performed. • Probability of detection studies for Category 1 damage use deterministic and probabilistic approaches, and those studies should validate that Category 2 through 4 damages will be detected through defined inspection intervals. • Civil Aviation Transport Category operators typically inspect aircraft structure at prescribed intervals (Daily, A, B, C, and D checks). • Inspections for Category 4 and 5 damage incidents are beyond typical inspection programs. • Inspections of severe damage that is created by unanticipated and anomalous ground or flight events are not considered during design.

Chapter/Section	Teaching Points
	- Conditional inspections are situations where inspection must be performed on structure well beyond the area of known impact. - Substantiation of repair design must be based on approved data for bolted and bonded repairs.
6.2 Structural Repair Development and Substantiation	- Damage configurations are affected by various factors, including energy and velocity of the source of damage, composite part configuration and material properties, and susceptibility to cyclical loading over time. - Viewing damage on one side of a composite normally does not reveal the full extent of damage, and non-visible damage resulting from large high-energy blunt impacts may hide large damages that are difficult to characterize. - Visual inspection of the surface of a laminate structure or sandwich structures does not reveal the full extent of damage of substructure damage, and a damaged part may conceal damage on other significant parts. - Flaws or defects that occur in manufacturing or maintenance, and which are undetected by the selected inspection schemes must retain ultimate load and residual strength load requirements when subjected to repeated load cycles over the part lifetime. - Primary composite structural components design must accommodate impact damages that may go undetected by having the capability of carrying ultimate loads, described as BVID. - VID may be serious enough to reduce structural capability below that required to carry regulatory loads. - Damage to a composite component beyond the limits of BVID needs more rigorous NDI inspections and is considered VID. - VID can range from damage that will still allow the component to retain limit load capability to larger damage that may compromise flight safety. - Visual inspection of critical components may be identified by Maintenance Planning Data documents to detect VID prior to becoming critical to flight safety, and damage detected visually requires more rigorous NDI inspections. - Regulatory agencies issue guidance for showing compliance of airworthiness requirements for composite structures. - The SRM, or equivalent documentation, is often the most complete maintenance document for providing instructions for damage inspection, disposition, and repair. If a repair design is not available within the SRM, several options are available. - The ideal approach within maintenance source documents is to provide operators with multiple repair options for a given damage situation. - Repair designs must meet the same airworthiness requirements as the base aircraft structure, and composite inspection techniques and repair design,

Chapter/Section	Teaching Points
	materials, and processes must be substantiated to meet airworthiness regulations. • Performance requirements include strength, stiffness, weight balance, and aerodynamic contour requirements. • Reverse engineering is not recommended for repair designs. • All composite inspection techniques and repair design, materials, and processes must be substantiated to meet airworthiness regulations. • Reverse engineering techniques for composite materials have not yet matured to an acceptable level of confidence. • Repairs require validation upon completion, and process control through authorized procedures and proper equipment in a controlled environment is required, including repair process documentation. • To substantiate a bolted repair, supporting approved data are derived from element level bolted joint tests to assess repair with unique joint geometries, materials, and fasteners. • To substantiate a bonded repair, supporting approved data are derived from coupon and element tests, and full-size repairs are typically assessed with large subcomponent and full component tests. • Source documentation as part of the maintenance and repair process and must be either consulted for damage inspection or repair instructions or filled out to maintain records of repaired components and repair materials. • Repairs detailed in typical OEM source documents must be designed to include damage tolerance and fatigue for critical components.
6.3 Teamwork	• All aspects of composite repair are interlinked, and teamwork is essential to accommodate unique characteristics of composite materials, processes, and design details. • Teams must possess knowledge and skill to satisfy procedural, regulatory, and practitioner skills, and team members must recognize skill limitations. • Team participants and functions include repair technicians, inspectors, engineers, management, and OEMs, with identified education, knowledge, skills, and responsibilities. • Effective maintenance and repair include structural inspection and damage detection, disposition of damage, repair fabrication, and resource knowledge when questions arise. • The OEM utilizes many disciplines to ensure that the source documentation such as the SRM contains guidance to perform accurate dispositions of damage, with instructions for performing approved repairs by operators and MROs. • Acquired skills should be continually demonstrated following initial training.

Chapter/Section	**Teaching Points**
	• Various human factors must be considered to assure valid and safe field repairs, especially for bonded repairs.
6.4 Repair Techniques	• Bolted and bonded repair techniques have advantages and disadvantages, and selection depends on geometry, configuration, and design objectives. • Both bolted and bonded repair require the restoration of any protective coatings such as paint and lightning strike protection. • Bonded repairs performed on aircraft typically utilize hot bonders at both field and depot locations. Autoclave bonded repairs for removed components are reserved for depot locations. • On-aircraft repairs under challenging environmental conditions require that permanent bonded and bolted repairs adhere to substantiated data, materials, and processes. Temporary bonded repairs, utilizing lower temperature cure materials, require inspection at prescribed intervals. • Many types of bonded repairs are available for a) laminate stiffened structure and b) sandwich structure, and bonded repairs are typically preferred for thin laminates and sandwich components. • Bonded repairs to composite structural components must meet the appropriate airworthiness requirements including material and process qualification, static strength ultimate load, and fatigue and damage tolerance. • Critical structures must have a bonded repair size limit no larger than a size that allows the repaired component to retain limit load after complete or partial failure of the bond line. • Data supporting bonded repairs must include inspections capable of detecting complete or partial failure (within arresting design features) of the bond line. • Two bonded repair processes are a) prepreg and b) wet layup. • Options may be provided in OEM source documentation for both a) permanent repairs or b) temporary or interim repairs. • Bonded repair process critical issues include surface preparation and moisture content of the damaged part. • Scarf repair provides the most structurally efficient patch, and the stepped lap approach is the next most efficient and often used for aerodynamically critical components. • Documented process control by following authorized procedures and proper equipment in a controlled environment is required for cure parameters, including temperature, vacuum, heat-up and cool-down rates, and must be documented. • Mitigating heat sink issues to reduce heat gradients during cure may be addressed by practice, and examples include zoned heater blankets and use of insulation.

Chapter/Section	Teaching Points
	• Bolted repairs are often used whenever part thickness would require a) extensive material removal for bonding, b) repairing components with complex geometries, or c) thick laminate or primary structure applications. • The potential for bolting to composite components during repair is a consideration during initial design when choosing layup and structural configurations. • For adhesively bonded patches with added fasteners, the added fasteners carry little load until the bond fails. There is a danger of damage to the bond line when installing the fasteners. • Functionality of restored protective coatings must meet original requirements and must be compatible with the composite material. • Non-uniform heating risks increase with the increased use, size, and complexity of composites in commercial transports and can cause an improper cure outside of material specifications, requiring special processes and equipment. • A variety of process practices, heat sources, and controllers are available or under development to mitigate non-uniform heating due to heat sinks, complex heating environments, non-uniform heat sources, and high ply count composite laminates.
7.1 Flutter	• Aeroelasticity is the interaction between inertial, elastic, and aerodynamic forces. • Wing divergence occurs when aerodynamic load creates deflection or twist of the wing. increasing aerodynamic load, thus creating more deflection, and subsequently more load, until failure occurs. • Aileron reversal occurs when of wing flexibility enables aerodynamic forces on the aileron to cause wing twist whereby loss of lift on the wing equals the increase of lift due to aileron deflection. • Flutter is a structural oscillation that is self-exciting or self-sustaining and can occur at certain frequencies and mode shapes, extracting energy from the airstream due to motion of structure. • Flutter vibration modes are determined by the mass distribution, stiffness distribution, geometry, and damping of structure and are excited by external forces that are independent of motion of structure. • Flutter compliance includes a structural model and an unsteady aerodynamic model. • Design changes may affect flutter characteristics, including mass and mass distribution, airframe stiffness and stiffness distribution, and profile changes of aerodynamic shapes. • Structural properties may change during operation. • Large category 3 and 4 damages can alter flutter characteristics, and any repair to a flight control panel must be considered for mass or mass

Chapter/Section	Teaching Points
	distribution effects on flutter characteristics even with retention of adequate residual strength margin.
7.2 Crashworthiness	• Crashworthiness is the ability of a vehicle to protect its occupants or cargo during a crash, and includes concept development to limit crash loads transmitted to aircraft occupants. • Crashworthiness is a systems approach with aircraft lay-out and design defining crash behavior, and systems focus includes structure, seats, seatbelts, cabin environment . • Crashworthiness emphasis includes seats, injury criteria, and overall aircraft/ systems design to allow for survivability and emergency egress. • Five conditions for survivability are: a) maintaining sufficient occupant space, b) providing protection from items of mass, c) providing energy absorption, d) eliminating post-crash fire hazards and allowing for a safe egress, and e) limiting loads transmitted to the occupant and providing adequate occupant restraint. • Crash event is the impact between an aircraft and ground surface resulting in substantial structural damage and is typically comprised of vertical and longitudinal velocity components. Different combinations of these components may define different levels of survivability. • Unlike damage tolerance, material processing, or static strength, crashworthiness requires a systems approach, and the whole system must work in an integrated fashion to guarantee a level of safety. • Crashworthy regulations focus on occupant protection during testing of seating systems and assumes a level of energy absorption from the airframe and certification requirements include peak load pulse magnitude, direction, and duration. • Special conditions are issued for new model airplanes such as A380, B787 and A350 because of novel or unusual design features, such as the Boeing 787-8 due to carbon-fiber-reinforced plastic (CFRP) used in the fuselage construction. • A composite airframe must meet various defined conditions for a range of airplane vertical descent velocities up to 30 ft/sec. • The main failure mechanisms associated with crash energy absorption are flexural deformation, axial crushing, and bolted joint failure. • Composites can fail in tensile fiber fracture, compressive fiber kinking, matrix cracking, shearing, or delamination, and various loading conditions, loading speeds, and geometric features will promote or inhibit different failure mechanisms, thereby providing different levels of energy absorption. • Certification by test relies on test alone and demonstration is empirical, and is typically used with seats and other areas which are viable.

Chapter/Section	Teaching Points
	• Certification by analysis supported by test evidence process relies on concurrent development of analysis methods and testing, and the building block approach is key to analytical validation process for crash simulation. • Certification by analysis alone is not viable for composites because it is not sufficiently accurate nor predictive for composites. • Composite airframe compliance with crashworthiness requirements has many challenges, including definition of test protocol, large-scale test expectations, dynamic testing, and progressive failure and damage analysis.
7.3 Fire Safety	• Civil aviation fire threat concerns include in-flight fires, post-crash fires, and fuel tank flammability. • In-flight fires occur within the pressurized area of the cabin during flight, and the safety objective for in-flight fires is to mitigate flame propagation in inaccessible areas. • Survivability during a post-crash fire depends on successful occupant egress before flashover by prolonging a) fire penetration, and b) flashover by limiting cabin materials by enhanced certification fire testing. • The safety objective for fuel tank flammability is to reduce vapor flammability levels of fuel tanks during all phases of taxi, takeoff, and landing. • Flammability regulations address cabin interior materials, and fuel tank flammability reduction and prevention of ignition sources. • FAA developed comparative analysis tool (FTFAM) which determines fleet wide flammability exposure of a fuel tank based on standardized distributions of variables including fuel tank environment, flight mission data, fuel properties, and tank thermal characteristics. • Regulatory assumptions are based on aluminum which a) does not burn at the same temperature as composite structure, and b) dissipates heat better than composite structure. Each regulation must be reviewed to determine if changing the structure/skin material will change the severity of the fire threat. • Carbon fiber composites provide excellent burn-through protection compared to traditional aircraft aluminum, but the thickness and construction of the material will dictate severity. • Research test results indicate that composite material fuselages can provide the same level of safety as that of a burn-through-resistant insulation assembly, considering fuselage burn-through and hazardous gas generation on the inboard side of the fuselage. • Wing tanks are typically non-flammable due to the absence of external heat sources and rapid cooling that occurs in flight through the aluminum skin.

Chapter/Section	Teaching Points
	• Under similar heating conditions, a composite fuel tank absorbs more radiant heat, resulting in higher ullage (air volume above the fuel) gas and liquid fuel temperatures, exhibiting higher flammability. • Flammability decreases rapidly in flight as ambient pressure decreases and the skin is cooled by convection.
7.4 Lightning Protection	• Lightning is a complex event that involves high current resulting from two areas in the atmosphere with opposite charge concentrations. • Carbon fiber composites are approximately 1000 times more resistive than aluminum and develops a much higher voltage drop from point to point on structure, whereas aluminum structure tends to have a degree of lightning protection due to better electrical and thermal conductivity. • Carbon fiber composites are susceptible to lightning damage and require specific lightning protection features. • The lightning effect on carbon fiber composites includes resin vaporization and delamination at lightning attachment points, sparking and hot gas ejection at fasteners, and high induced current and voltage on wiring and tubes. • Lightning tends to initially attach to the aircraft extremities, such as the wing tips and the nose radome. Initial attachment locations should be protected against direct attachment damage. • Lightning attachment zones define locations on the aircraft where lightning is likely to attach, and lightning zone definitions are required to support fuel system, structure, and system lightning protection. • Design goals include maintaining structural integrity, reducing lightning transients on electrical and electronic systems, controlling lightning current through control rods and cables, hydraulic tubes, and hinges, and preventing lightning sparks and burn-through for fuel tanks and fuel systems. • Protection concepts can prevent lightning puncture by adding metal to outside surfaces by using aluminum, copper or bronze mesh or foil, and selecting suitable fastener and fastener installation processes. • Lightning protection regulations address structure, fuel system, and systems. • Lightning protection features required to show compliance with regulations are significantly affected when carbon fiber composites are used for aircraft structure.

B Student surveys (2016)

B.1 Student survey observations and conclusions

Based on participant feedback from courses delivered between 2013 and 2015, the following conclusions for future improvements were noted.

- Maintain content depth, since most students are practicing engineers wanting additional composites technology and certification process knowledge
- Course improvements should focus on a) organization, b) consistent format, and c) slide clarity.
- Re-consider grading rubric. Students can easily pass the course and with limited learning under the current methodology. Three options:
    - Revert to requiring commenting at least three times on three separate days.
    - Utilize peer evaluation of brief essays as a part of the grading scheme.
    - Revise approach on discussion boards. Currently, there are too many threads, which require detail design knowledge. Discussion boards should focus on principles, supported as needed by detailed design, reversing the emphasis. A review of the 2014 and 2015 CSET course discussion boards provided additional material for establishing threads.

B.2 Course history overview

On average, students spent between 6 and 11 hours (based on a 9-week course) on Blackboard per week, as advertised. See below for further suggestions.

- The higher hours in CSET 2014 (Fall) were distorted by two students who spent excessive times in the course: The average drops to 8.7 hours per week with those two deleted from the average.
- Based on a survey, combined with Blackboard information, the average time spent across all delivered CSET courses was 11.3 hours per week. Recommend adjusting course advertising to reflect “approximately 10 hours per week studying for the course”. (Note: 11.3 hours is considered higher than actual due to additional two weeks added to 2015 course, reducing hours)

- Increasing CSET by 2 weeks achieved a reduction in time per week by students in the course to ~5 hours (15 – 20% reduction), which was one goal for making that change
- Grades and discussion board posts were used to assess student participation. Overall, changing the requirement for CSET 2015 to not require three posts on three separate days caused a huge drop in posts per week per student, or from over six to less than two. At the same time, easing discussion board requirements resulted in higher average scores. It is recommended that this policy be reassessed, and incorporating peer review as a part of the grading scheme (discussed above).

B.3 Student objectives for taking CSET

- Fifty percent of students have experience in Composites Engineering. Another 25% have Aerospace Engineering and wish to extend their knowledge into Composites Technology and Certification practices.
- Focus on CSET should be to continue key composite engineering technical issues, but organized more 'orderly', such as CMfgT.
- Focus on the certification framework – this is somewhat intermingled with the technology discussions and related more to organization than adding/subtracting content.
- Involvement (Grades and Weekly Postings) did not show a significant variance among the stated objectives.

B.4 Participation in classes (regulatory, industry/military, academic)

- Two thirds of students came from the military, industry, or NASA (39). The balance was primarily FAA and other regulatory agencies. (24)
- Grades were higher for industry than for regulatory (96% vs. 82%)
- Weekly postings did not show a significant variance among the organizations

B.5 Experience level

- Nearly 90% of the classes were practicing engineers
- Involvement comparisons are not significant based on experience level segmenting, although what data exists would indicate not a lot of variances with bigger samples.

B.6 Survey detail

The following charts shown in Tables B1-B4 were derived from information available on Blackboard and a student survey and form the basis of the above conclusions. Although Wichita State University deleted much of the information (other than student introductions) for the Fall 2013 course, and no information exists for Spring 2013 course, due to software upgrades, the results and conclusions would likely have been unaffected.

Table B1. Discussion participation arranged by student objectives

Weekly Postings in Discussion Boards by Stated Objective	**CSET 2013 (spring)**	**CSET 2013 (fall)**	**CSET 2014 (spring)**	**CSET 2014 (fall)**	**CSET 2015**	**Average Over All Courses**
Engineering background: learn fundamentals of CSET	NA	NA	5.8	6.3	3.3	**5.1**
Practical Aerospace INDUSTRY background: extend knowledge into composite and certification (e.g., past focused on monuments)	NA	NA	10.9	4.5	1.0	**5.5**
Practical Aerospace ENGINEERING background: extend knowledge into composites (e.g., past focused on metals)	NA	NA	7.8	5.4	1.5	**4.9**
Experienced in COMPOSITE ENGINEERING practice but needs framework in certification/substantiation or needs refresher	NA	NA	5.6	7.4	1.9	**5.0**

Table B2. Student objectives distribution and grades

Student Objectives Distribution	**CSET 2013 (spring)**	**CSET 2013 (fall)**	**CSET 2014 (spring)**	**CSET 2014 (fall)**	**CSET 2015**	**Total**
Engineering background: learn fundamentals of CSET	NA	4	1	2	0	**7**
Practical Aerospace INDUSTRY background: extend knowledge into composite and certification (e.g., past focused on monuments)	NA	3	2	2	2	**9**
Practical Aerospace ENGINEERING background: extend knowledge into composites (e.g., past focused on metals)	NA	6	2	6	5	**19**
Experienced in COMPOSITE ENGINEERING practice but needs framework in certification/substantiation or needs refresher	NA	8	8	6	8	**30**
TOTAL w/o CSET 2013 (spring)	NA	21	13	16	15	**65**
CSET 2013 (spring) *includes 3 dropouts	21					**86**

Table B3. Student grades by stated objective

Grades by Stated Objective	**CSET 2013 (spring)**	**CSET 2013 (fall)**	**CSET 2014 (spring)**	**CSET 2014 (fall)**	**CSET 2015**	**Average Over All Courses**
Engineering background: learn fundamentals of CSET	NA	41%	93%	84%	94%	**78%**
Practical Aerospace INDUSTRY background: extend knowledge into composite and certification (e.g., past focused on monuments)	NA	NA	103%	92%	85%	**93%**
Practical Aerospace ENGINEERING background: extend knowledge into composites (e.g., past focused on metals)	NA	79%	92%	86%	104%	**90%**
Experienced in COMPOSITE ENGINEERING practice but needs framework in certification/substantiation or needs refresher	NA	79%	84%	73%	94%	**83%**

Table B4. Student attendance, grades, discussion participation, and hours

COURSE HISTORY OVERVIEW						
	Weeks excluding prerequisite	**Number Students**	**Average Grade**	**Average Posts/Week (Total Students)**	**Average Posts/Week (Individual Students)**	**Average Hours in Blackboard/Week (Individual Students)**
CSET 2013 (spring)	9	21	70%	NA	NA	NA
CSET 2013 (fall)	9	21	75%*	NA	NA	NA
CSET 2014 (spring)	9	13	89%	60.7	6.7	6.2
CSET 2014 (fall)	9	16	82%	98.4	6.2	11.1
CSET 2015	11	15	94%**	27.4**	1.8**	5.2***
Survey % Time Outside Blackboard						48%
Weighted Average						7.6
Computed Study Time						11.3
TOTAL		**86**				

*3 students dripped out and not included in average

** Discussion boards simplified with essay option, improving scored, reducing posting requirements

*** Addition of 2 weeks prior CSET with approximately the same content

Student feedback on CSET improved after the 2016 improvements, as shown below in Table B5.

Table B5. Student feedback (5 is highest possible score)

Year CSET Delivered		**2019**	**2018**	**2017**	**2016**
Number of Surveys/Total Number of Students		**15/18**	**16/17**	**13/17**	**8/9**
1.	The syllabus provided clear course objectives and explanations for learning expectations.	4.1	4.4	4.6	4.4
2.	The prerequisite added to the value of this course by preparing me for the more advanced content contained in the main course.	3.9	4.3	4.6	4.8
3.	The course context (excluding the laboratory and preprequisite) achieved the overall objective as stated in the syllabus, “This course will provide to student a background in the techniques, methodoligy and safety issues regarding the structural engineering and certification of composite materials utilized in commercial aerospace.”	4.2	4.2	4.6	4.8
4.	I liked all of the different subject areas that were taught in this course.	4.3	4.2	4.4	4.5
5.	The detail in this course was apppropriately balanced in terms of content volume and complexity throughout the different topics.	3.5	4.0	4.1	4.5
6.	I read/looked at the majority of the optional slides/content provided in this course.	4.5	4.6	4.4	4.5
7.	The time which I spend learning the course content was 10 hours or less per week.	4.1	3.8	3.7	3.3
8.	The video testemonials added value to this course, were relevant, and the nature and purpose of the messages were clear.	3.4	4.0	4.2	4.1
9.	The Blackboard platform which encourages student interaction through disucssion boards enhanced my learning and retention of the teaching materials.	3.9	4.4	4.4	4.0
10.	I liked using Blackboard because of its flexibility whereby I could actively participate at a time when it was convenient for me.	4.3	4.4	4.7	4.3
11.	Blackboard was easy to navigate through (e.g it was easy to access different sections of the course through the menu buttons).	4.0	4.1	4.5	3.4

Year CSET Delivered **Number of Surveys/Total Number of Students**		**2019** **15/18**	**2018** **16/17**	**2017** **13/17**	**2016** **8/9**
12.	I was able to easily download the PDF files from the Blackboard site.	4.4	4.7	4.8	4.6
13.	The notes in the PDF files (yellow bubbles) were easy to use and read.	3.3	3.8	3.7	3.6
14.	I could easily contact my instructor if I had any questions or concerns.	4.3	4.4	4.5	4.3
15.	The instructors, as a group, were active and engaged in this course.	4.7	4.6	4.5	4.4
16.	I knew what was expected of me as a student and the basis for student grades.	4.3	4.6	4.5	4.3
17.	The discussion board topics were representative of the module subject matter.	3.9	4.4	4.5	4.5
18.	I was interested in the majority of the discussion board topics which increased the value of this course.	4.3	4.5	4.5	4.6
19.	When I was less knowledgeable about a topic, I was given a reasonable amount of time to study the materials and actively participate in the discussion threads.	3.9	4.1	4.3	3.9
20.	Having more knowledgeable students in the class facilitated the learning process in the discussion boards.	4.4	4.4	4.5	4.8
21.	The frequency and quality of the student and instructor interaction were adequate.	4.3	4.5	4.3	4.5
22.	There were times during the discussion boards when I felt hesitant (or embarrassed) to answer because the discussion threads had become too specialized and were beyond my ability to contribute.	3.2	3.5	3.2.	3.0
23.	I liked having a class with a mix between FAA and industry students/instructors because it facilitated the learning process in the discussion boards.	4.5	4.5	4.6	4.8
24.	The exam questions reflected the teaching points in a clear and balanced fashion across all modules.	3.9	4.3	4.5	4.1
25.	The length of the exam and the time it took me to complete it were appropriate for assessing my learning of the teaching points.	4.4	4.3	4.3	4.1
26.	The length of the course (12 weeks) was not an issue for me.	3.8	4.0	4.0	3.7

C Correlation between original (2015) and modified (2020) CSET

Modifications made to the CSET course between 2015 and 2020 were based on course feedback, A tracking table ensured content was retained through the modification process. Table C1 shows the correlation between the final 2020 revision and the 2015 content organization.

Table C1. The CSET 2020 revision correlation with version 2015

New CSET Module (2020)	**Original CSET Module Content (2015)**
Module 1.0	Modules 1.0, 2.0, 3.1
Module 2.0	Modules 3.2, 3.4, 3.5, 6.0
Module 3.0	Modules 3.3, 3.5, 3.6
Module 4.0	Modules 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, 4.10, 4.12, 4.13, 4.14, 6.0
Module 5.0	Modules 3.3, 4.7, 5.0
Module 6.0	Modules 4.7, 4.14, 6.0
Module 7.0	Modules 7.1, 7.2, 7.3, 7.4

D Discussion board topics

An important CSET learning process is the participation of learners with subject matter experts and other course participants. This is done using practical topics presented through the discussion board. Table D1 lists current CSET topics and discussion points.

Table D1. CSET discussion topics

Topic	**Discussion points**
Technical Characteristics for Composite Airframe Structures	▪ How would you modify the list of top ten “Key Technical Characteristics for Composite Airframe Structures” described in module 1.0 in terms of a) additions or deletions, and b) order of importance? ▪ Alternatively, if you agree with the list without any changes as described in the reading material, how would you justify that conclusion?
Material Specification Equivalency	▪ A statement is made … “it is assumed by many applicants that all materials purchased per a material specification are the same.” Provide your perspective on this statement, through actual or hypothetical examples and include your opinion as to how prevalent this assumption is in aerospace. ▪ NOTE: As recently as the 1990s, a materials specification often included alternate materials, and the specification requirements were often minimum values since it was believed that an increase in base strength would improve all structural properties, with little to no links with material qualification tests. Current composite guidance does not accept such practice for material control.
Non-Fly Away Materials	▪ Non-fly away materials, such as bagging materials, bleeder cloth, parting film, and peel-ply, are used in composite manufacturing. ▪ Should specifications and quality control procedures for non-fly away materials be as rigorous as for flyaway materials? Why or why not?

Topic	**Discussion points**
Material Suppliers	▪ You are responsible for designing a secondary structure composite part. Purchasing identified three suppliers, which provide material to the same specification and begins a competitive bid. Lowest price determines the selection. ▪ From an engineering standpoint, you see potential issues and advise Purchasing as follows: (List one issue and expand on it).
Material specification	Your manager, under pressure to contain costs, is proposing that a new material be adapted that has been used previously since the material is ‘mature’. You are not certain that this will, in fact, reduce cost, and raise the following issues (List one issue and expand on it)
New applications of composite materials	Discuss the potential choice of carbon-fiber-reinforced plastic (CFRP) for the front and rear spars of the wing main toque boxes of new aircraft, and why some design details of the CFRP spars will differ from their metal counterparts.
Environmental issues	Select one environmental issue that must be accounted for in the design of aircraft structures and discuss how it may affect carbon fiber reinforced composite structure versus an equivalent aluminum structure.
Design values	In what ways can a designer use publicly available material data to design and certify composite aircraft structure, and what are the advantages and disadvantages of this approach?
Bolted joints	▪ On a new commercial airplane program, you are responsible for the design of the terminal fittings, which attach the composite (CFRP) vertical stabilizer to the fuselage. ▪ Fittings are among the most challenging types of construction because they transfer high loads in multiple directions. ▪ Deciding if major fittings such as the terminal fittings attaching the vertical stabilizer to the fuselage would be composite or metal requires careful consideration of many factors. ▪ Propose which you would favor, metal (which type) or composite and discuss the reasons for your selection.

Topic	**Discussion points**
Manufacturing/design interface	▪ Flaws and/or defects induced by processing can affect the mechanical properties of a composite part. ▪ Pick one structural detail and discuss how the part geometry and the process selected (including tooling) may induce flaws/defects in the final part. ▪ Discuss mechanical properties that can be affected by these flaws.
Bonded joints	▪ Bonded joints have the perceived advantages of aerodynamic smoothness and aesthetics. ▪ The absence of fasteners may also reduce stress concentrations. ▪ Despite these advantages, describe any technical challenges regarding the decision to select bonded joints.
Scaling	▪ Scaling can be an issue for composite manufacturing. ▪ Consider an OEM, who previously designed and produced a composite main torque box for the horizontal stabilizer of one of their airplane models and now wishes to scale that technology to a main toque box for a wing. ▪ Discuss some issues that scaling up may produce and discuss some ways to mitigate these issues.
Integrated product development teams (IPDT)	▪ An integrated product development team (IPDT) typically includes designers, manufacturers, cost, and maintenance specialists. ▪ Describe an experience where an IPDT was positively, or negatively influenced by the presence of these specialists at various times in the design process. ▪ How would you have changed the participation, timing, and level of influence of team participants, if any?
Impact damage	Give an example of a configuration change that could increase the damage tolerance of a composite structural component.
Environmental conditioning	▪ Typically, the critical environmental condition for static testing is "elevated temperature wet"

Topic	Discussion points
	because many properties of composite materials are somewhat reduced compared to "room temperature ambient". ▪ Do you agree that the fatigue test of a sub-component specimen (for example, the sub-component test is a 5-stringer panel compression test with barely visible impact damage) should be performed at the same elevated temperature-wet condition that was used for the static test? ▪ Why or why not?
Proof of structure	▪ The service damage that may be considered the most difficult to simulate in structural tests is impact damage. ▪ Discuss potential structural details and boundary conditions representative of real structure and impact details (kinetic energy, velocity, impactor size and mass, etc.) that properly characterize the impact event.
Standardizing test programs	▪ Standardizing test programs exhibit challenges related to categorizing various combinations of damage and structure conditions. ▪ For example, based on hail damage understanding in terms of energy and size, different representations of energy and size on the upper skin of a wing and the radom should be considered. ▪ Provide your perspective on various approaches and challenges, including examples and their corresponding challenges, in developing standardized damage testing.
Certification by test	▪ Your manager decides to adopt a ‘certification primarily by test’ approach on a major new development project based on his perception that this would reduce cost and lead-time. ▪ List some of the advantages and disadvantages of this approach, including cost, lead-time and situation or circumstances that could either support or alter his decision.
Load enhancement factor (LEF)	▪ Additional load- or life-enhancement factors are used in structural substantiation to account for material variability.

Topic	**Discussion points**
	▪ These factors are applied to develop the required level of confidence in structural repeated load tests, relative to the design load and life values. ▪ Discuss how such factors are derived and why a LEF is often more desirable for composites.
Damage categories and damage tolerance	▪ Describe one damage category and discuss how damage in this category can affect damage tolerance evaluations to demonstrate the required residual strength of a specific composite primary structural component. ▪ Comment on differences in the inspection methods used for initial composite damage detection and subsequent inspection steps used to determine the full extent of the damage.
Damage threat assessment	Describe an approach for defining the damage threats to a structural component, such as aileron, flap, or fuselage.
Damage tolerance	Select a specific defect or type of damage to a horizontal stabilizer main torque box of a part 25 commercial airplane and propose an approach to demonstrate damage tolerance to this defect or damage type.
Values	▪ There exist qualification values, design values, and acceptance values (the values that the incoming material must exceed for use in the factory). ▪ Explain the relationship among the various values, including comparing the relative sizes of the values in a specific application.
Inspection programs	▪ What kind of conditional inspections may be included in the in-service inspection program for an aircraft with a composite fuselage?
No growth validation	▪ During a full-scale fatigue test of a composite wing, damage (deliberately inflicted on the test article to validate the no-growth approach for Category one damage) grew during the testing. ▪ Discuss some options and potential approaches.
Manufacturing anomalies	▪ You are to support the engineering effort in dealing with the effect of manufacturing anomalies, such as local wrinkling of upper skin panels combined with small variations in

Topic	**Discussion points**
	surface contour, that were found during ramp-up production of an already certified composite wing. ▪ Your goal is to understand the effect of these anomalies and provide recommendations for extending the existing allowable limits (if possible). ▪ Recommend building block tests and discuss some of the challenges you think are important.
Quality control	▪ In addition to adhering to approved processes, the quality of composite parts during a production run can be further assessed by non-destructive and destructive testing. ▪ Discuss one of these methods, including the advantages and disadvantages of your selection.
In-service damage	▪ The pilot, performing his first flight of the day walk-around inspection of his part 25 airplane, observes scuffed paint and a dent in the lower sill of the forward service door cutout of the composite fuselage. ▪ The airplane is at a line station where maintenance is not available. ▪ The pilot documents the damage in the aircraft logbook and reports it to you, a maintenance engineer, at the main maintenance base. ▪ What would be your course of action for evaluating the damage and who should be involved in the decision process as to the need for repair and/or type of repair?
Complex repairs	▪ Describe a scenario involving non-uniform heating during out of autoclave curing of a composite. ▪ In your example, describe circumstances which may have resulted in non-uniform heating, and how this might be compensated for during the curing process, including equipment and methods selection.
Fire safety	In the event of an engine explosion on a runway, compare the response of a composite fuselage with that of an aluminum fuselage, with regards to potential fire.

Topic	**Discussion points**
Lightning strikes	▪ Lightning strikes can be detrimental to composite structures. ▪ Discuss an example of a lightning strike protection scheme for a composite fuselage.
Flutter	How can a repair affect the flutter characteristics of a composite sandwich flight- control panel such as a rudder?

E Prerequisite

Students study the prerequisite materials during the first week of class to bring all learners to a common understanding of composites technology. This equips students for the content and discussion boards in subsequent CSET activities. This appendix details the topics included in the prerequisite materials.

E.1 Introduction to aircraft structure composite materials

Composite materials were introduced to the commercial aircraft industry during the early 1960's, consisting primarily of glass fiber and epoxy resin. Development of more advanced fibers such as boron, Kevlar, and carbon offered the possibility of increased strength, reduced weight, improved corrosion resistance, and greater fatigue resistance compared to aluminum.

The early success of the first simple components, such as wing spoilers and fairings, led to the use of advanced composites in more complex components such as ailerons, flaps, nacelles, and rudders. The increased specific stiffness and strengths of composites over aluminum, coupled with weight-driven requirements caused by fuel shortages, led to the application of thin-skin sandwich structures.

E.1.1 Characteristics of typical composite materials

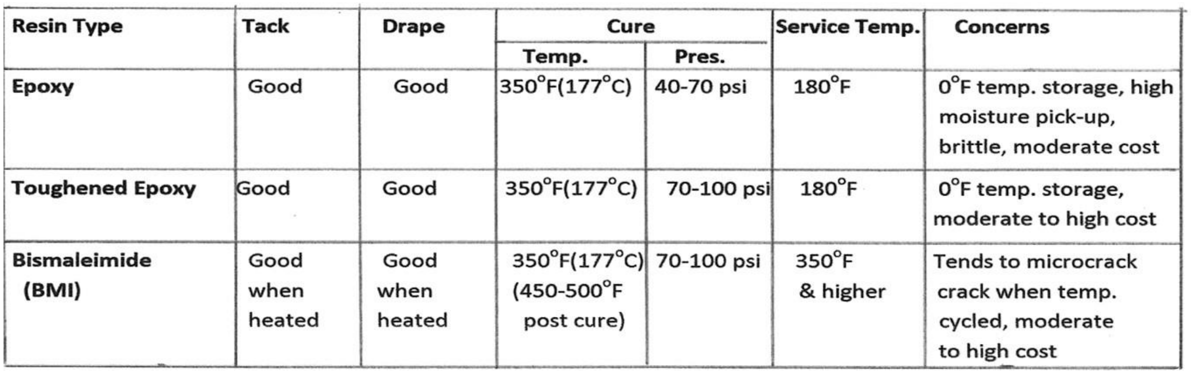
When two or more materials with very different properties combine, they form a composite material. The different materials work together to produce a new material, which combines all the properties of the previously separate materials. Within the composite, it is still possible to tell the different materials apart. They do not tend to blend or dissolve into each other. Typical ingredients (or constituents) within a composite material are resins and fibers.

E.1.1.1 Resins

A resin is called a matrix when used in conjunction with reinforcing fibers, i.e., a composite consisting of fibers and resin. In modern composite materials applications, there are many resins available and numerous products within each type. The term "resin" normally describes relatively low viscosity liquid materials that form the matrix of a composite when cured. Viscosity describes the degree of fluidity and flow. For example, water is a "thin" (low viscosity) fluid that flows easily; honey is much thicker and exhibits high viscosity. The most widely used resins in commercial aircraft structural applications are thermosetting resins. A thermosetting resin (or plastic), also known as a thermoset, is a polymer material that irreversibly cures. The cure may be done through heat (generally above 120 °C [250 °F]), through a chemical reaction (two-part epoxy, for example), or irradiation such as electron beam processing. Thermoset materials are usually liquid or malleable prior to curing and designed to mold into their final form or used as adhesives. Some examples of thermosetting resins are polyester, epoxy, phenolic, bismaleimide (BMI), vinyl ester, and polyimide.

Another resin type used in aircraft composite applications is thermoplastic. Thermoplastic resins have molecules that are generally not cross-linked, meaning, the resin can be repeatedly melted and reused. Usually, no chemical change occurs when a thermoplastic is cured. Thermoplastic resin usually starts out in solid pellet form and changes shape with the addition of heat and pressure. Composite material systems that use thermoplastic resins are generally more difficult to form or manipulate than are those that use thermoset resins. One obvious advantage thermoplastics have over thermosets is the ability to be reused or re-cured, another is that thermoplastics are generally tougher and less liable to delaminate compared to thermosets.

Epoxy resins are the most used resin in aircraft structural components. Virtually all modern commercial transports use epoxy resins for their composite structural components. The new Boeing 787 utilized a toughened epoxy resin for some of the large primary structural components, such as the stabilizer and wing main torque boxes and the pressurized fuselage sections. The benefit of the more expensive toughened materials is that it is more damage resistant when compared to the materials using the more brittle regular epoxy resins. Phenolic resins used for aircraft interior parts such as floor panels, galley and toilet modules, and overhead storage bins because exhibit improved flammability resistance. Polyimide and BMI resins are typically used in higher service temperatures applications. Polyester, vinyl ester, and epoxy resins are used extensively in boat building as well as many other uses. Figure E1 shows some different types of resins used in aircraft structural applications and their attributes.



Resin Type	Tack	Drape	Cure		Service Temp.	Concerns
			Temp.	Pres.		
Epoxy	Good	Good	350°F(177°C)	40-70 psi	180°F	0°F temp. storage, high moisture pick-up, brittle, moderate cost
Toughened Epoxy	Good	Good	350°F(177°C)	70-100 psi	180°F	0°F temp. storage, moderate to high cost
Bismaleimide (BMI)	Good when heated	Good when heated	350°F(177°C) (450-500°F post cure)	70-100 psi	350°F & higher	Tends to microcrack crack when temp. cycled, moderate to high cost

Figure E1. Aircraft quality resin types

Wet-lay-up resins are typically two-part systems, whereby a curing agent is mixed with a base resin and the mixture is then brushed onto layers of fiberglass, carbon fiber, aramid fiber, or other fibers. These liquid resins may be cured to a solid product at room temperature or at elevated temperatures to accelerate the chemical reaction. Before mixing, resin and curing agents are individually measured to the correct pro portions and then thoroughly mixed. This is essential to achieve the required strength and temperature properties of the final composite part. The required curing time is also very important. Each resin has a minimum curing time at a specified temperature that is required to achieve full cure.

Alternatively, the resin can be supplied already mixed and applied to the fiber reinforcement (fabric or tape) in a form called prepreg (short for pre-impregnated). Prepreg resin is typically supplied in a roll as unidirectional fiber-reinforced tape or fabric between plastic or paper release sheets. This must be removed before assembling the layers (the lay-up operation), otherwise the layers of prepreg will not stick to each other during the curing process. The resin at this point is at the "B" stage, or partly cured condition, and must be kept in a freezer until use. In this condition, the prepreg has a shelf life of six to twelve months depending on the resin formula. As with wet-layup resins, curing time and temperature are important to achieve full cure.

E.1.1.2 Adhesives

Adhesives are used to bond composite parts together and are used for bonding metals, such as aluminum alloys, titanium alloys, and occasionally corrosion resistant steel. Adhesives are chemically similar to composite matrix resins but are of higher viscosity to prevent the adhesive flowing out of the bonding interfaces and leaving them “resin starved.” Two types of adhesives are typically used in bonding composites; paste adhesives and film adhesives.

Paste adhesives: Two-part paste adhesive systems cured at room temperature are usually of about “toothpaste” viscosity when completely mixed. These adhesives need to be measured out accurately and the two parts thoroughly mixed. Many two-part paste adhesives can be purchased as kits containing the correct amounts of Part “A” and Part “B” to give the required mix ratio. Fillers such as microbeads may be measured and added to the adhesive mix to thicken it and/or to ensure the proper thickness bond line. Epoxy adhesives are the most common type used for bonding aircraft structural composite parts.

Film adhesives: Film adhesives are adhesives supplied in the “B” stage, or partly cured condition. Film adhesives are a thin film of adhesive (often on a scrim cloth) between plastic release sheets. Film adhesives come in various areal weights (per square foot or square meter). They can be cured at different temperatures depending on the resin formulation.

The choice of film adhesives over paste adhesives typically depends on the application. Film adhesive has a very controlled thickness, which is an advantage for bond strength, convenience, and working life for laying down the adhesive for large, bonded assemblies. However, film adhesive is more expensive and has a limited freezer life (similar to epoxy prepreg life) compared to the indefinite shelf life of paste adhesives.

E.1.1.3 Fibers

Three fiber types most used in composite aircraft structures are carbon, glass, and aramid. These fiber types are easily distinguished from one another: Carbon is black, glass is water clear, and aramid is yellow opaque. Quartz fiber is sometimes used for radomes and boron fiber patches are often used to repair metal parts that exhibit fatigue cracks. All fibers, except boron, which is too thick and stiff to be woven, can be made into fabrics with many different weave styles or into unidirectional tapes. Boron fibers, which are very strong, have been used in the past on military applications, but their use is limited due to their cost and lack of malleability.

Carbon fibers: Carbon fibers are the most employed fiber for structural aircraft components. Carbon fibers are often called graphite fibers, but the correct name for the fibers used in all strengthening and reinforcing applications is carbon. Aircraft applications include wing, fuselage, stabilizers (horizontal and vertical), elevators, ailerons, main wing flaps, and rudder structures. Carbon fibers are also used in undercarriage doors, engine cowlings, engine fan and propeller blades, helicopter rotor blades, and in undercarriage components for some helicopters. Carbon fiber can be supplied in several grades of strength, modulus, and forms. Carbon fibers are often woven into fabric (or cloth) forms for original part and repair prepregs or dry fiber mats for wet layup repairs.

Glass fibers: Glass fibers have good radio frequency transmission properties and are not electrically conductive, so they are ideal for radomes. Glass fiber is commonly used as reinforcements for epoxy materials in composite face sheets of sandwich construction used for secondary structural components, such as fairings, on commercial aircraft. Some small aircraft and unpowered gliders use glass fibers as reinforcements for composite material systems used in main structural components, e.g., fuselages and wings. Glass fiber reinforced composite materials are often used in the construction of rotor blades for helicopters. Glass fibers are also used for galley components, floor panels, and overhead stowage bins. Glass fibers are available in two basic types: "E" glass and "S" glass. "E" glass fiber is less costly and the most used, whereas "S" glass fiber has better mechanical properties and is used when the additional cost can be justified.

Aramid fibers: Aramid fibers are a class of heat-resistant synthetic fibers that used in aerospace and military applications. Aramid fibers are supplied in two main types for aircraft applications; these are Kevlar® and Nomex®. Kevlar® has a high strain-to-failure strength, but tends to absorb moisture excessively, which may decrease the mechanical properties of the composite over time. Nomex® has a lower strength but an excellent thermal, chemical, and radiation resistance. In aircraft applications, Nomex® is used for cores in sandwich applications.

E.1.1.4 Fabric/tape scrim or prepreg

To make a strong, durable composite part or a repair to a composite part, it is essential to select the correct fiber type, matrix, and areal weight of fabric or tape with the right surface finish. When fabric is cut from a roll, a label with full identification details must be attached or included with the cut piece. For example, surface finish (or fiber "sizing") details, once fabric is removed from the roll, can cause difficulties without proper identification, as there is no simple means of identifying the finish used on a fabric. In addition, some composite layups may use fabrics and tapes of different areal weights at certain points in the layup or layers of aramid or glass are added at special positions. If not properly identified, this can result in not all the plies in a layup being of the correct material, orientation, or weight.

The strength and stiffness of a single tape ply is very high in the longitudinal direction (essentially that of the fibers), whereas the strength and stiffness in the transverse direction is very low (essentially that of the ply resin).

Typical tape material is provided in 6 or 12 inches in width. Other unidirectional composite material forms are tows (narrower than tape material forms at roughly 0.1 to 0.25-inch width) used in filament winding thick sections such as rocket booster shells. Tape materials are generally used to lay down significant layers of plies to form flat or gently curved structural parts such as skins for wings, stabilizers, and fuselages. Tow material is often used in tow placement machines to lay down material on curved mandrels (e.g., for fuselage structure).

Woven fabric composite material is typically used to form more difficult structural shapes such as stiffeners, ribs, and frame sections.

Figure E2 lists some forms of composite materials, their relative advantages, and disadvantages.

FORM	ADVANTAGES	DISADVANTAGES
TAPE	MAX. STRUCTURAL PROPERTIES, DESIGN FLEXIBILITY	DRAPABILITY, POSSIBLE FIBER MIS-ALIGNMENT
BI-DIRECTIONAL WOVEN FABRICS	GOOD DRAPABILITY REDUCED LAY-UP COSTS	SOME LOSS OF PROPERTIES DUE TO FIBER CRIMP, WIDTH LIMITATIONS, LESS DESIGN FLEXIBILITY
UNIDIRECTIONAL FABRICS	IMPROVED DRAPABILITY, FIBER ALIGNMENT, MINIMAL REDUCTION IN FIBER	SLIGHT WEIGHT PENALTY
STITCHED FABRICS, PREFORMS	PROVIDES EXCEPTIONAL FIBER STABILITY NEED FOR PULTRUSION, RESIN INJECTION MOLDING, PROVIDE DEPTH DIRECTIONAL STRENGTH	WEIGHT PENALTY, INCREASE COST

Figure E2. Material forms advantages and disadvantages

Added to this list should be tow (filament bundle) forms. Tow and filament material forms are like tape products in that they are unidirectional and can be laid down by machines. The difference between tow and tape is the width of the product. Tow is supplied either with resin, in prepreg form, or without resin. Filament winding is a fabrication technique for manufacturing composite material, often in the form of cylindrical structures. The process involves winding filaments under varying amounts of tension over a male mandrel. These filaments can either be wound dry and then coated with resin before they are laid down (wet winding) or prepreg can be used. The mandrel rotates while a carriage moves horizontally, laying down fibers in the desired pattern.

A fiber-reinforced composite such as carbon-fiber-reinforced plastic (CFRP) or glass-fiber-reinforced plastic (GFRP) is only strong or stiff in the direction of the fiber, with the resin typically providing little strength or stiffness. The lower of the two properties controls the transverse strength of a unidirectional composite ply. The first is the resin strength itself and the second, which may govern the result, is the resin to fiber bond strength. The strength of the bond to the fiber can be greater than the strength of the resin itself. This requires the use of the correct finish, or sizing, on the dry fiber surfaces.

The angle of each ply establishes the strength and stiffness of the laminate, and each layer or ply must be laid up in the direction given on the drawing or other approved documentation. Part drawings and structural repair manuals (SRMs) will normally contain ply tables showing the material type and layup direction of each ply in a part. An orientation clock, or warp clock, is also shown on each drawing sheet to give the layup direction of each ply relative to a key direction on the part. The “warp” or 0° direction of a fabric is the length of the roll, and its strength is generally greatest in this direction.

E.1.1.5 Laminate orientation code

Unidirectional laminae: ±45 indicates two unidirectional plies starting with a +45 followed by a -45. +45 indicates one +45 unidirectional ply.

Fabric laminae: Fabric plies are identified by either an "F" following the ply angle, or the ply may be placed in parentheses.

The angle value represents the direction of the warp fibers.

- 0F indicates a woven fabric ply placed with the warp fiber in the 0^0 direction.
- 90F indicates a woven fabric ply placed with the warp fiber in the 90^0 direction.
- ± 45F indicates a woven fabric ply placed at either a + or $–45^0$ direction.
- + 45F indicates that the warp fiber must be placed in the $+45^0$ direction.

Figure E3 shows examples of a laminate stack up or layup, whereby “s” defines a laminate layup that is symmetrical at about the mid-plane (or centerline).

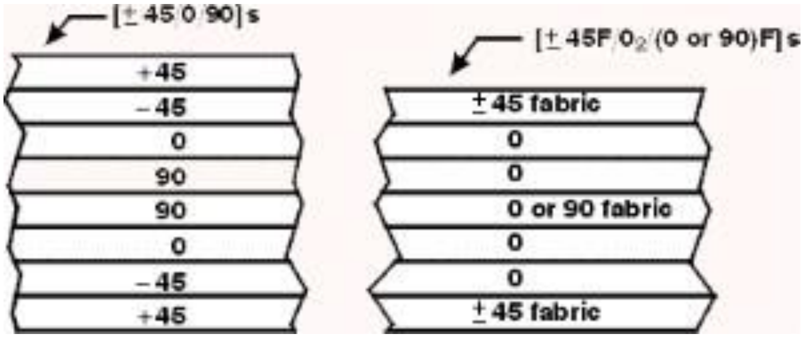


Figure E3. Laminate orientation examples

E.1.1.6 Sandwich core materials

A considerable range of sandwich core materials exists, each serving its own specific purpose, although many are used for a range of components. The factors that determine choice are density, strength, upper temperature limits, moisture absorption, and cost. A core material must be carefully selected to match the environment in which it will be used. As an example, balsa wood can be a good core material but only if it is not exposed to moisture. When foam cores are used in boat hull construction, they must be of the "closed cell" type to avoid water absorption in the event the outer skin is damaged.

Typical core materials used in composite aircraft structural sandwich parts are:

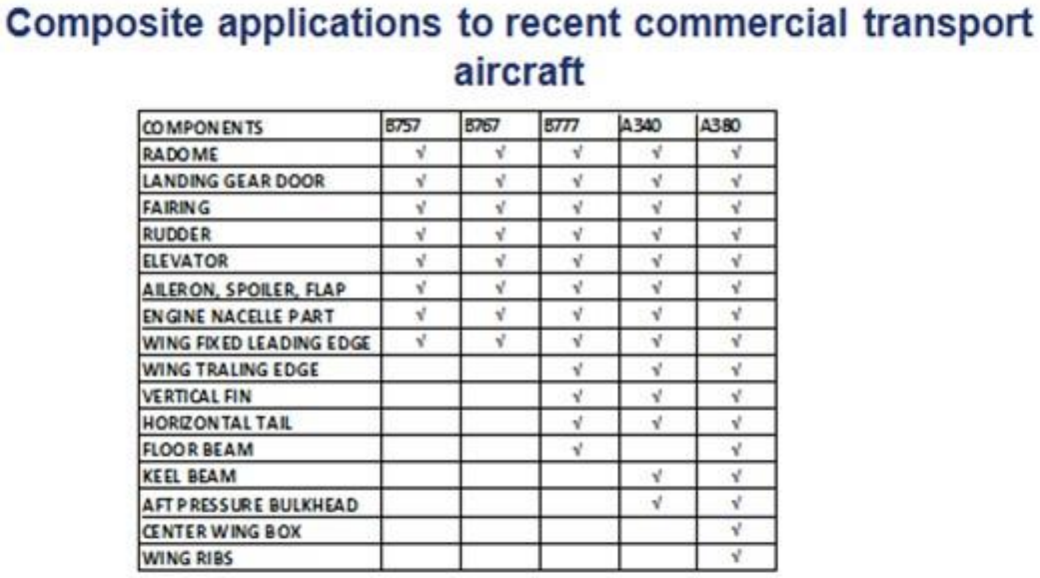
- Aramid paper honeycomb
- Glass cloth honeycomb
- Aramid cloth honeycomb
- Aluminum alloy honeycomb

Honeycombs are supplied in a range of cell sizes, cell shapes, and core densities, with some cell shapes enabling better formability than others, and each typically with properties significantly different along their length and width directions. The choice of core type for specific applications depends on the requirements, e.g., strength, stiffness, and environment. As an example, for most secondary structural sandwich applications such as fairings and fixed panels on commercial aircraft, aramid paper honeycomb (i.e., Nomex®) core is used. For critical flight control panels that require additional strength and stiffness such as main wing flaps, aluminum honeycomb core is often chosen.

E.1.2 Composite applications to aircraft structures

The high strength-to-weight properties of composite materials are especially attractive for airframe manufacturers wishing to improve performance and fuel efficiency of both military and commercial aircraft.

The use of composites in commercial aircraft has increased over the years, although at a slower rate than for military applications. Later aircraft developments since 2000 have composite structural weight percentages from approximately 25% (Airbus A380) to 50% (Airbus A350 and Boeing 787). Currently the Boeing 787 has added very significant composite components, such as the wing main torque box and the fuselage pressure hull. The Airbus A350 also employs a composite wing main torque box and a fuselage pressure hull. Figure E4 shows how the number of composite applications to commercial aircraft structural components has increased over the years.



Composite applications to recent commercial transport aircraft

COMPONENTS	B757	B767	B777	A340	A380
RADOME	√	√	√	√	√
LANDING GEAR DOOR	√	√	√	√	√
FAIRING	√	√	√	√	√
RUDDER	√	√	√	√	√
ELEVATOR	√	√	√	√	√
AILERON, SPOILER, FLAP	√	√	√	√	√
ENGINE NACELLE PART	√	√	√	√	√
WING FIXED LEADING EDGE	√	√	√	√	√
WING TRALING EDGE			√	√	√
VERTICAL FIN			√	√	√
HORIZONTAL TAIL			√	√	√
FLOOR BEAM			√		√
KEEL BEAM				√	√
AFT PRESSURE BULKHEAD				√	√
CENTER WING BOX					√
WING RIBS					√

Figure E4. Composite applications to recent commercial transports

E.1.3 Composites versus metals

Metals are homogeneous and isotropic with similar properties in all directions (although aluminum has a grain direction that affects its properties in each direction). Unlike metals, composite properties are not uniform in all directions. Composite laminates or the face sheets of sandwich components are made up of multiple plies of the unidirectional or fabric composite material to form the load-carrying structure. Composite materials can be tailored to meet strength and stiffness requirements by adding plies at different angles.

There is a potential for reduced manufacturing costs while using composites due to fewer fasteners and less part count. A typical metal transport aircraft structural component such as a wing torque box contains many parts and thousands of fasteners to join those parts together. The same wing torque box fabricated from composite material will employ fewer fasteners and parts due to stiffening elements (e.g., stringers and stiffeners) being co-bonded or co-cured to skins, spars, and ribs.

Composite materials tend to have greater resistance to fatigue damage than do metals, and this is a decided bonus for aircraft structures that are tension critical (e.g., wing torque box lower skins and pressurized fuselage). In laminate composites, if specific conditions exist (sufficiently high enough loading and out-of-plane loading) damage will propagate through delamination rather than through thickness cracking as in metals. This is an advantage in applications for tension loading structures, but not so for compression loaded structures.

Composites also do not corrode like metals, and therefore provide an advantage when employed in commercial fuselages which get very wet from ground-air-ground cycles, passengers, and passenger amenities. However, composite materials tend to have greater sensitivity to the aircraft environment than metals do and therefore there is a need to protect polymers (e.g., epoxies) from UV degradation, and erosion from rain and sand. For fiber reinforced epoxy composites used in most aircraft structural applications, heat and moisture can seriously reduce strength and stiffness; hence high temperature applications are the domain of resins such as BMIs and metal matrix composites (where a metal alloy, such as aluminum, is used in lieu of a resin to support the reinforcement).

Table E1 shows the relative densities of typical composite fibers compared to typical metal materials used in aircraft structures. There is a potential for saving weight for aircraft structural components.

Table E1. Composite materials density comparisons

Materials	**Density (lb/in.^{2})**
Aramid (Kevlar 49)/epoxy	0.046 -0.05
Carbon/epoxy	0.055 -0.059
Fiberglass/epoxy	0.065 -0.07
Boron/epoxy	0.07 -0.075
Aluminum	0.10
Titanium	0.16

There are significant differences between metals and composite material systems (fiber-reinforced plastics) in their stress-strain curves. The stress-strain response of commonly used fiber-dominated orientations of composite materials is almost linear to failure, although some glass fiber and ceramic fiber composite materials exhibit nonlinear or bilinear behavior. This is contrasted to metals that exhibit nonlinear response above the proportional limit and eventual plastic deformation above the yield point. The stress-strain curves for composite material systems are very straight and this factor requires composites to be given special consideration in structural details where there are stress risers (holes, cutouts, notches, radii, tapers, etc.). These types of stress risers in metal are not a major concern for static strength analysis (they do play a big role in durability and damage tolerance analysis, however). In composites they must be considered in static strength analysis. In general, if these stress risers are properly considered in design/analysis of laminated parts, fatigue loadings will not usually be critical.

Figure E5 illustrates a curve of the aluminum stress-strain to failure compared to straighter stress-strain to failure of some fiber/epoxy composite materials. Aluminum stress-strain behavior is useful for redistribution of loads (e.g., joints with multiple fasteners) when a structure is subject to overloads and for absorbing energy (e.g., aircraft crash dynamics). The behavior under load of composite materials requires considerable care when designing critical joints with multiples fasteners and when designing for crash dynamics (e.g., lower fuselage and floor structure).

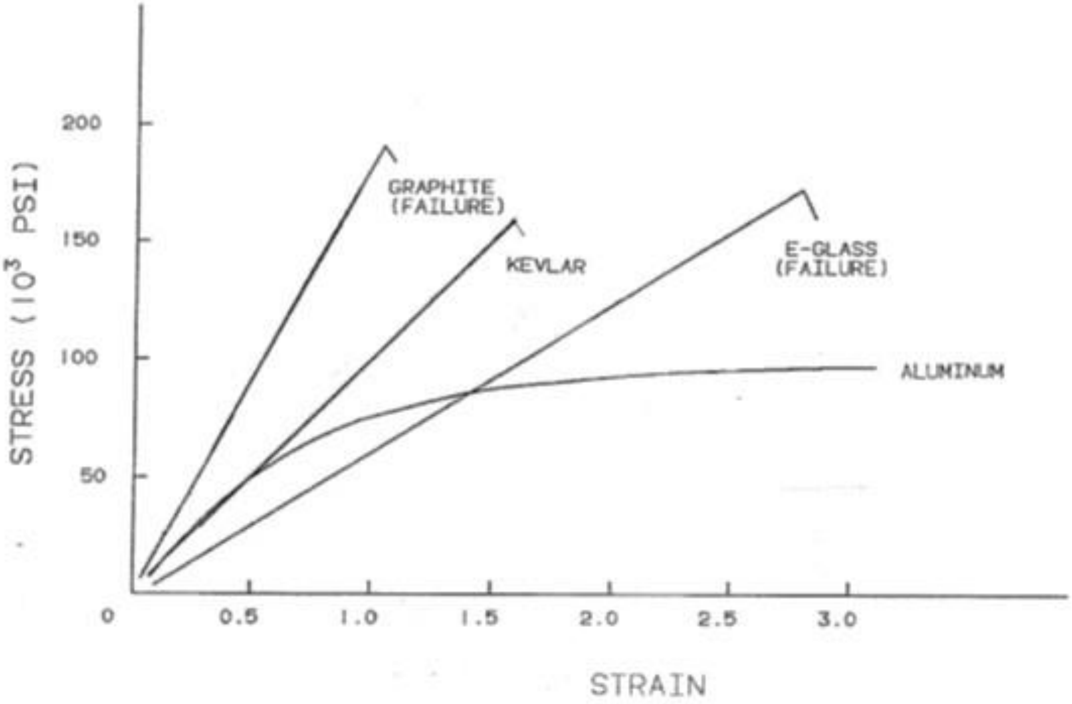


Figure E5. Stress/strain behavior of composites and aluminum

E.1.4 Design and manufacturing options

The design of composite structure is complicated by the fact that every ply of a laminate structure must be defined. Drawings or design packages must describe the ply orientation, its position within the stack, and its boundaries. This is straightforward for a simple, constant thickness laminate. For complex parts with tapered thicknesses and ply build-ups around joints and cutouts, design can become complicated. Furthermore, the need to maintain relative balance and symmetry throughout the structure increases the difficulty.

To improve the quality and performance and reduce the development and production cost of complex composite structural systems, "concurrent engineering" has become an accepted design approach. New products or systems are developed jointly and concurrently by a team, or Integrated Product Team or IPT, composed of designers, stress analysts, materials and processes, manufacturing, quality control, cost estimators, and support engineers, specializing in reliability, maintainability, and survivability. Composites cannot be efficiently designed without concurrence. Tooling and processing have significant effects on the design and assembly of composite parts. Parts and process are so interdependent it could be disastrous to attempt sequential design and manufacturing phasing.

Another factor approached differently in composite design is the accommodation of thickness tolerances at interfaces. If a composite part must fit into a space between two other parts or between a substructure and an outer mold line, the thickness requires special tolerances. A composite part thickness is controlled by the number of plies and the per-ply-thickness. Each ply has a range of possible thicknesses that can vary depending on the processing (e.g., compaction, bleed, and cure). A group of individual plies, which are laid up to form the laminate, may not match the space available for assembly within other constraints. This discrepancy can be handled by using shims or by adding "sacrificial" plies to the laminate for subsequent machining to a closer tolerance than is possible with nominal per-ply-thickness variations. The use of shims has design implications regarding load eccentricities. Another approach is to use closed die molding at the fit-up edges to mold to the exact thickness needed.

Design and manufacturing options and constraints include the effects of stacking sequence. A stacking sequence effect is ply angle orientation. Figures E6 and E7 illustrate these effects.

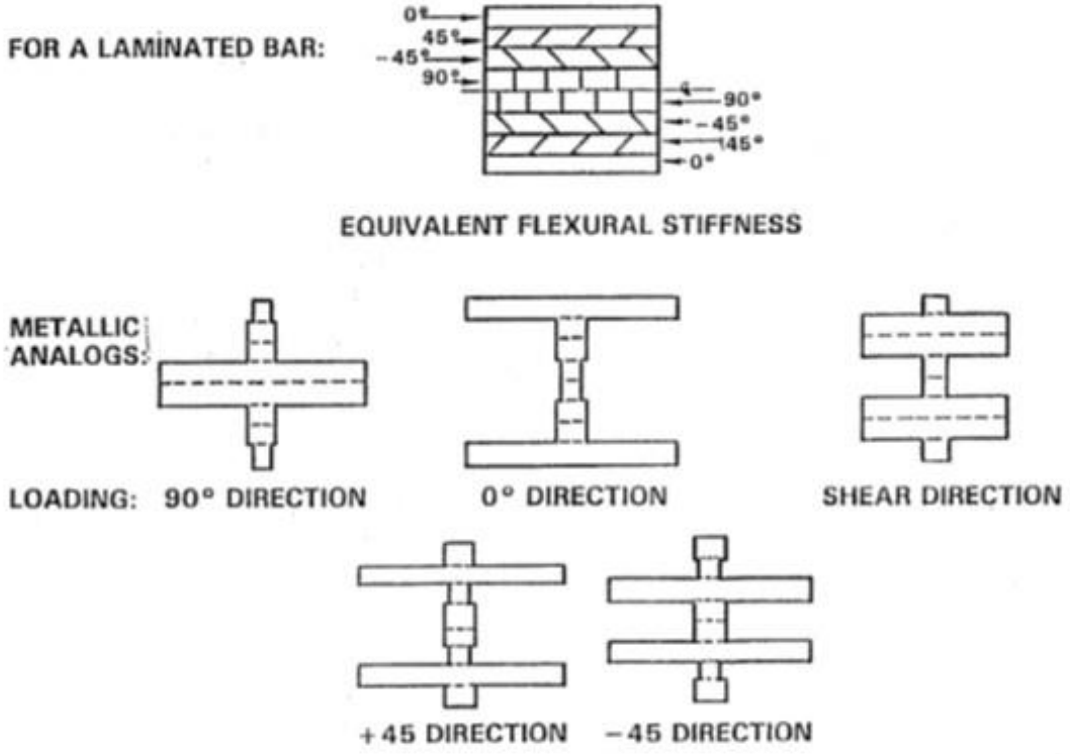


Figure E6. Stacking sequence with metallic analogs

Figure E7 shows the effect of applying a load to an unsymmetrical laminated plate causing coupling between extension, shear, bending, and twisting.

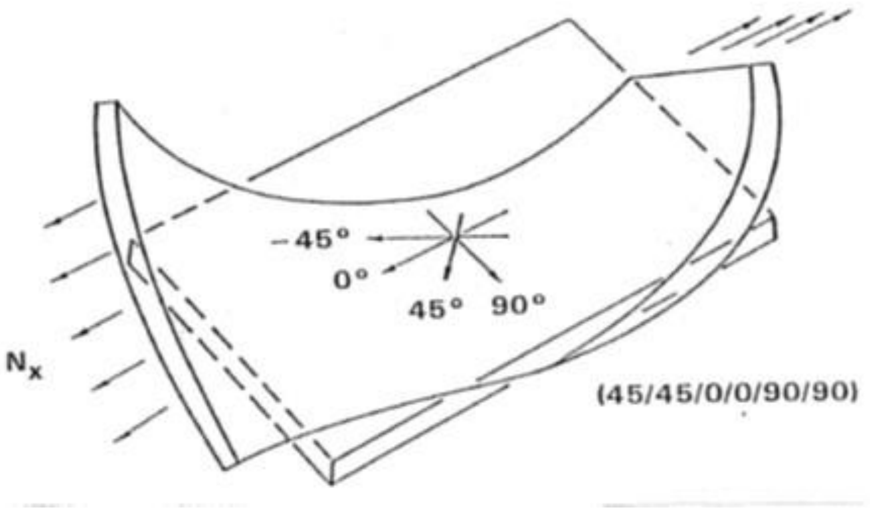


Figure E7. Unsymmetrical laminated plate effect

Stacking order of plies should be balanced and symmetrical about the laminate mid-plane. Any unavoidable unsymmetrical or unbalanced plies should be placed near the laminate mid-plane. This will help prevent warpage after cure and reduce residual stresses. It will also eliminate "coupling" stresses. A laminate is symmetric when the plies above the mid-plane are a mirror image of those below the mid-plane. Symmetrical lay-ups help to avoid the thermal twisting of parts as they cool down after curing. Tooling coefficient of linear thermal expansion (CTE) mismatches are concerns. To reduce any effects from CTE mismatches, tooling materials must be carefully chosen. Carbon/epoxy composite and Invar are a good CTE match and used for larger parts.

Fiber-dominated laminates should be used wherever possible. Fibers carry most of the load because the resin is relatively weak and has little stiffness. This minimizes matrix and stiffness degradation. The [0°/±45°/90°] orientation is recommended for major load carrying structures. When there is multiple load conditions, laminates should not be optimized for only the most severe load case. Optimizing for a single load case can produce excessive resin or matrix stresses for the other load cases. A minimum of 10% of the fibers should be oriented in each direction to help with multiple load conditions and load redistribution around holes, cutouts, and in the event of damage. The anisotropy of special laminates, while more complicated, enables a designer to tailor a structure for desired deflection characteristics.

Composites are most efficient when used in large, relatively uninterrupted structures. The cost is also related to the number of detail parts and the number of fasteners required. These two factors drive designs towards integration of features into large co-cured or co-bonded structures. Well-designed, high-quality tooling will reduce manufacturing and inspection costs and rejection rates and result in high quality parts. Large co-cured assemblies should be utilized as much as possible to lower cost due to reduced part count and assembly time. However, if the assembly requires overly complex tooling, the potential cost savings can be negated. Large assemblies must include consideration for handling and repair. To avoid scab-on reinforcements and similar last-minute disruptions, structural designs and the associated tooling should be able to accommodate design changes associated with the inevitable increase in design loads for subsequent airplane models.

Material type influences performance characteristics as well as producibility factors. Not all aircraft structural parts are suited to composite construction Material selection should be based on a thorough analysis that includes consideration of performance, cost, schedule, and risk. Risk can be the size of a part that may have to be scrapped due to the presence of unacceptable defects. Some large composite parts that are complete wing skins or spars cost will display high scrap cost. Because of high scrap costs of large parts, OEMs expend much effort to create "effects of defects" programs to understand the effects of manufacturing defects more readily.

Ease of inspection of structures, both during production and in-service, must be considered in the design. Anomalies, which are unacceptable, described as defects or damage, are assumed following manufacturing and during service. Problems are more easily discovered if a structure can be easily inspected.

Improper definition or management of the stresses around discontinuities can cause premature failures in composite structural components. In finite element analysis (FEA), a fine mesh must be used in regions of high stress gradients, such as around cut-outs and at ply and stiffener drop-offs, to understand the stress gradients in these areas. Fiber-dominated composite laminates are generally linear to failure, and the material will not yield locally and redistribute stresses. Stress risers reduce the static strength of the laminate and should be eliminated or reduced whenever possible. Conditions that cause peel stresses should be avoided or minimized. This includes excessive abrupt laminate terminations or co-cured or co-bonded structures with significantly different flexural stiffnesses. Peel stresses are out-of-plane to the laminate and in its weakest direction.

E.1.5 Regulations, guidance, and information sources

E.1.5.1 Regulations

FAA prescribes regulations governing all aviation activities in the United States. These regulations are in Sub-chapter C of 14CFR. The rules are designed to promote safe aviation and protect pilots, passengers, and the public from unnecessary risk. For this course, the focus is on those regulations that apply to the certification of specific products (aircraft, engines, and propellers):

Part 21 – Certification Procedures for Products and Parts

Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Airplanes

Part 25 – Airworthiness Standards: Transport Category Airplanes

Part 27 – Airworthiness Standards: Normal Category Rotorcraft

Part 29 – Airworthiness Standards: Transport Category Rotorcraft

Part 33 – Airworthiness Standards: Aircraft Engines

Part 35 – Airworthiness Standards: Propellers

European Aviation Safety Agency (EASA) provides Certification Standards (CS), which are equivalent to FAA regulations. The Transport Canada Civil Aviation (TCCA) has issued Canadian Aviation Regulations (CARs) which are equivalent to the FAA's and EASA's regulations.

E.1.5.2 Airworthiness directives

The FAA, TCCA, EASA, and other civil aviation authorities issue an Airworthiness Directive (AD) to direct specific actions to ensure flight safety of aircraft.

E.1.5.3 Guidance (Advisory circulars and policy statements)

The FAA issues guidance providing support information for showing compliance with regulatory requirements. Guidance includes ACs and PSs. An AC presents information concerning acceptable means, but not the only means, of complying with regulations. A PS gives guidance or acceptable practices on how to find compliance with a specific Code of Federal Regulations (CFR) section or paragraph. PSs are explanatory and not mandated and are not project-specific.

AC20-107B "sets forth an acceptable means, but not the only means of showing compliance with the provisions of 14 CFR parts 23, 25, 27 and 29 regarding airworthiness type certification requirements for composite aircraft structures involving fiber reinforced materials such as carbon and glass fiber reinforced parts."

Documents can be located through the internet:

1. FAA links for Federal Aviation Regulations (FARs), ACs, ADs, PS, and other documents: www.faa.gov
2. FAA Tech Reports (technical data resulting from FAA sponsored research and development)
3. EASA Acceptable Means of Compliance (AMCs)
4. SAE Aerospace Information Reports (AIR) Reports
5. Composite Materials Handbook - CMH-17 (formerly MIL Handbook 17)

AC20-107B provides the foundation for CSET. It "sets forth an acceptable means, but not the only means of showing compliance with the provisions of 14 CFR parts 23, 25, 27 and 29 regarding airworthiness type certification requirements for composite aircraft structures involving fiber reinforced materials such as carbon and glass fiber reinforced parts."

Volume 3 of CMH-17, “Materials Usage Design and Analysis”, provides specific guidance and information which is relevant to this course. The Composite Materials Handbook provides information and guidance necessary to design and fabricate end items from composite materials. The primary purpose is the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials. In support of this objective, the handbook includes composite materials properties that meet specific data requirements. The handbook therefore constitutes an overview of the field of composites technology and engineering, an area which is advancing and changing rapidly. As a result, the document is constantly changing as sections are added or modified to reflect advances in the state-of-the-art.

The following guidance and technical center reports provide further information on topics addressed in CSET.

- “Static Strength Substantiation of Composite Airplane Structure” [PS-ACE100-2001-006, December 2001]
- “Material Qualification and Equivalency for Polymer Matrix Composite Material Systems” [PS-ACE100-2002-006, September 2003]
- “Substantiation of Secondary Composite Structures” [PS-ACE100-2004-10030, April 2005]
- “Certification Testing Methodology for Composite Structures, Volumes I and II” [DOT/FAA/CT-86/39, October 1986]
- “Handbook: Manufacturing Advanced Composite Components for Airframes” [DOT/FAA/AR-96/75, April 1997]
- “Advanced Certification Methodology for Composite Structures” [DOT/FAA/AR-96/111, April 1997]
- “Material Qualification and Equivalency for Polymer Matrix Composite Material Systems” [DOT/FAA/AR-03/19, September 2003]
- “Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Unidirectional Prepregs” [DOT/FAA/AR-02/109, March 2003]
- “Guidelines for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Fiber-Reinforced Polymer Composites” [DOT/FAA/AR-02/110, March 2003]
- “Guidelines for Analysis, Testing, and Nondestructive Inspection of Impact-Damaged Composite Sandwich Structures” [DOT/FAA/AR-02/121, March 2003]

- "Effects of Surface Preparation on the Long-Term Durability of Adhesively Bonded Composite Joints" [DOT/FAA/AR-03/53, July 2003]
- "Bonded Repair of Aircraft Composite Sandwich Structures" [DOT/FAA/AR-03/74, February 2004]

E.2 Materials, processes, and manufacturing

FAA airworthiness requirements mandate the use of material and process control documents as ways of managing the manufacture of the parts and materials. The intent of these documents is to ensure that materials and fabrication processes used to manufacture composite aircraft structures provide consistently sound and safe aircraft.

E.2.1 Material and process specifications

Final material is created during part fabrication. Design properties of a structural part are dependent on both the materials and the fabrication process used to produce that part.

Specifications for materials and fabrication processes must ensure compliance with engineering requirements.

E.2.1.1 Material specifications

Material specifications are documented controls established to ensure the consistency of the raw materials being purchased to manufacture products.

AC20-107B states: "A material specification is a detailed description of the criteria for the constituents, construction, appearance, performance of a material, apparatus, etc., or of the standard of workmanship required in its manufacture".

The composite material user typically prepares material specifications, which define incoming material inspection procedures and supplier controls to ensure the materials used in composite construction will meet the engineering requirements. These specifications are based on material allowables generated by development test programs. The acceptance criteria for tests must be specified to assure that production parts will be fabricated with materials that have properties equivalent to the materials used to build the test specimens needed to develop the allowables.

The user material specifications typically require the suppliers to provide evidence that each production lot of material in each shipment meets the material specification requirements. This evidence will include test data, certificate of conformity, affidavits, etc., depending upon the user quality assurance plan and purchase contract requirements for a material.

Historically, large OEMs developed their own material specifications, such as for prepreg (fiber and uncured resin), and suppliers qualified their products to these specifications. Alternatively, OEMs and other composite part fabricators can now use industry specifications created for a supplier material.

Material specifications are essential in protecting the cured composite mechanical properties used for designing the part. It is the responsibility of the part manufacturer to ensure form, fit, and function of the finished parts by controlling materials.

E.2.1.2 Process specifications

Process specifications are documented requirements of the manufacturing process being used to fabricate products. A process specification controls all the critical aspects of manufacturing composite structure, also known as “documented controls”. The ultimate properties and quality of composites are dependent on processing since the material is being made while being shaped into a part. This differs from metals whereby material formulation and properties are largely fixed when procured. One composite or adhesive material, bought under a single material specification, may be used by multiple processes (e.g., parts cured in an autoclave versus repairs cured in a heat blanket); therefore, it is essential that each process be defined so that it can be controlled to produce repeatable and reliable parts.

The user material and process specifications set procedures and requirements for storage of prepregs, resin systems, and adhesives to maintain acceptable material quality. A process specification also defines the rest of the process requirements including material handling, ply layup, bagging, cure, and inspection (pre-cure and post-cure). Tooling for lay-up is subject to tool proofing and qualification procedures to demonstrate that the tooling can produce parts that conform to drawing and specification requirements when used with the specified materials, lay-up and bagging methods, and cure profile. In addition, cured material specimens made from the tool should be tested to ensure they meet specified mechanical and physical properties.

The process specification document will establish requirements to control the composite work area environment. The requirements should be commensurate with the susceptibility of materials to contamination by the shop environment. Contamination restrictions in environmentally controlled areas may affect the manufacturing process. These restrictions typically include controls that prohibit the use of uncontrolled sprays such as silicon contamination, exposure to dust, handling contamination, fumes, oily vapors, and the presence of other particulate or chemical matter. Conditions under which operators may handle materials should also be defined. Lay-up and clean room air filtrations and pressurization systems should be capable of providing a slight positive pressure. Inspection and calibration requirements for autoclaves and ovens must also be defined.

AC21-26A states: “The manufacture of acceptable and reliable composite structures depends on the type of process controls employed during the manufacturing cycle. If all pertinent process variables are adequately controlled, there is added assurance that the parts and structure produced will be acceptable. The quality system should, therefore, establish and implement a plan which verifies that… the parameters affecting...process capability is operating under controlled conditions.”

Process control documents (PCDs) are documented controls which define the manufacturing details of a specific manufacturing facility which is compliant with the governing Process Specification. PCDs are controlled “recipes” to produce materials that conform to the requirements of material specifications. A precise control of composite material processing not only improves part quality, but also directly reduces the overall manufacturing cost by eliminating process defects thus reducing repair, rework, and scrap.

E.2.2 Material and process control

This section will provide the following:

- Basics for controlling Composite Materials
- Basics for controlling Composite Manufacturing Processes
- An overview of statistical tools typically used to control materials and processes

E.2.2.1 Material control

The data obtained in the material qualification program should form the basis for establishing specification limits. Additional properties such as historical supplier data may also be considered if they are relevant for the given material. Quality control in a production environment involves inspection and testing of composites in all stages of material manufacture and part fabrication. Tests must be performed by the material supplier on the fiber and resin as separate materials, as well as on the prepreg material. The user of the prepreg must perform receiving inspection and revalidation tests, in-process control tests, and nondestructive inspection tests on finished parts.

The user material specifications typically require the suppliers to provide evidence that each production lot of material in each shipment meets the material specification requirements. This evidence will include test data, certification, inspection affidavits, etc., depending upon the user quality assurance plan and purchase contract requirements for a material. The test reports contain data to verify the conformance of material properties to user specifications and acceptance standards. Acceptance test requirements may vary from user to user. However, the tests must be enough to assure the material will meet or exceed the engineering requirements. A typical example of acceptance tests required for carbon/epoxy unidirectional tape will be in two parts. The first part concerns uncured prepreg properties. The purpose of these tests is to assure that the resin and fibers are within acceptable limits. The second part involves tests on cured laminates or laminae. The mechanical property tests should be selected to reflect important design properties. They can be direct tests of a property or a basic test that correlates with critical design properties.

Receiving inspection test requirements should address test frequency and, in the event of initial failure to satisfy these requirements, re-test criteria. Test frequency is a function of the quantity of material (weight and rolls) in a batch. Typical testing may include specimens from first, last, and random rolls. Retest criteria should be included for the cured lamina tests so that the material is not rejected because of testing anomalies. If a material fails a test, a new panel from the same suspect roll of material should be fabricated and used to rerun that specific test.

E.2.2.2 Process control

Process control is an ongoing aspect of production with any out-of-control conditions being investigated immediately after being identified. Process capability is a single measure of the process that need not be recomputed unless the process has changed, which can be determined using the process control charts. Process control is used to determine whether a process is stable and predictable. It can separate common cause variation from special cause variation. Statistical techniques are used to measure, eliminate, or reduce variability in dependent variables caused by extraneous sources.

During lay-up of composite parts, certain critical steps or operations must be closely controlled. Requirements and limits for these critical items must be stated in the user process specifications. This is known as in-process control.

The standards for quality control documentation requirements are found in military and federal regulations such as the Federal Aviation Regulation Part 21 "Certification Procedures for Products and Parts" used by FAA production approval holders.

The quality assurance department for the user has responsibility for verifying that the fabrication processes are carried out according to engineering process specification requirements. Control of a wide range of activities is needed to control the fabrication process, including:

- Material control
- Materials storage and handling

- Tooling
- Facilities and equipment
- Lay-up in-process control
- Part cure
- Process control specimens (Many manufacturers require special test specimens to be laid-up and cured along with production parts)
- Nondestructive inspection

E.2.2.3 Statistical tools for material and process control

Process control determines whether a process is stable and predictable. Statistical techniques are used to measure, eliminate, or reduce variability caused by extraneous sources.

SPC provides more precise control of specification-controlled items, including materials, parts, and components, which are purchased by fabricators of precision products. The traditional approach of specifying minimum values only meets or exceeds specification-defined minimums. No attempt is made to monitor or control actual variation of the part being purchased or manufactured and anything meeting “spec minimums” is acceptable. This option may not protect design values. The object of statistical process control is product consistency by minimizing variation and understanding root causes of those variations.

SPC quantifies the expected variation of a process. This quantification of variation allows users to achieve consistency and make improvements through goal setting and reduction of variation, thereby increasing the capability of a process to meet specifications.

- SPC allows manufacturers better control of their processes and more accurate assessment of the expected results.
- SPC provides an objective scientific method for evaluating process schedule and emphasis. SPC provides an objective scientific approach for assessing improved, decreased, or no effect in quality.
- SPC provides a framework for economically improving the product.

Many composite products have their own unique processes and material forms. SPC is needed to monitor the key properties and parameters. Understanding sources of variation is important for defining key metrics.

Unique features of SPC for Composites

SPC is performed on physical and chemical properties.

- Examples for prepreg: Per ply thickness, fiber areal weight, resin content, liquid chromatography.
- Examples for carbon fiber: Density, yield, sizing

SPC is performed on mechanical properties:

- Examples for prepreg: Tensile strength and modulus, compression strength and modulus, interlaminar shear and modulus.
- Examples for carbon fiber: Ultimate tensile strength and modulus.

Grouping of material terminologies used in SPC

- “Rational subgroup” = “Convenient grouping of material” = “Batch” or “Sub-Batch.”
- Grouping of material is determined by the manufacturing and testing processes.

E.2.3 Manufacturing

E.2.3.1 Typical composite manufacturing processes

Composite Laminate Fabrication

Structural composite laminate fabrication typically consists of uncured fiber reinforced epoxy prepreg tape and fabric material plies formed while curing into final configuration using heat and pressure. The heat and pressure can be supplied by a variety of methodologies. A pressurized oven, referred to as an autoclave, cure parts, which are ‘bagged’ to provide vacuum pressure. Heated press processing is another alternative. A fabrication process is typically complicated with many parameters that can affect the quality of the composite component.

Construction processes are those used to bring various forms of fiber and fabric reinforcement together to produce the reinforcement pattern desired for a given composite part or end item. The resin may or may not be in its final chemical or physical form during placement of the reinforcement. Construction processes include both manual and automated methods of fiber placement, as well as adhesive bonding and sandwich construction.

The basic steps of a typical hand layup process as outlined in Figure E8 are as follows:

- Material is removed from the freezer, warmed to room temperature, and individual plies are cut and positioned on a layup tool.

- If required, any air must be removed using a debulk cycle. Some thicker laminates and laminates with materials that use toughened resin are “double debulked” to adequately remove the air.
- The ply stacks are ‘bagged’ using a vacuum bag with thermocouples, breather and bleeder plies

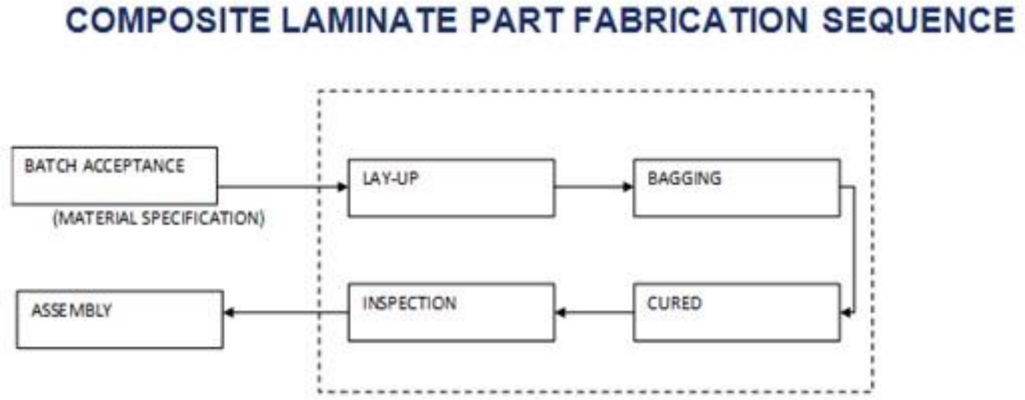


Figure E8. Manual laminate layup process

Sandwich Construction

The fabrication procedure is similar to a laminate fabrication procedure with the exception that a layer of adhesive is often used on both sides of the core. However, the use of honeycomb core requires a reduced level of autoclave pressure to prevent core crushing. Typical autoclave pressure used for laminate stiffened parts is approximately 70-100 psi, whereas the autoclave pressure used for sandwich parts is 35-40 psi.

Sandwich structural configurations are used for flight control panels and fairings. These configurations typically feature thin laminate face sheets bonded to honeycomb core.

Figure E9 (provided courtesy of Heatcon Composite Systems) depicts a typical sandwich structural arrangement.

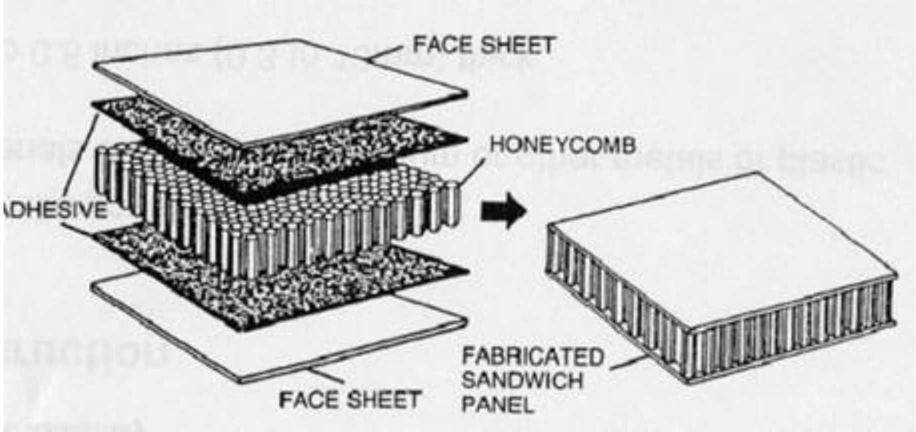


Figure E9. Sandwich construction

Automated Tape Lamination

Composite tape lamination machines have been in use in industry since the 1970s (e.g., F-16 empennage skins). The early developmental machines were usually custom made for the aerospace industry in small machine shops under the guidance of developmental engineers. Once the technology was proven in the laboratory, commercial machine tool manufacturers began producing and further developing tape laying machines for industrial applications. A typical process sequence is presented below in Figure E10:

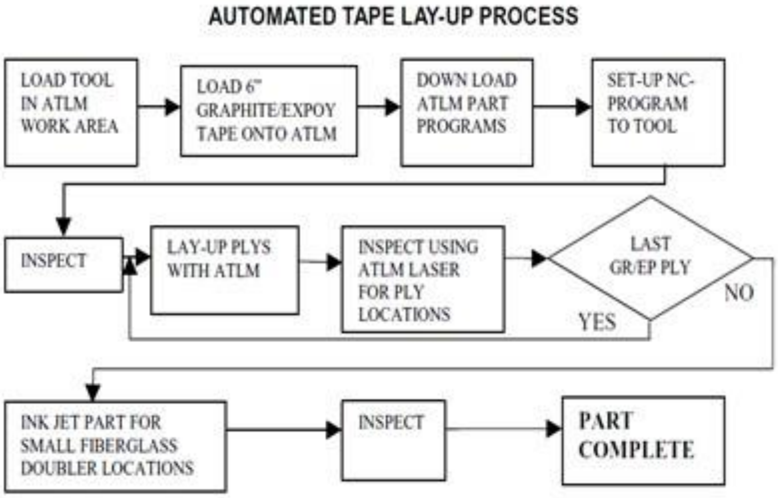


Figure E10. Automated tape layup rocess

Figure E11 shows an example of an automated tape layup machine (ATLM).

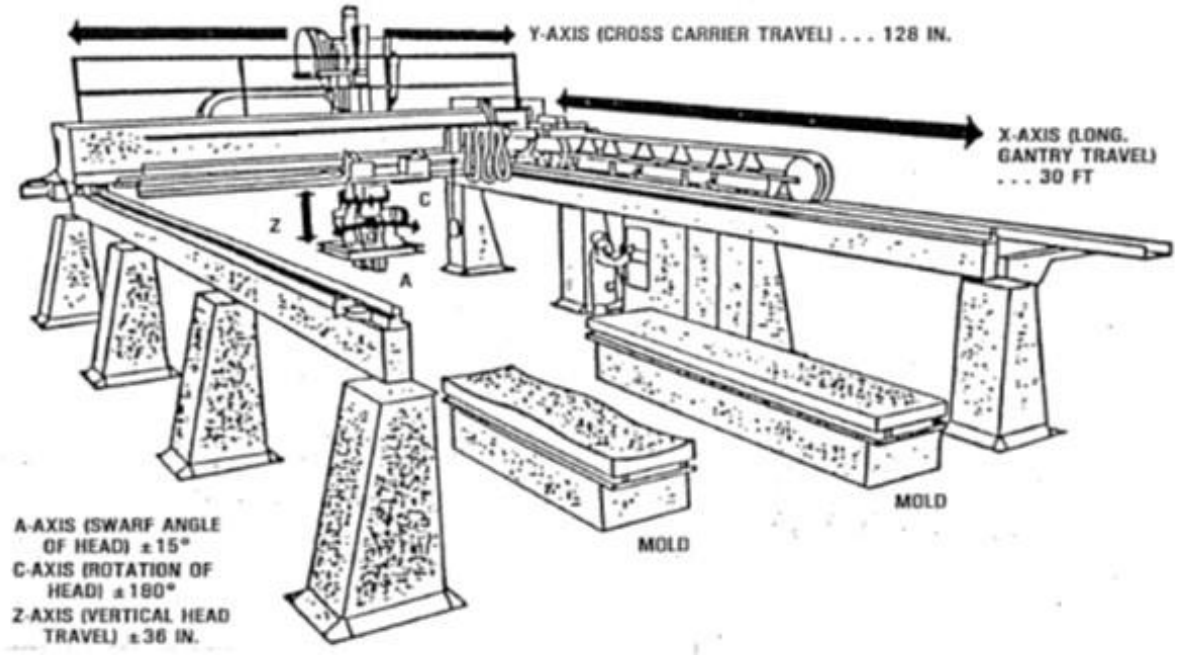


Figure E11. Automated tape layup machine (courtesy Cincinnati Milacron)

The use of an ATLM allows lay-up of unidirectional composite tape in 3″, 6″, and 12″ widths. The machines can lay up 10-20 lb./hr., compared to 2-3 lb./hr. for typical hand layup operations. Automated tape laying enables fabrication of large composite components using a minimum of manual labor without the ergonomic problems associated with personnel climbing onto large tools to lay-up parts. The use of ATLMs has the potential to avoid debulk cycles due to better compaction from the pressure applied by the ATLM head as each layer of tape is laid down. Material utilization is increased by at least 50% when compared to historical manual lay-up data. The process can be used on flat or contoured parts; the current commercial heads have a contour limit of 30° out of a horizontal plane. Typical applications in the aerospace industry are for wing and empennage components as well as control surfaces with mild contours.

If more contour is required such as a fuselage component, a custom machine or automatic tow placement would be required.

Automated Tow Placement/Fiber Placement

Fiber placement is an automated machine process utilizing narrow strips of composite material (preimpregnated tows or slit prepreg tape) taken from multiple spools. The machine collimates the material into a band generally up to 6 inches wide, which is a function of the individual tow width, the number of tows a particular machine can process, and/or the width that the part geometry can accommodate and laminates the material onto a tool work surface. As each band is placed, some machine heads can add or drop individual tows to either widen or narrow the bandwidth accordingly. This capability, allowing a true fiber orientation to be maintained on a contoured surface, is unique to the fiber placement process. The process allows material to be placed only where needed thereby greatly reducing material scrap factors. Figure E12 presents a typical workflow for tow/fiber placement.

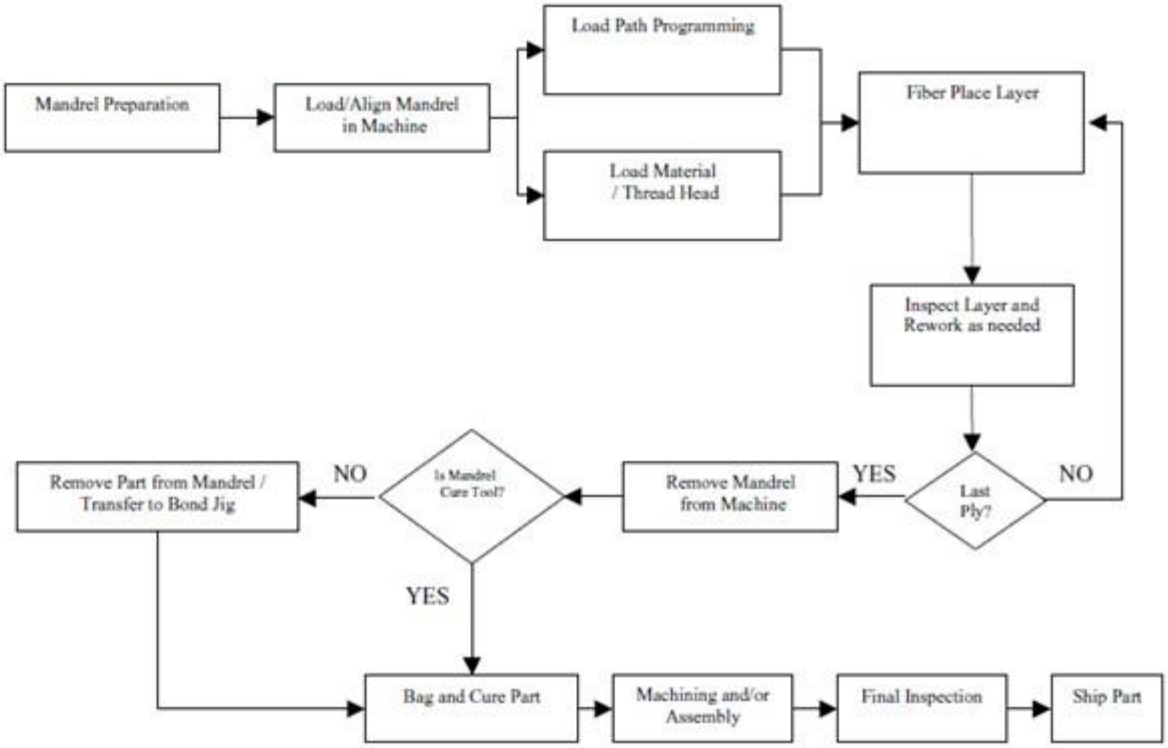


Figure E12. Workflow for tow/fiber placement

Resin Transfer Molding

Resin transfer molding (RTM) is a closed molding process that offers a dimensionally accurate and high-quality surface finish composite molding, using liquid thermoset polymers reinforced with various forms of fiber reinforcements. Typically, polymers of epoxy, vinyl ester, methyl methacrylate, polyester, or phenolic are used with fiberglass reinforcement. Other reinforcements are offered for more demanding applications such as aramid, carbon, and synthetic fibers either individually or in combination with each other.

The matrix selection of polymer and reinforcement dictates both molding material cost, as well as molding mechanical and surface finish performance. Along with the polymer and reinforcement, the addition of mineral fillers may be added to enhance fire retardation, flex modulus, and surface finish.

Reinforcements are presented in their dry form to the mold either in binder-bound chopped mats, random-continuous strand mats, or woven cloth formats. The fiber either has been "preformed" to the exact shape of the molding tool in a previous operation or is hand-tailored during the loading process in the molding tool. After the fiber is installed into the mold, a premixed catalyst and resin is injected into the closed mold cavity encapsulating the fiber within. The primary surface of the molding may be gel-coated, a process of spraying the mold surface before installing the fiber. If a gel coat is not required, the exterior finish would be the same from the front to the back of the molded part.

Reaction Injection Molding

In contrast to RTM, where resin and catalyst are premixed prior to injection under pressure into the mold, reaction injection molding (RIM) injects a rapid-cure resin and a catalyst into the mold in two separate streams. Mixing, and the resulting chemical reaction, occurs in the mold instead of in a dispensing head. Automotive industry suppliers combine structural RIM with rapid preforming methods to fabricate structural parts, but their operational requirements are generally not suitable for aircraft applications as the mechanical properties are inferior. Programmable robots have become a common means to spray a chopped fiberglass/binder combination onto a vacuum-equipped preform screen or mold. Robotic spray-up can be directed to control fiber orientation. A related technology, dry fiber placement, combines stitched preforms and RTM. High fiber volumes (e.g., as high as 68 percent) are possible, and automated controls ensure low voids and consistent preform reproduction, without the need for trimming.

Vacuum-Assisted Resin Transfer Molding

Vacuum-assisted resin transfer molding (VARTM) processing produces much of the same one-smooth-sided product as prepreg fabrication, but it can be more cost-effective. As the name implies, VARTM uses vacuum to pull the resin through the bagged preform to impregnate the reinforcement with the aid of a consumable flow-media layer to help the resin flow. It is sometimes used with shaped caul plates to produce smooth surfaces on both the bagged side and the tool side, but the part thickness is not precisely controlled. This enables the “male” and “female” pieces of the mold to be much lighter, resulting in a significantly reduced price of fabrication for limited production runs. VARTM is typically one-sided tool surfaces as the flow media is on the bag side of the part. Shaped caul plates are sometimes used if a smooth surface is needed on the bag side of the part. RTM resins are often 350^0 F curing systems and are higher for BMI.

RTM tends to be more expensive than VARTM because it requires more expensive tooling with precise cavity dimensions, but it produces more consistent parts. The advantage of RTM over VARTM is precision of geometry of all surfaces due to matched molds. It is only cost effective when production runs are high enough to justify the cost, or if the required precision of the end item mandates the process. VARTM thickness is controlled by the bulk of the material and not the mold cavity. The resin is generally introduced under vacuum for RTM as it is in VARTM, but then the mold is pressurized during cure to avoid shrinkage-related surface anomalies during resin cure. Therefore, RTM tooling needs to be structurally stable during the pressurization after mold fill is complete to maintain the precise shape established by the mold cavity.

Resin Film Infusion

Resin film infusion (RFI) is a hybrid process in which a dry preform is placed in a mold on top of a layer or interleaved with layers of high-viscosity resin film. Under applied heat, vacuum, and pressure, the resin is drawn into the preform which results in a uniform resin distribution, even with high-viscosity, toughened resins because of the short flow distance through the part thickness.

Braided Composites

Textile industries using two -or three-dimensional weavings can create one-piece preforms, which are then injected with resins and cured using RTM, RFI, or VARTM processes. Braiding technology has the potential for reducing composite manufacturing costs of difficult to fabricate, complex structural components. Braiding technology has been improved to the point that near-net-shaped fiber preforms of complex-shaped composite materials can be fabricated. Cost of labor is the biggest individual cost. Automation technology is the most efficient way to reduce production costs. The braiding process fabricates a preform or final shape while it generates the woven form. This product form is a unique fiber reinforcement, which can use pre-impregnated yarn as well as dry fibers. The main advantage of the braiding process is its ability to conform to odd shapes and maintain fiber continuity while developing high damage tolerance compared to unidirectional and laminated products. This advantage allows formation of square, oval, and other cross-section shapes. The braided preform can be drawn tightly against a male tool or mandrel in much of the same way as a Chinese finger puzzle when it is pulled tightly along its longitudinal axis. The three-dimensional form of braiding has evolved to the point of allowing the non-uniform cross-sections to be fabricated while maintaining weaving in all three planes. The uses of braiding have varied during its development. The best-known example of braided structure is the fiberglass and carbon fishing rods that became popular in the 1980’s. Braiding has also found uses in pressurized piping and complex ducting. A demonstration of its versatility is the open-wheel racecar body which was fabricated by braiding. The process has also been used in rocket applications for engine cases and launchers. In biaxial and triaxial braiding, a mandrel is usually used to form the braid. The mandrel also acts as the mold for the final product. Braided performs, shown below in figure E13, are typically used for RTM or VARTM processed parts.

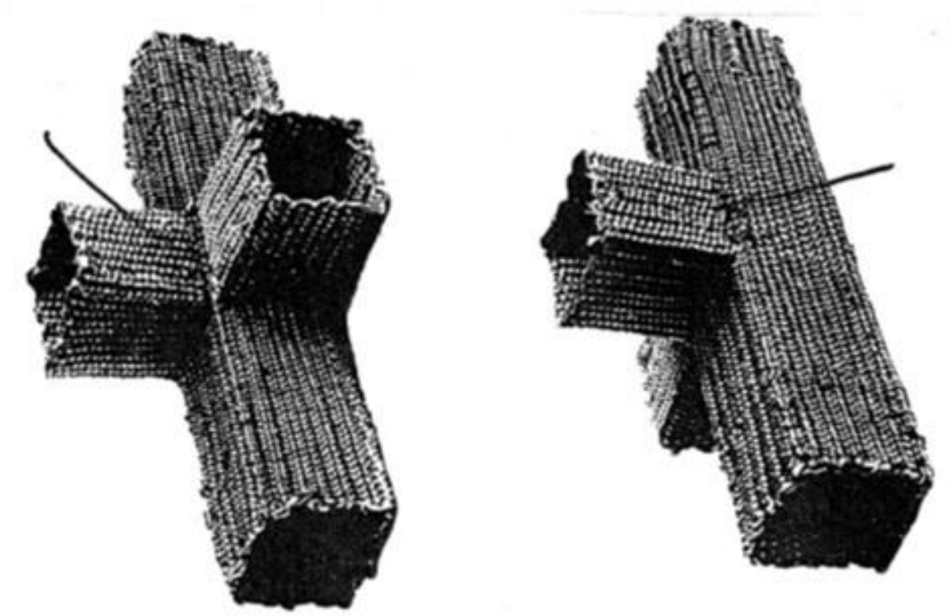


Figure E13. Braided integrally woven joint preforms

Filament Winding

Filament winding is an automated process in which a continuous fiber bundle (tow or tape), either pre-impregnated or wet impregnated with resin, is wound on a removable mandrel in a pattern. The filament winding process consists of winding onto a male mandrel that is rotating while the winding head moves along the mandrel. The speed of the winding head as it moves along the mandrel in relation to the rotation of the mandrel controls the angular orientation of the fiber reinforcement. The following general steps are used for filament winding:

1. The winder is programmed to provide correct winding pattern.
2. The required number of dry fiber or prepreg roving/slit tape spools for the specified band width are installed on the winding machine.
3. When wet winding, the fiber bundle is pulled through the resin bath.
4. The fiber bundle is pulled through the eye, attached to the mandrel, the winding tension is set, and the winding program is initiated.

5. When winding is complete, the mandrel is disassembled as required and removed from the part if the part is to be cured on a female tool, otherwise the part is trimmed and prepared for cure on the male mandrel.

E.2.3.2 Composite curing methods

Different processes for curing composite parts may be selected, such as autoclave, oven, heat blanket, and closed-cavity molds.

- Autoclaves, ovens, and heat blankets use vacuum bags but have different complexity and apply heat differently.
- Autoclaves apply uniform heat and higher pressure to consolidate laminates more fully.
- Specialized silicone rubber heat blankets are used to bond and cure composite structures using vacuum bagging techniques. Blankets provide heat and vacuum pressure and may incorporate several different heating zones if the composite part being cured has varying thickness and sub-structure. Heat blankets are often used for field repair.
- Closed-cavity molding offers a dimensionally accurate and high-quality surface finish composite molding but requires external or integral heating for accelerated curing of thermoset materials.

OEMs using ovens are limited in the scope of parts that they can produce. Part configurations with complex shapes and contours require the full pressure of an autoclave in addition to a vacuum to prevent bridging and produce more complete compaction. Autoclaves, illustrated in Figure E14, are much more expensive and complicated, compared to ovens, but are capable of curing more complex shapes as well as being better suited for bonding numerous parts into subassemblies.

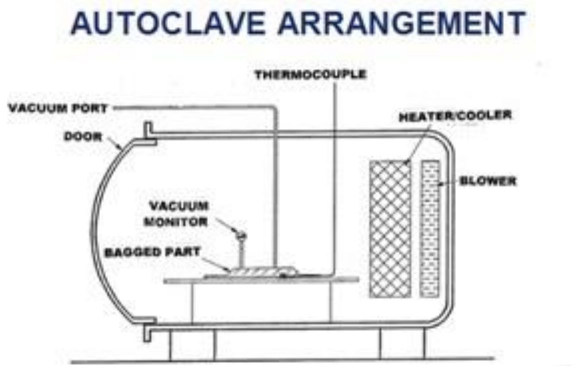


Figure E14. Autoclave illustration

Both oven and autoclave processes still require the same fabrication steps with the only difference being the addition of consolidation pressure that an autoclave provides. Closed-cavity molding, such as RTM and compression molding, typically uses liquid thermoset polymer resins reinforced with various forms of fiber reinforcements. Materials are presented to the mold and then heated for cure.

Other techniques sometimes used for curing composite parts are the following.

- Electron-beam, or e-beam curing, is an efficient curing method for thin laminates. In E-beam curing, the composite layup is exposed to a stream of electrons that provide radiation, causing polymerization and cross-linking in radiation-sensitive resins. X-ray and microwave curing technologies work in a similar manner. An advantage for e-beam curing is that heat is not required to cure the part, allowing the use of low-temperature tooling materials such as plastics and cardboard.

- Ultraviolet curing involves the use of UV radiation to activate a photo-initiator added to a thermoset resin, which, when activated, sets off a cross-linking reaction. UV curing requires light-permeable resin and reinforcements.

- Pultrusion is an automated process for the continuous manufacture of composites with a constant cross-sectional area. A continuous reinforcing fiber is integral to the process and the finished product. Pultrusion can employ prepreg thermosets, thermoplastics, or wet resin processing where the continuous fiber bundle is impregnated in a resin bath. The wet resin process was developed around the rapid addition reaction chemistry exhibited by thermoset polyester resins, although advances in resin and catalyst systems have made the use of epoxy systems commonplace. In pultrusion, the material is cured in a continuous process that can provide large quantities of high-quality cured shapes. The material is drawn through a heated die that is specially designed for the shape being made. This process is limited to parts with constant cross-sections such as rods, tubes, I-beams, and channels. The pultrusion process works well with quick-curing resins and is a very low-cost method for high-production parts.

The following pultrusion illustration (see Figure E15) shows a continuous method for constant thickness sections pulled through a thermal die to cure the resin. It is potentially a low-cost method with excellent dimensional control, high volume, and fully automated.

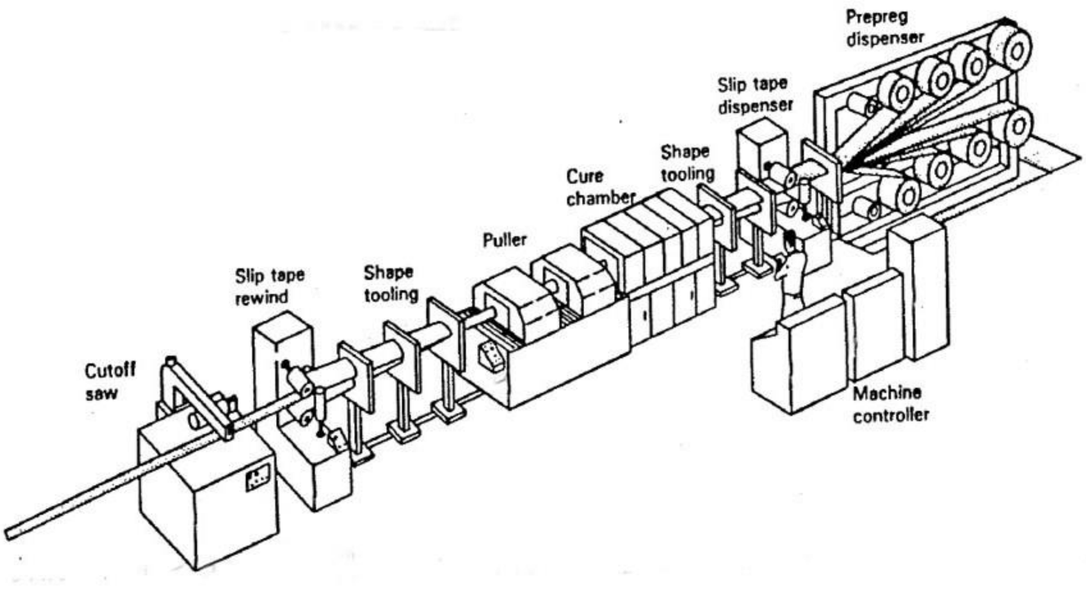


Figure E15. Pultrusion illustration

Thermoplastics

The thermoforming process, as applied to thermoplastic fiber-reinforced composite materials, is generally divided into two categories: melt-phase forming (MPF) and solid-phase forming (SPF). Thermoforming capitalizes on the rapid processing characteristics of thermoplastics.

The composite thermoforming process can be broken down to four basic steps:

1. The material is heated to its processing temperature external to the forming tool. This can be accomplished with radiant heat in an oven.
2. The oven-heated material is rapidly transferred rapidly and accurately to the forming tool.
3. The heated material is pressure-formed with matched die set tooling into the desired shape.
4. The formed laminate is cooled, and its shape is set by sinking the heat into the tooling.

MPF is performed at the melting point of the thermoplastic matrix. It requires sufficient pressure and/or vacuum application during the forming process to provide complete consolidation. The MPF process is preferred when sharp contour changes requiring some level of resin flow are a characteristic of the part geometry. SPF is generally performed at temperatures between the onset of crystallization and below the peak melting point. This temperature range provides enough formability while the material remains in a solid form. SPF allows forming of a pre-consolidated sheet to be performed without a consolidation phase, but it is limited to part geometries exhibiting gentle curvatures. If the forming process produces defects, the thermoplastic sheet can be reheated and reformed.

Compression molding is a method of molding in which a preheated polymer is placed into an open, heated mold cavity. The mold is closed with a top plug and pressure is applied to force the material to contact all areas of the mold. Throughout the process, heat and pressure are maintained until the polymer has cured. While the compression molding process can be employed with either thermosets or thermoplastics, most applications use thermoset polymers. Advanced composite thermoplastics can also be compression molded with unidirectional tapes, woven fabrics, randomly orientated fiber mat, or chopped strand.

Creep forming-vacuum hot forming is ideally suited for curing thick thermoplastic skins. The die is an integrally heated and cooled system in which the panel is loaded into the die and covered with a vacuum bag to apply atmospheric pressure; the combination of heat and pressure allows the panel to be creep-formed into shape. Figure E16 depicts a typical creep-forming arrangement for shaped thermoplastic laminates:

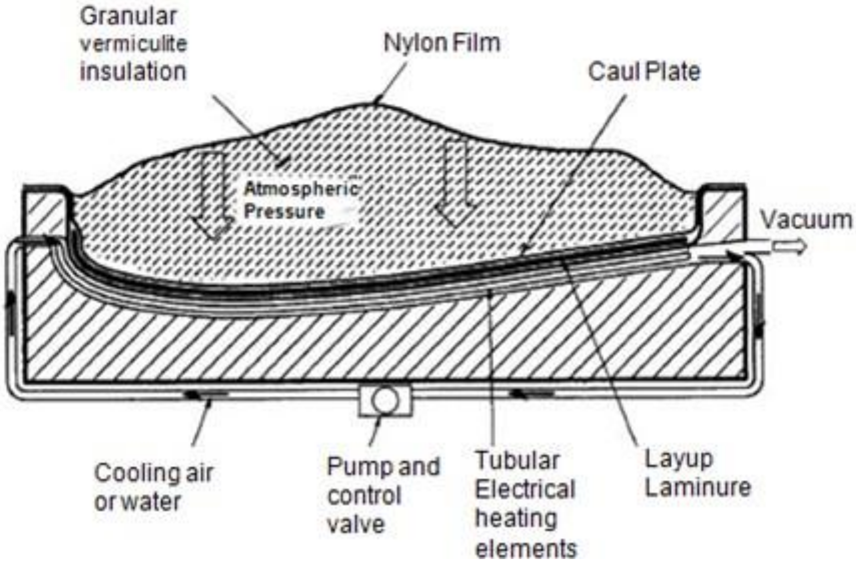


Figure E16. Vacuum hot forming illustration

E.2.3.3 Composite manufacturing facilities, tooling, and equipment

Production quality tooling is needed to produce a significant number of parts. Tooling material determines the capability of producing high-quality parts. CFRP tooling is light, reasonably inexpensive with little or no thermal mismatch issues, but usually requires periodic re-work and typically will have a limited life. Steel tools, especially INVAR alloys, are more expensive and much heavier, but have longer production lives. A typical layup tool is shown in figure E17.

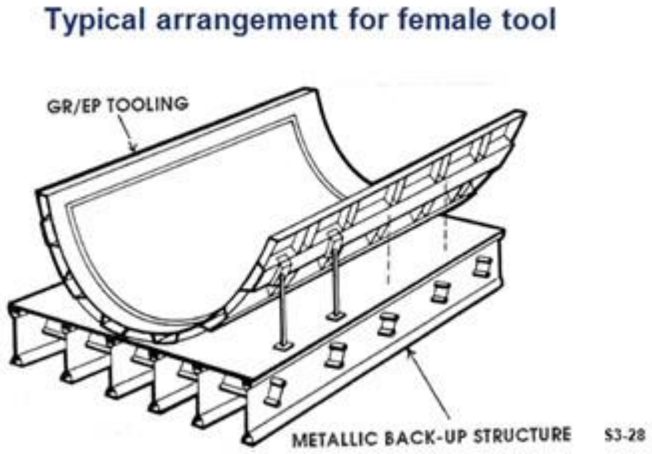


Figure E17. Composite tooling illustration

Typical layup practice includes the following elements:

- All film adhesives, prepregs, dry fibers, resins, and catalysts are stored to qualified standards. Records are kept ensuring that materials are within their working and storage lives and in good condition at the time of use.
- Personnel are properly trained in the composite fabrication process. They have experience with fabricating parts, and are familiar with their job roles.
- Layup of composite parts are in a clean room with positive pressure and where temperature and humidity are closely controlled, airborne particles are kept meet minimum requirements, and all materials, adhesives, and the surfaces of tooling must be free of contaminates.
- Activities are scheduled to minimize delays between layup of the part and the cure cycle to avoid exceeding material working and storage life limits.
- The pressure, temperature, heat-up rate, cure cycle, and cool down rate are monitored throughout the cure. These parameters are strictly monitored to produce quality composite parts and reduce rejected parts. Nondestructive evaluation (NDE) cannot be used to assess in-

process quality. Therefore, in-process quality assessments of these parameters ensure processing conformance to requirements since NDE methods lack the ability to assess bondline quality. While bondline flaws can be detected, bondlines with no air gap and no strength, known as ‘kissing bonds’, cannot be identified by NDE procedures. Bond strength of a kissing bond can only be determined by destroying the part through mechanical test.

E.2.3.4 Manufacturing Defects and Disposition

Typical Manufacturing Defects

The structural properties of composite elements and parts are created during the fabrication cycle, and defects and accidental damage can affect the part strength and stiffness. Defects in and damage to composite parts during the fabrication cycle can reduce structural performance of those parts. The strength and stiffness of composite laminates and bond assemblies can be reduced, sometimes significantly, by contamination, processing errors, and delaminations and disbonds caused by impact damages.

The major steps of manufacturing composite aircraft parts are:

- Material handling
- Laminate ply lay down and core assembly (for sandwich)
- Part fabrication/processing
- Part assembly
    - Co-cure or co-bonded processing
    - Secondary bonding
    - Fastening
- Finish machining
- Part transportation/storage

Numerous defect and damage types can result from the above steps of the manufacturing process, some of which are listed below.

- Porosity
- Warpage
- Local resin content variations
- Weak or kissing bonds

- Microcracks
- Delaminations
- Inadvertent edge cuts
- Surface gouges and scratches
- Damaged fastener holes
- Impact damage

MRB organizations, or the equivalent, are responsible for dispositioning rejected parts to prevent additional manufacturing cost by participating in corrective action analysis. Dispositions may include repair or rework, scrapping the part or material, or using the part or material as is. Corrective action may be taken to reduce the number of repetitive errors or defects in the fabrication process.

For major repetitive rejections, corrective action committees, typically composed of mid-level management personnel, address problems that may cross departmental lines, problems unresolved by departmental corrective action activities, root causes of repetitive problems, and high cost and frequency problems. Follow-up is assigned to ensure corrective action is effective.

E.2.3.5 Composite part assembly

Bonding Assembly

Bonding assembly, or structural bonding, is a form of composite fabrication, whereby bonded structures are bonded interfaces between separate elements or components. Bonding assembly may include composite-to-composite, composite-to-metal, and metal-to-metal bonds. In many of these bond configurations, at least one of the elements needs surface preparation prior to the bonding operation. The methods used for surface preparation of the separate parts to be bonded depend on the materials being bonded, such as using phosphoric acid for anodizing aluminum. An adherend is the surface that adheres to another by adhesion. In most composite structural applications, to eliminate cost, weight, and complexity, bonding can replace many expensive fasteners. Therefore, structural bonding should be considered as a critical part of composite structural design and development.

Adhesive bonding is applicable to a range of structural applications. Metals and composites may be joined in single-lap or double-lap joints, step joints, or scarf joints. Adhesive bonding may also be used to attach stiffeners to skins to increase stiffness. Lightweight sandwich construction methods depend on adhesive bonding to attach face sheets and edge members to the sandwich core. Adhesive bonding for repair applications is usually based on variations of these types of joints. Examples of bonded joints are illustrated in Figure E18.

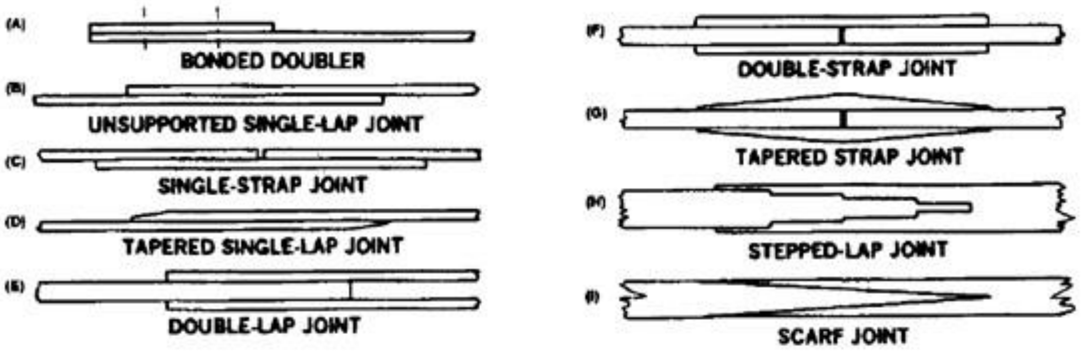


Figure E18. Types of bonded joints

A single overlap joint is the simplest form of adhesive bonded joint. One adherend is simply bonded to one side of the other adherend to form the joint. Single-lap joints are susceptible to out-of-plane peel stresses due to bending moments caused by load path eccentricity as the load passes from one adherend to the other. This peel effect may be reduced by employing longer overlap lengths. In addition, tapering of the adherends at the end of the overlap can reduce peel and shear stresses at the ends of the joint.

Double overlap joints are formed by bonding two outer adherends to one inner adherend. Because the neutral axes of both sides of the joint are aligned, peel stresses are virtually eliminated. However, the additional layer in the joint adds to manufacturing complexity and can result in non-uniform adhesive thickness.

Multi-step joints are formed by machining steps in the adherends and placing adhesive on each step. Step joints have the advantage of significantly increasing the load, which can be carried by the joint because each step contributes to the load being transferred. Step joints are more difficult to manufacture than single or double lap joints.

Scarf joints are formed by tapering the adherends; this can result in a more uniform shear stress distribution compared to other types of joints. Because the neutral axes of the adherends are aligned, peel stresses are reduced, and because adhesives are relatively weak in tension, it is necessary to use shallow scarf angles to reduce tensile stresses in the adhesive. Typical scarf angles are less than 1:15 (3.8°). For thick composite structures, this can result in impractical scarf lengths and mechanically fastened joints are often preferred, especially for joints with high load transfer. Scarf joints are also difficult to manufacture because of the close tolerances required for machining the scarf and the risk of breaking the tip off the scarf during the machining operation. Bonded repairs typically utilize the scarf joint, where damage is removed. Wet plies of adhesive and composite material are laid down in the tapered hollow of the part followed by curing the repair.

Sandwich panel technology is highly dependent on adhesive bonding. An adhesive layer bonds the face sheet to the core, and adhesives bond the edge members to the face sheets. Core splices and core-to-edge member bonds are performed using expanding foam adhesives that fill gaps in the core.

Adhesive bonding may also be used to attach various shapes of stiffeners onto flat or curved sheet material to produce stiff, strong structures.

In composite-to-composite bonding there are three basic types of bonds:

- Co-curing: Composite elements to be bonded are uncured prior to the bonding operation. In this type of bonding, the bond can be achieved by chemical reaction of the resins of each element, or a layer of adhesive can be used. Film adhesive would typically be used. Principal advantages derived from the co-cure process are an excellent fit between bonded components and guaranteed surface cleanliness.

- Co-bonding: One or more of the composite elements is pre-cured prior to the bonding operation. This type of bonding method can also include composite to metal bonding. A layer of adhesive is required in all cases to create the bond, and the adhesive can be either film or paste adhesive. The pre-cured composite elements or the metal element will require surface preparation prior to the bonding operation to eliminate bondline contamination. In cobonded skin/stiffener designs, the adhesive film, placed into the interface between the stiffener and the skin, increases fatigue and peel resistance.

- Secondary bonding: All elements are pre-cured prior to the bonding operation. In this type of bonding, all elements will require prior surface preparation to eliminate bondline contamination. This is also the case for metal bonding.

With structural bonding, unlike other forms of composite fabrication, bond weakness or small anomalies or defects cannot be reliably detected in the bondlines after the bonding process. Apart from macro-voids, other smaller defects such as micro-voids, weak bonds, or “kissing bonds” (no gap between the adherends but no adhesion) cannot reliably be detected in structural bondlines with current NDI techniques. Thus, to ensure adequate bond strength and durability, the specific bonding process steps must be strictly followed, and is often validated by mechanically testing a witness coupon fabricated during the same process.

Fastened Composite Assembly

Mechanically fastened joints for composite structures have been used since the mid-1960’s, when high modulus, high strength composites first came into use. It was found early that the behavior of composites in bolted joints differs considerably from that of metals. Because of the composite laminate construction, mechanical fasteners, and assembly techniques that are common to metallic structure such as riveting and interference-fit fasteners, can result in damage to advanced composite structure. As a result, manufacturers had to develop special fasteners, hole drilling, hole/fastener fit, and installation methods to ensure that the composite parts are assembled without damage. Special drill bits are used for carbon and aramid composites, with higher drill rotational speeds, lower drill feed speeds, and special titanium bolts which are tailored to composites. These special fasteners typically feature larger footprint areas, which improve pull-through strengths. Galvanic corrosion susceptibility between carbon and aluminum has reduced the use of aluminum fasteners that are in direct contact with carbon. Bolted joints in composites often require shims due to tolerance buildup of the composite parts, but the unshimmed gap allowance is generally much less than for similar metal bolted joints due to lower allowable clamp-up and susceptibility to hole damage from bolt bending. Pull-through failure modes are critical for countersunk fasteners in composite joints, so most fabricators will use tension head fasteners even in shear-only applications.

Mechanically fastened joints can be divided into two groups - single row and multi-row designs. Lightly loaded non-critical joints employ a single row of fasteners. The root joint of a wing, or a control surface, is an example of a highly loaded joint, where the entire load accumulated on the aerodynamic surface is off-loaded into another structure. In this case, a multi-row bolt pattern is usually required to distribute the load. Most of the critical mechanical joints encountered in aircraft structures employ multiple fasteners. The number and type of fasteners needed to transfer the given loads are usually established by airframe designers by considerations of available space, producibility, and assembly.

Assembly processes are not conventionally covered within composite material characterization but can have a profound influence on the properties obtained in service. As seen with test coupons, edge and hole quality can dramatically affect the results obtained. While these effects are not usually covered as material properties, an engineering trade-off between part performance and the time and effort expended toward increased edge and hole quality is an important consideration. These effects must be considered along with the base material properties.

E.2.3.6 Composite manufacturing regulations and guidance

Regulations addressing composite manufacturing are:

1. FARs 23.605, 25.605, 27.605, and 29.605: Fabrication methods

As an example, FAR. 25.605 — Fabrication methods:

- The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.
- Each new aircraft fabrication method must be substantiated by a test program.

2. Guidance for composite manufacturing can be found in Advisory Circulars and Composite Materials Handbook CMH-17

Advisory Circulars:

- AC20-107B "Composite Aircraft Structure" specifies guidance for materials and fabrication development in paragraph 6. The following are excerpts from paragraph 6:

"Specifications covering processing procedures should be developed to ensure that repeatable and reliable structure is being manufactured. The means of processing qualification and acceptance tests defined in each material specification should be representative of the expected applicable manufacturing process. The process parameters for fabricating test specimens should match the process parameters used in manufacturing actual production parts as closely as possible."

"Once the fabrication processes have been established, changes should not occur unless additional qualification, including testing of differences is completed."

"Process specifications and manufacturing documentation are needed to control composite fabrication and assembly. The environment and cleanliness of facilities are controlled to a level validated by qualification and proof of structure testing. Raw and ancillary materials are controlled to specification requirements that are consistent with material and process qualifications. Parts fabricated meet the production tolerances validated in qualification, design data development, and proof of structure tests. Some key fabrication process considerations requiring such control include material handling and storage; laminate layup and bagging (or other alternate process steps for non-laminated material forms and advanced processes); mating part dimensional tolerance control; part cure (thermal management); machining and assembly; cured part inspection and handling procedures; and technician training for specific material, processes, tooling, and equipment."

- AC21-26A "Quality System for the Manufacture of Composite Structures" specifies guidance for the quality control of the manufacture of composite parts; material and specifications for resins, fibers, material forms (prepregs, etc.) and adhesives; specifications for the fabrication of parts (laminate layup, wet layup, filament winding, etc.); assembly of components (bonding, sandwich, etc.).

3. Composites Materials Handbook CMH-17 Chapter 2 provides information on:

   - Composite fabrication processes: Hand lay-up, automated tape placement/automated tape lamination, automated tow placement/fiber placement, braiding, filament winding, pultrusion, sandwich construction, and adhesive bonding.

   - Cure and consolidation processes: Vacuum bag molding, oven cure, autoclave curing processing, press molding, integrally heated tooling, pultrusion die cure and consolidation, resin transfer molding, and thermoforming.

   - Assembly processes for both bonding and mechanical fastening.

E.3 Composite structural design and analysis

Composites exhibit attractive properties such as high stiffness and strength-to-weight ratios, reduced sensitivity to cyclic loads, improved corrosion resistance, and the ability to tailor configurations (geometry and stacking sequence) to specific loading conditions for optimum performance making them prime candidate materials for use in aerospace applications.

The increase in the use of composites with the increased complexity of analysis necessary to efficiently design components requires reliable analysis and design methods that can assist engineers in implementing composites in aircraft structures.

Issues affecting the utilization of composite materials include a) the relative high cost of the raw material, b) the cost of processing those materials, and c) the assembly of parts. The cost of mechanically joining carbon composite parts, because of the necessity of using titanium bolts rather than aluminum rivets to avoid galvanic corrosion of the rivets, has increased the use of bonded joints such as skin-stiffener connections.

Buckling is the sudden deformation of a structural component under load. Low interlaminar and out-of-plane strength and low impact resistance have forced a reduction in allowed buckling levels. For example, no buckling is allowed at operating loads or, in some cases, below design limit load of structural details, such as skins, webs of spars, beams, and ribs, to reduce out-of-plane loadings on bonded joints and interfaces between plies. This reduction in allowed buckling levels has the effect of limiting potential weight savings over equivalent aluminum structures.

E.3.1 Typical composite structural design details

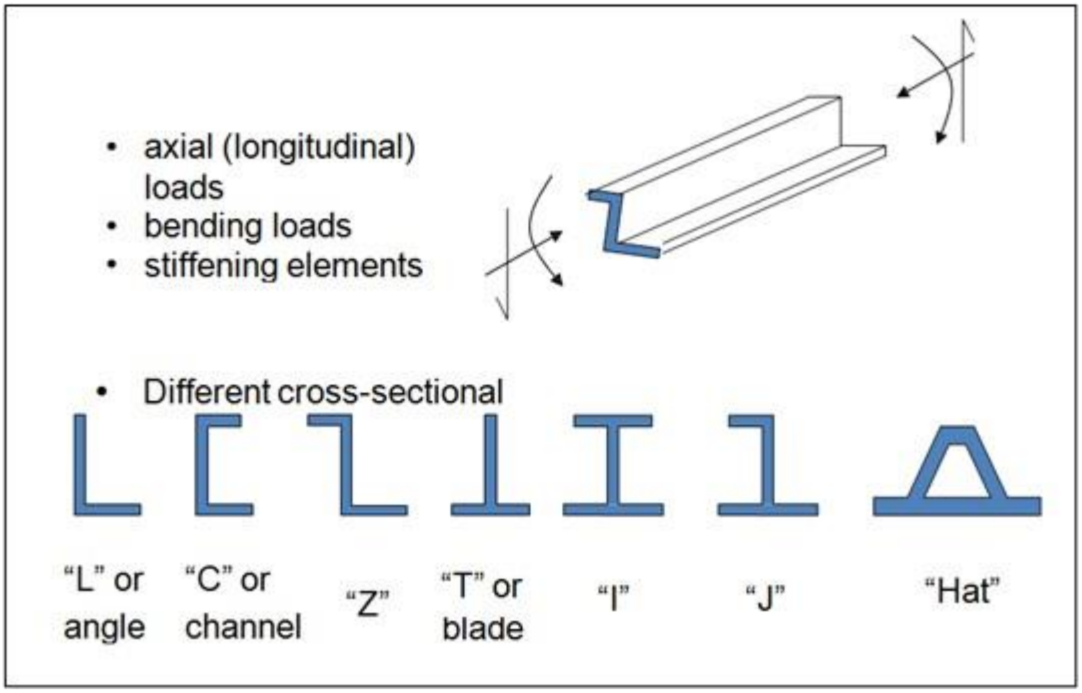
For many composite aircraft structural details, while like those of metal, have differences that are usually based on three main issues.

1. Composite laminate out-of-plane strength is usually much less than that of metals, such as aluminum, steel, and titanium, and composite parts must be designed to minimize the effect of secondary loads.
2. Mechanical properties of composite parts may be more seriously affected by fabrication processes and potential defects than metals, although some processing steps of metals, such as heat treatment and post-machining treatment, can affect static and fatigue strengths.
3. To minimize processing costs, most fabricators restrict laminate layup ply orientation angles to 0, +45, -45, and 90 degrees to speed and simplify the fabrication process.

Fabrication methods often dictate design guidelines to be used in practice to avoid surprises and to generate robust designs. As an example, in laminates where the thickness or ply stack is changed, plies are dropped or added in the interior of the laminate as close to mid-plane as possible to avoid peel effects or ply separation issues. These limitations can affect the mechanical performance of laminates.

Beams (Stringers, Stiffeners, Panel Breakers)

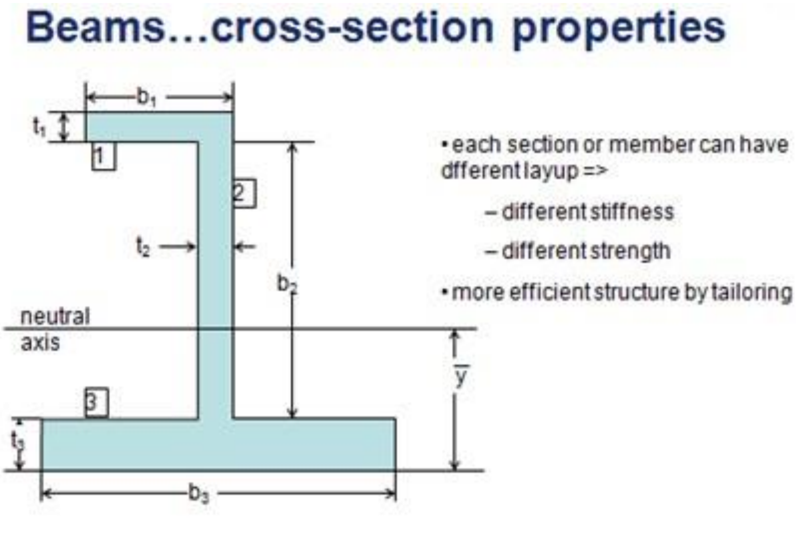
Composite beams are part of aircraft structural components for the same reasons as for metals. Manufacturing limitations and low out-of-plane strength are two principal differences. In addition, many stiffening details such as stringers and stiffeners are bonded, co-bonded, or co-cured to the skins to minimize assembly costs, whereas most stiffening details in metallic structures are fastened. Low out-of-plane strength of typical bondlines requires the minimization of secondary loads, often accomplished by choosing stiffeners or stringers that have symmetric skin attachment flanges. This tends to limit the use of Z, L, or C section stiffeners as depicted in Figure E19.



- axial (longitudinal) loads
- bending loads
- stiffening elements
- Different cross-sectional

Figure E19. Types of skin attachment flanges

Metal beams or stiffeners are typically modified in cross-section to account for increases or decreases in loads and stiffness requirements by machining the flange or web thicknesses. Beam cross-sectional properties are shown in Figure E20. To account for changes in loads or stiffness



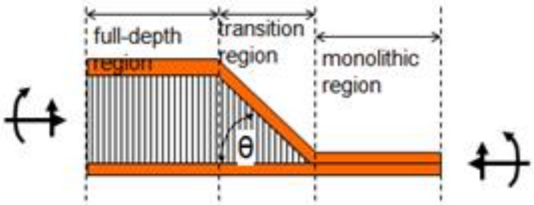
Beams…cross-section properties

- each section or member can have dfferent layup =>
  - – different stiffness
  - – different strength
- more efficient structure by tailoring

Figure E20. Beam cross-sectional properties requirements, the various composite beam and stiffener element laminates can be tailored by changing the layup and/or stacking sequences, or by adding or eliminating plies.

Sandwich structural design details

Sandwich configurations are often employed for aircraft parts that have high stiffness and medium or low load requirements. Examples include flight control panels and fairings, which were among the early users of composites. Moisture can be absorbed into the sandwich core, which is typically honeycomb, resulting in significant structural degradation. Typical composite honeycomb core is of a treated paper material such as Nomex™ and metal bond core, which is usually made from expanded aluminum honeycomb. Moisture will cause strength and stiffness degradation of the Nomex™ core and corrode the aluminum core. Typical composite or metal bond sandwich configurations employ ramp downs to minimize moisture ingression from edge closeouts. Sandwich ramp-downs create offset, or eccentric, loadings, however, and must be designed to minimize this effect as shown in Figure E21.



- eccentricity poses problems; sandwich bends even under in-plane load
- large deflections for typical panel size

Figure E21. Sandwich structure eccentric loading

The full-depth thickness is determined by panel requirements, which includes buckling and strength in the presence of damage. The monolithic area is determined by the attachment requirements, such as bearing strength and bonded joint analysis requirements. The transition must be a smooth transition from monolithic to full depth providing sufficient plies at the ramp to transfer load evenly as illustrated in Figure E22.

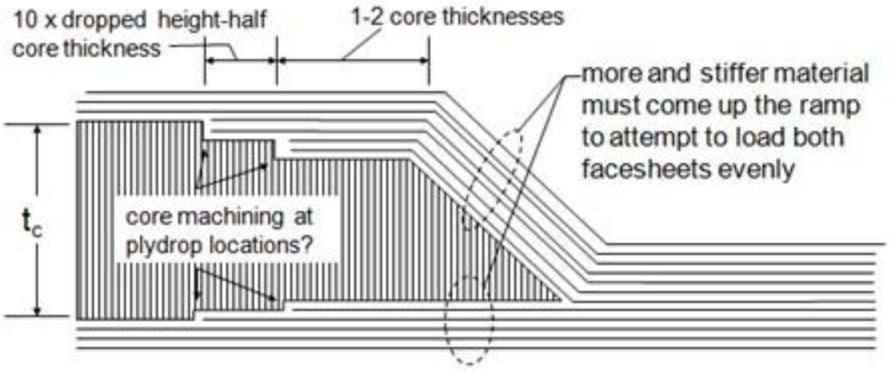


Figure E22. Sandwich structure ramp down design practices

Another issue for sandwich ramp down design is core crushing caused by pressure from the ramp angle. The typical way to minimize the effect of core crushing in the ramp area is to use small ramp angles as illustrated in Figure E23.

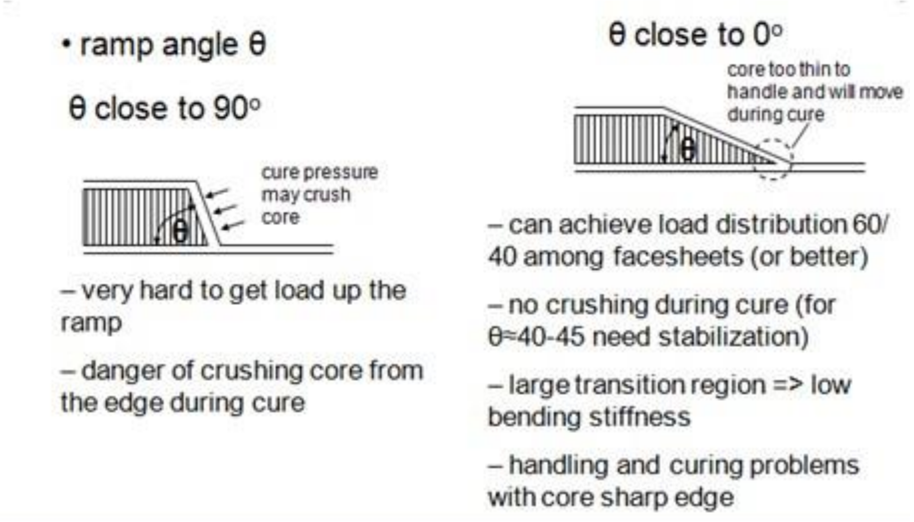


Figure E23. Sandwich structure ramp angle design practices

Lugs and Fittings

Previously, most critical joints connecting composite structural components, such as fuselage-vertical stabilizer terminal fittings, flight control panel fittings, and horizontal stabilizer pivot and jack-screw fittings, either have been transitioned to titanium from the composite or have incorporated titanium reinforcements. Recently, carbon composite terminal fittings either have incorporated laminates or RTM processed preforms. Some aircraft employ composite tubular struts; to connect, the tubes must be transitioned into lugs. In the example below, the lug is bonded to the interior wall of the composite tube end using a paste adhesive. In other applications, the lugs have been mechanically fastened to the tube ends.

Typical composite lugs have relatively thick cross-sections and processing thick defect-free sections can be difficult. Thick section composites can also be defined from the standpoint of fabrication effects associated with many plies. Process induced stresses can be significant and, therefore, warrant special attention. Additional fabrication issues include residual stresses, wrinkling, micro-cracking, exotherm, volatile removal, and compaction. Defects will often be present in the final product and additional fitting factors may be required, depending on the criticality of the applications. The required fitting factor for critical joints is 1.15, and due to the potential for undetected flaws in composite lugs and fittings, an additional factor may be required. Example use of composite lug is shown in Figure E24.

Figure E24. Composite lugs

E.3.2 Basics of laminate theory and composite failure modes

Composites, by definition, are heterogeneous, anisotropic, materials. Mechanical analysis, however, assumes that the material is homogeneous. This apparent conflict is resolved by considering homogeneity on microscopic and macroscopic scales. While microscopically, composite materials are heterogeneous, on the macroscopic scale, composites appear homogeneous and respond homogeneously when tested.

- The analysis of composite materials uses effective properties, which are based on the average stress and average strain.
- Composites are often orthotropic. Orthotropy is the condition expressed by variation of mechanical properties as a function of orthogonal, or perpendicular, orientation. Lamina that exhibits orthotropy displays large differences in properties between the 0° and 90° directions. If a material is orthotropic, it contains planes of symmetry. It can be characterized by four independent elastic constants.
- Some composite material properties are nonlinear. The amount of nonlinearity depends on the property, type of specimen, and test environment. The stress-strain curves for composite materials are frequently assumed linear to simplify the analysis.
- One consequence of the microscopic heterogeneity of a composite material is the thermal expansion mismatch between the fiber and the matrix. This mismatch causes residual strains in the lamina (and laminate) after curing. The corresponding residual stresses are often assumed not to affect the material's stiffness or its ability to strain uniformly.

The lamina/laminate coordinate axes used for all properties and a summary of the mechanical property notation are shown in Figure E25.

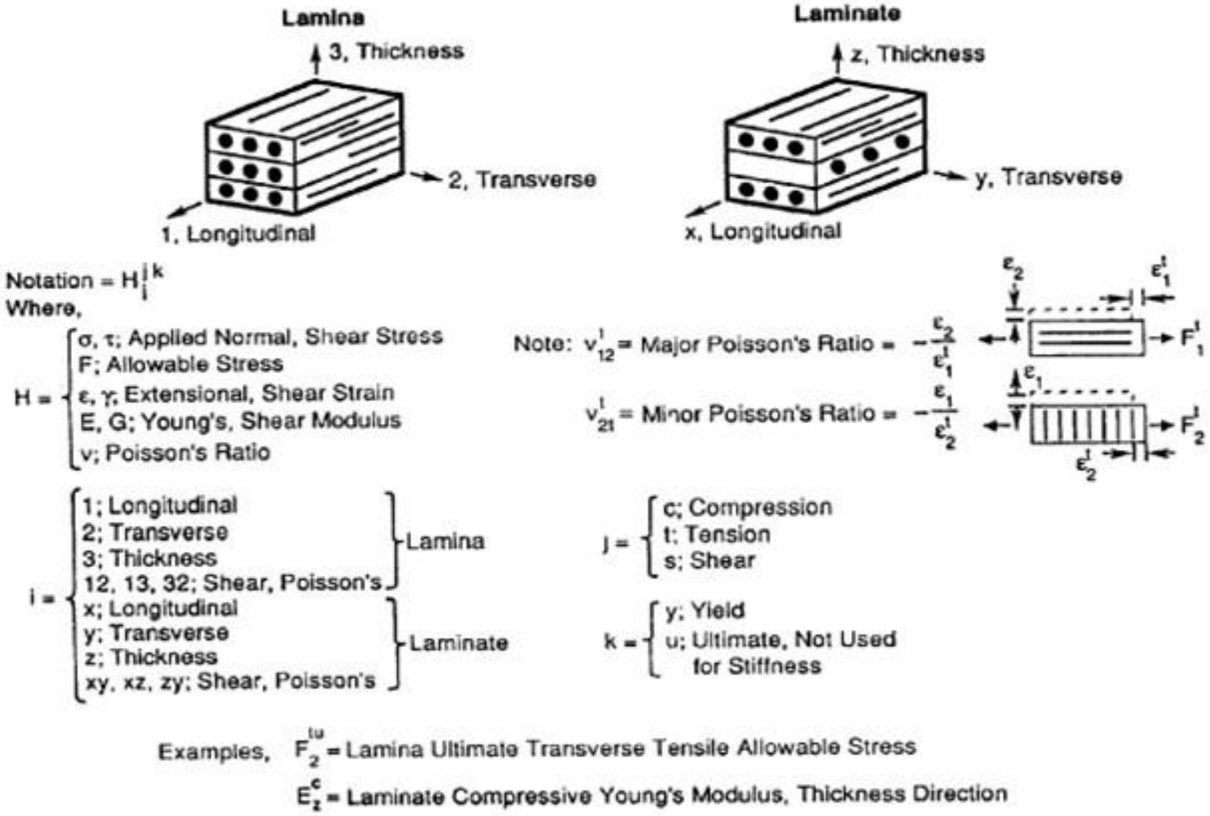


Figure E25. Lamina/laminate mechanical property notation

E.3.2.1 Lamination theory

The development of procedures to evaluate stresses and deformations of laminates is dependent on the principal that the thickness of laminates is much smaller than the in-plane dimensions. A typical thickness value for individual plies range between 0.005 and 0.010 inch. Consequently, laminates that are 8 to 50 plies are thin plates and, therefore, can be analyzed on the basis of the simplifications of thin plate theory.

In the analysis of isotropic thin plates, in-plane loading and bending are analyzed separately. The former case is described by plane stress elastic theory and the latter by classical plate bending theory. This separation is possible since the two loadings are uncoupled for symmetric laminates; when both occur, the results are superimposed.

The classical assumptions of thin plate theory are:

1. The thickness of the plate is much smaller than the in-plane dimensions.

2. The shapes of the deformed plate surface are small compared to unity.
3. Normal interactions to the undeformed plate surface remain normal to the deformed plate surface.
4. Vertical deflection does not vary through the thickness.
5. Stress normal to the plate surface is negligible.

Laminate construction is shown in Figures E26 and E27.

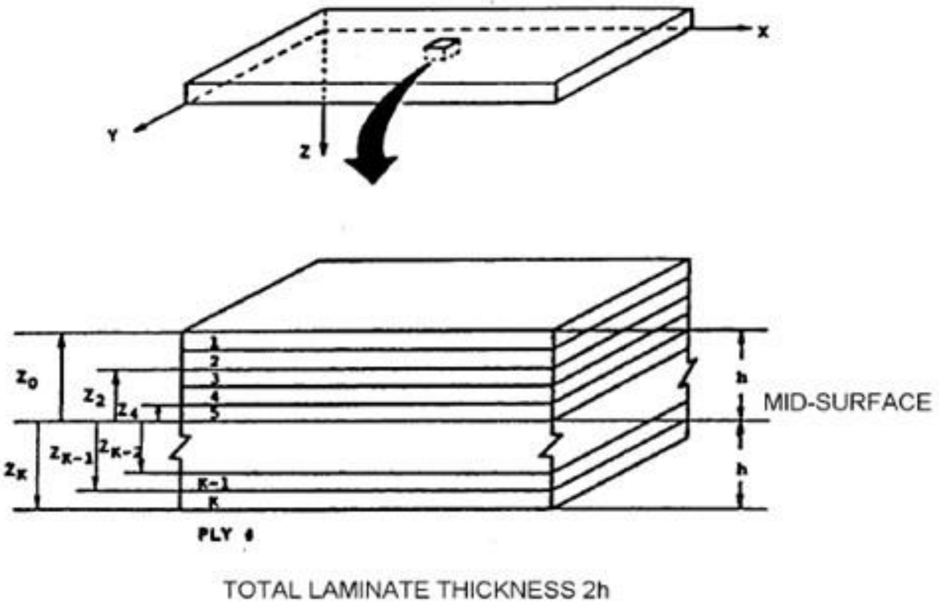
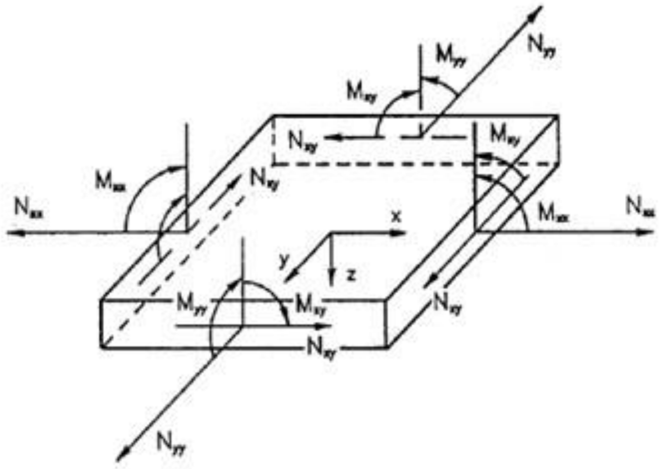


Figure E26. Laminate construction



$$\{N\} = \int_{-h}^{h} \{\sigma_x\} dz$$

$$\{M\} = \int_{-h}^{h} \{\sigma_x\} z dz$$

Figure E27. Lamination theory stress and moment illustrations

For convenience, stress and moment resultants are used in place of stresses for the development of lamination theory.

Classical lamination theory (CLT) has been used to predict the internal stress state, stiffness, and dimensional stability of laminated composites. The constitutive law for CLT couples extensional, shear, bending, and torsional loads with strains and curvatures. Residual strains or warpage due to differential shrinkage or swelling of plies in a laminate have also been incorporated in lamination theory using an environmental load analogy. The combined influence of various types of loads and moments on laminated plate response can be described using the ABD matrix as follows as shown in Figure E28.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

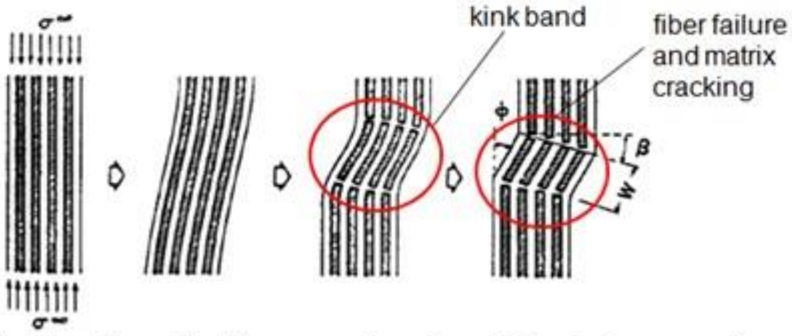
where N are loads, M are moments, ε are strains, κ are curvatures and

A_{ij} = extensional and shear stiffnesses
B_{ij} = extension-bending coupling stiffnesses
D_{ij} = bending and torsional stiffnesses

Figure E28. The ABD matrix

E.3.2.2 Composite failure modes

When a laminate is under compression, if the fiber/matrix bond is sufficiently strong, the fibers behave as beams in an elastic foundation and locally buckle. Fiber kinking is illustrated in Figure E29.



- this is the fiber kinking or micro-buckling failure mode

Figure E29. Composite buckling

Some failure modes for composite structures are the same as for metal structures, illustrated in the following figure. These include column buckling, material failure, local crippling, and inter-fastener buckling. Also shown are composite failure modes such as potential bond-line failures, such as skin-stiffener separation and shear-tie disbonds. Any structural connection with eccentricities, as in the shear-tie connection, would be fastened like metal shear-ties.

Failure modes for stringers, stiffeners, and panel breakers are shown in figure E30.

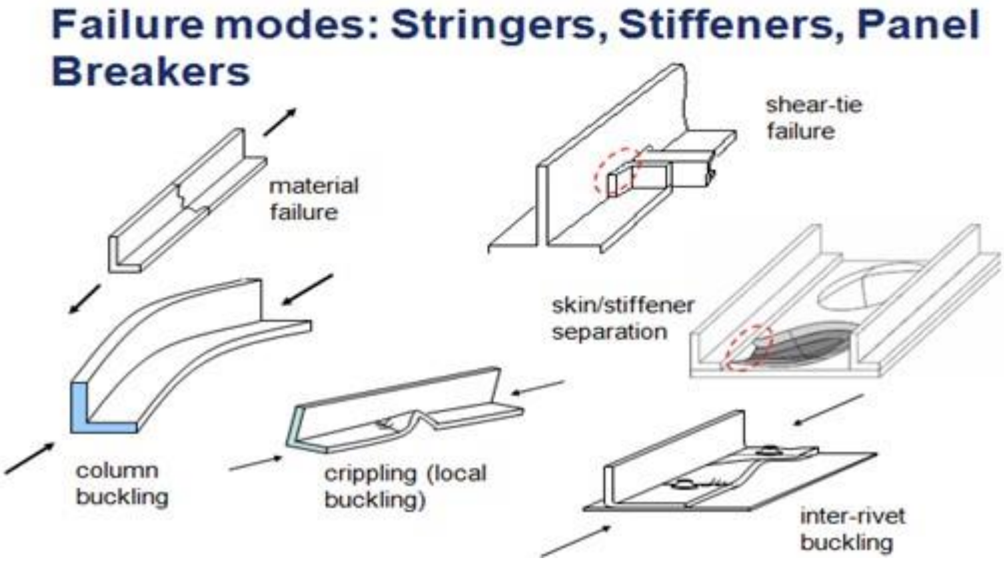


Figure E30. Composite Failure Modes

In skin-stiffener interfaces, even before buckling, the tendency for skin-stiffener separation exists due to the need for interlaminar stresses to develop at the flange/skin interface (and other ply interfaces) to balance the far-field loads as illustrated in Figure E31.

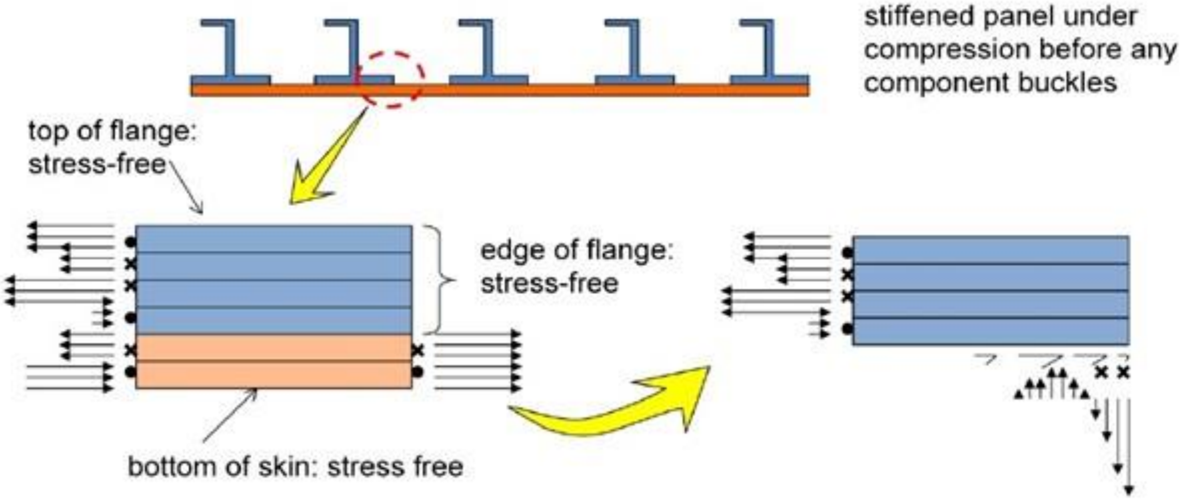


Figure E31. Skin-stiffener interface separation

These interlaminar stresses may combine to cause delamination and thus lead to skin/stiffener separation as shown in Figure E32.

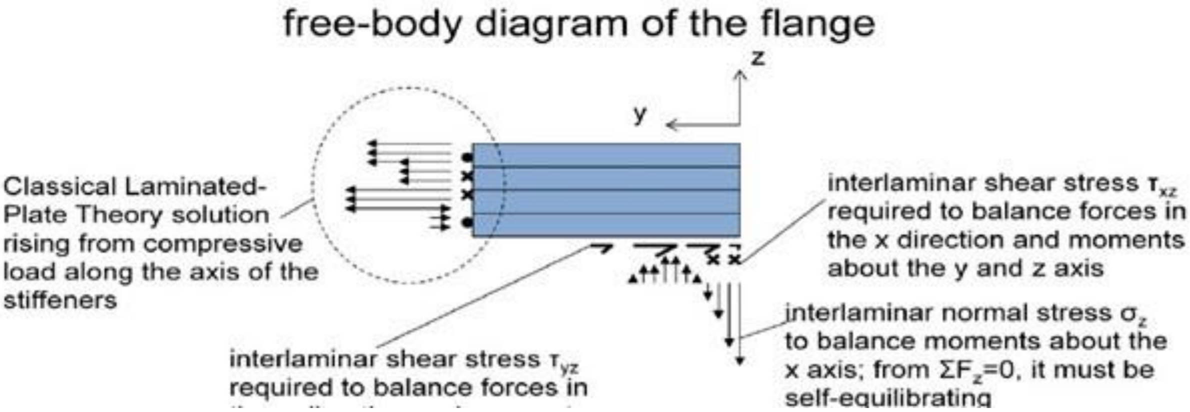


Figure E32. Free-body flange diagram

The configuration of the stiffener, stringer, or frame affects resistance to skin buckling between stiffening details. In the illustration below, composite closed hat bonded to skins increases resistance to buckling compared to an open L-section configuration. Although the bond-lines of closed section stiffeners will have peel stresses, as shown in Figure E34, which must be considered.

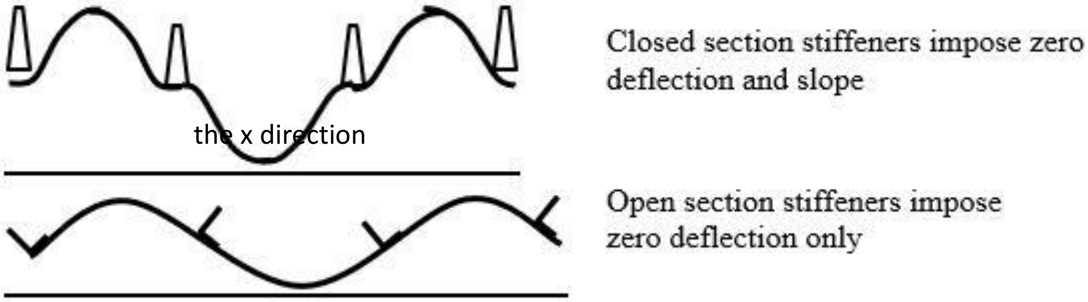


Figure E34. Stiffener configuration effects on buckling

Sandwich failure modes for composite sandwich panels, consisting of carbon or glass/epoxy face sheets typically with Nomex™ honeycomb core, are the same for metal bond sandwich made of aluminum face sheets with aluminum honeycomb core. Modes of failure include:

- Panel buckling whereby the whole sandwich panel is buckling
- Facesheet strength failure under tension, compression, and shear

- Shear crimping, precipitated by core shear failure usually after facesheet antisymmetric wrinkling
- Facesheet dimpling or intra-cellular buckling, with facesheet buckling between cell boundaries
- Adhesive strength failure under tension and shear
- Core strength failure under tension, compression, and shear

The various modes are depicted in the Figure E35.

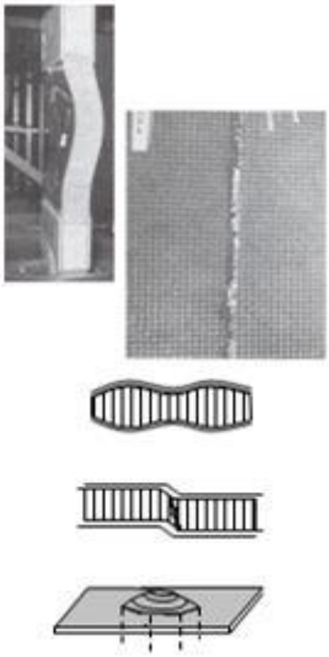


Figure E35. Sandwich panel failure modes

Failure modes for composite lugs and fittings are similar to those for metal lugs, with the exception of delaminations. Critical joints, such as terminal fitting lugs that transfer high loads, require thick cross-sections, and the fabrication of thick laminates can result in process-induced residual stresses, which may be factors in delaminations being a governing failure mode.

E.3.3 Environmental considerations

Metal and composite structures are affected differently by aircraft environments, and more environmental effects must be considered for composite structures compared to those of metals. With higher sensitivity to many environments, composites require additional test data, but are generally not susceptible to corrosion. Environmental effects must be accounted for in-design and proof of structure substantiation. Assessment of environmental effects is a significant activity for the composite material and structure test program. Some of these environmental effects include:

- Ground-air-ground temperature/moisture
- Local heat sources
- Operating fluids – hydraulic fluids, oils, solvents, anti-icing, fuels, contaminants
- Ultraviolet rays
- Airstream erosion
- Hail, bird, debris impacts
- Lightning strike

The effects of environments are evaluated and substantiated in different ways.

- Design properties testing is used to evaluate:
    - Temperature, moisture, some fluids
    - Impacts
- Material selection is used to avoid degradation of properties
    - Fluids (de-icing fluids, solvents, hydraulic oils, etc.)
- Protection schemes are employed to guard against:
    - UV, erosion, lightning strike, etc.
- For primary structural components such as wing and empennage main torque boxes and fuselage pressure shells, the minimum thickness should be sufficient as to prevent hail impact damage

- For more lightly loaded structural configurations such as sandwich, the facesheet minimum thickness should be 3 or more plies to keep moisture from seeping into the structure and to provide some measure of impact damage resistance

Temperature and moisture absorption may have significant effects on composite materials. Aircraft ground and in-fight temperatures must be established for each unique aircraft structural component, considering the operational conditions, structural configurations, and exterior surface coatings. In some cases, test data for extended exposure to elevated temperatures must be obtained. Thermal analyses are often required to establish minimum and maximum structural temperatures. Temperature of aircraft structure can rise well above the ambient conditions due to several factors.

- Paint colors, type
- Orientation on aircraft
- Structural configuration: laminate-stiffened, sandwich, thickness, sub-structure

Several typical sources of local heating include:

- Engine bleed air
- Anti-icing air or electrical heating elements
- Air conditioner units
- Avionics/ black boxes
- Auxiliary power unit (APU) heat and exhaust
- Engine heat and exhaust
- Greenhouse effect in small airplane cockpits/cabins

E.3.4 Mechanical properties and design values

Final product properties are subject to the processing method used to fabricate composite parts. Mechanical properties and design values are directly linked to the fabrication process. If the process is modified, then test data is required to either validate that the mechanical properties from the original process are still acceptable for the modified process, or to establish a new set of properties and design values.

It is imperative to understand and document the full-scale part fabrication process prior to performing the allowable and design values testing. If this is not performed, tests may have to be repeated with the final process.

Key design properties are as dependent on the fabrication process used to produce the final product as they are on the raw material, and design values must be linked to both of the materials and processes used to fabricate parts.

Analytical methods used in design determine the specific allowable for which design values must be developed. Different analyses require different property inputs, and there is no single generally accepted industry approach for composite design/analysis.

E.3.4.1 Allowables vs design values

Allowables and design values have often been incorrectly used interchangeably.

- Allowables are the statistical regulation of data
- Design values are used for designing the structural components and calculating margins of safety

The CFR 2X.613 regulation refers to design values that are based on statistically derived allowables modified through correction values to account for the range of conditions encountered by the structure throughout the aircraft's operations, including for example temperature, moisture, or other special environmental conditions.

The following documents are recognized by the regulatory authorities and are accepted sources of material allowables:

- Metallic Materials Properties Development & Standardization (MMPDS) (Formally Military Handbook 5) is a source of allowables and methods for deriving metallic material allowables
- Composite Materials Handbook (CMH-17) (formerly Military Handbook 17) is a source of methods for deriving composite allowables and methods for deriving composite design values

An "allowable" value is a directly calculated basis value from a significant sample of test data

- A basis value is an estimate of lower bound strength

A "design value" may be one of the following.

- An estimate of a basis value, using conservative estimates of the scatter factor and lower bound test data
- An allowable baseline value times factors to account for environment, geometry, fasteners, etc.
- An allowable value reduced to provide extra conservatism for unknown effects

E.3.4.2 Laminate strength properties

Laminate-based strength properties are the foundation of the building block in-plane strength tests. These strength properties must cover the range of layup, joint, impact, and configuration parameters (“design space”).

- Multidirectional fiber layups
- Unnotched, open/filled hole, post-impact, large notch
    - Tension and compression – stress or strain
    - Laminates, sandwich face sheets
- Bending – unnotched, open/filled hole, post-impact
- Bolted joints
    - Bearing stress
    - Bearing/bypass interaction – stress and strain
    - Fastener pull-thru load
- Local buckling, crippling stress
    - Stiffener section elements

E.3.4.3 Structural strength properties

These types of properties are linked to specific geometric and fabrication process configurations and cannot be evaluated using simple flat coupons.

- Curved laminates (radius details)
- Post-buckled stiffened panel stress with various levels of impacts
- Stiffener pull-off

- Stiffener flange/cap bending, transverse loading
- Beam shear web stress; stable, post-buckled, with/without cutouts
- Sandwich panel edge band, ramp details
- Bolted joints
- Bonded joints

E.3.4.4 Design value knockdown factors

Statistically based allowables are a subset of the values used for structural analysis, and many empirical (and sometimes analytically) based factors that are applied to obtain the design values used to calculate structural margins. These factors cover the design space for the application. Factors are derived to cover the effects of the following:

- Environment
- Temperature, moisture, exposure time, cycles
- Impact damage
- Geometry (width, hole diameter, edge distance, thickness, etc.)
- Fasteners
    - Type (specific pin, collar, washers, head style)
    - Diameter
    - Hole tolerance
    - Installation torque/clamp-up

Design value factors are not normally calculated using statistical based value methods and are not based on datasets as large as those used to obtain allowable values. Factors are usually derived as ratios of average test data versus a baseline average value. This is acceptable since a factor is applied to an allowable or a design value derived from an allowable.

E.3.5 Design criteria and objectives

The need for design criteria has emerged from several different sources. Each major aircraft manufacturer produces “Design Requirements and Objectives” (DR&O) or “Structural Design

Criteria" for each new aircraft model. These DR&Os are derived from regulations, loads, environmental conditions, damage threats, service requirements, flight-test data, previous design and service experience, and manufacturing quality. In the case of at least one major aircraft manufacturer, their requirements are more conservative than the requirements of the country-of-origin regulatory agency. This is due to service experience, in-house engineering experience, and flight test experiments. In the case of composite structural applications, service experience basis is not nearly as extensive as that for metallic structures and a degree of conservatism is appropriate.

A DR&O for a proposed composite structural application will contain criteria to address issues unique to structures manufactured with composite materials. Two of these issues are damage threats and manufacturing quality. Damage threats are much more of an issue for composite structures because of impact damage, and the fact that the OEM is the material manufacturer means that manufacturing reliability and repeatability are issues. Design criteria have a large impact on the developmental and certification test programs. Documenting and agreeing on design criteria early in a program is important.

A DR&O guides and demonstrates a disciplined process for design, material and material processing selection, analysis, linkage to fabrication processes, and repair design and processes. It also documents damage threat assessments and demonstrates an understanding of the regulation compliance approach. Design criteria for composite structure should encompass durability, static strength, damage tolerance, and repair substantiations. These criteria are no different from those for metallic structure. There are, however, differences in the approach to compliance with some of these criteria.

The following is a list of design criteria that are appropriate for composite structures:

- Materials, processes, specifications
- Design practices
- Structural configurations
- Laminate stacking sequences and manufacturing limitations
- Environments
- Handling (robustness)
- Stiffness and stability
- Strength

- Bolted joints
- Bonded joints
- Durability
- Damage tolerance
- Repair

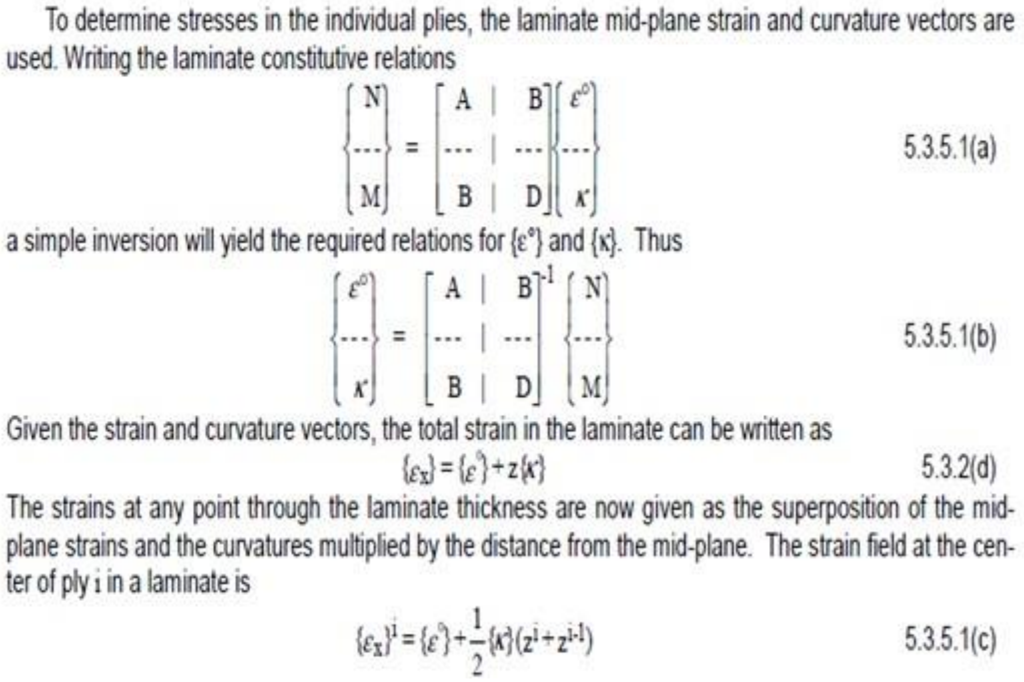
While many of these criteria are similar to those appropriate for metallic structure, some are approached differently. As an example, environment considerations for metallic structures focus on temperature, moisture, and ground-air-ground cycling, but the environmental issues of operating fluids, UV, airstream erosion, hail, and lightning strike affect the mechanical properties of metallic structures less when compared to composites.

E.3.6 Sizing checks for composite structures

E.3.6.1 Laminate stress analysis

The physical properties defined earlier enable any laminate to be represented by an equivalent homogeneous anisotropic plate or shell element for structural analysis. The results of this analysis include the definition of stress resultants, bending moments, temperature, and moisture content at any point on the surface that defines the plate. With this definition of the local values of state variables, a laminate analysis can be performed to determine the state of stress in each lamina to assess margins for each critical design condition.

E.3.6.2 Stresses due to mechanical loads



To determine stresses in the individual plies, the laminate mid-plane strain and curvature vectors are used. Writing the laminate constitutive relations

$$\begin{Bmatrix} N \\ --- \\ M \end{Bmatrix} = \begin{bmatrix} A & | & B \\ --- & | & --- \\ B & | & D \end{bmatrix} \begin{Bmatrix} \varepsilon^{o} \\ --- \\ \kappa \end{Bmatrix} \qquad 5.3.5.1(a)$$

a simple inversion will yield the required relations for $\{\varepsilon^{o}\}$ and $\{\kappa\}$. Thus

$$\begin{Bmatrix} \varepsilon^{o} \\ --- \\ \kappa \end{Bmatrix} = \begin{bmatrix} A & | & B \\ --- & | & --- \\ B & | & D \end{bmatrix}^{-1} \begin{Bmatrix} N \\ --- \\ M \end{Bmatrix} \qquad 5.3.5.1(b)$$

Given the strain and curvature vectors, the total strain in the laminate can be written as

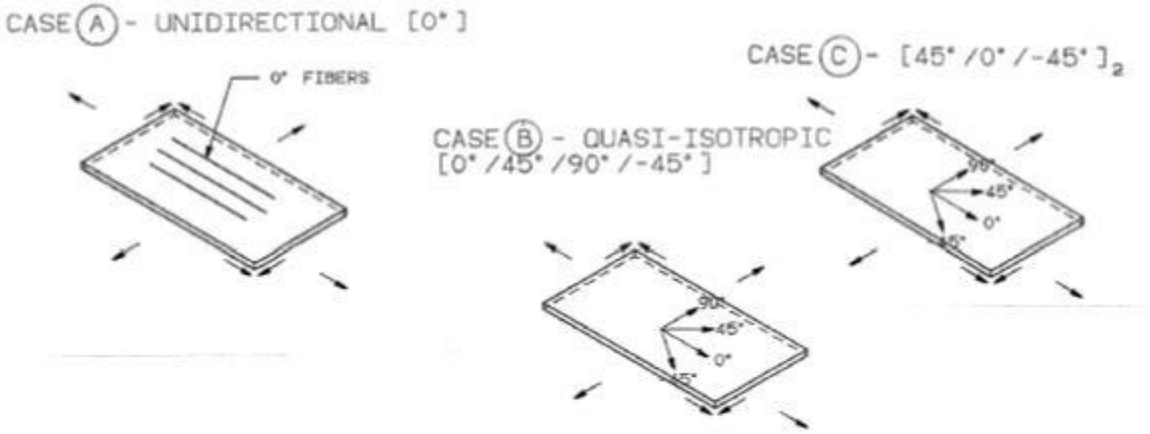
$$\{\varepsilon_x\} = \{\varepsilon^{o}\} + z\{\kappa\} \qquad 5.3.2(d)$$

The strains at any point through the laminate thickness are now given as the superposition of the mid-plane strains and the curvatures multiplied by the distance from the mid-plane. The strain field at the center of ply i in a laminate is

$$\{\varepsilon_x\}^{i} = \{\varepsilon^{o}\} + \frac{1}{2}\{\kappa\}(z^{i} + z^{i-1}) \qquad 5.3.5.1(c)$$

Figure E37. Analysis of stress due to mechanical loads

The effect of ply angle orientation on the strength and stiffness of a carbon composite laminate is shown in Figure E38.



	$F_{X\,tu}$ (KSI)	E_X (MSI)	Fy_{tu} (KSI)	E_y (MSI)	$F_{XY\,su}$ (KSI)	G_{XY} (MSI)
CASE A	160	18.4	8.9	1.35	10	.75
CASE B	61	7.1	61	7.1	30	2.0
CASE C	94	10.7	40	3.1	40	2.7

Figure E38. Effect of ply-angle orientation on strength and stiffness

The diagrams below illustrate how a laminate reacts to in-plane loads. In the diagram (A), axial load on the laminate produces similar strains in each laminate ply but due to the differing ply moduli, different stresses. Similarly, in diagram (B) bending load produces differing stresses based on each ply’s stiffness.

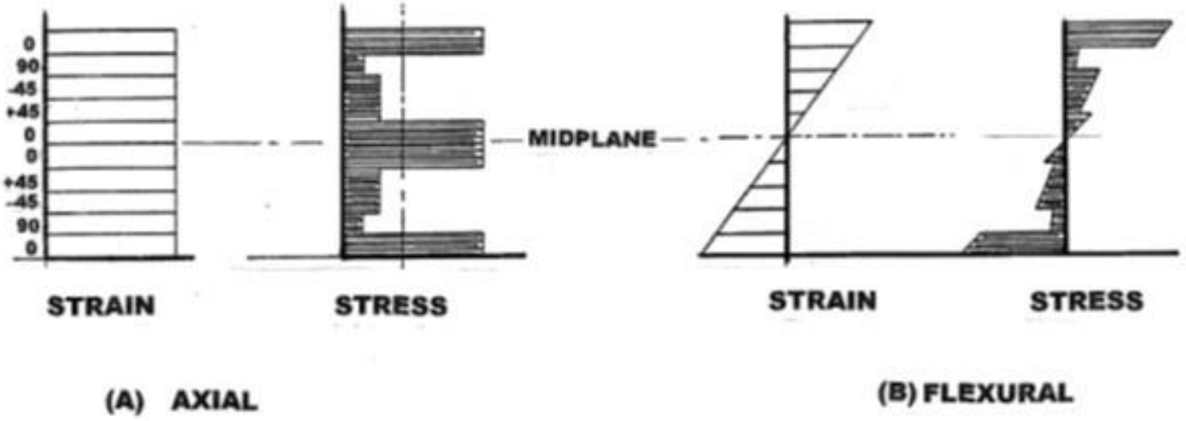


Figure E39. Laminate reaction to in-plane loads

E.3.7 Manufacturing-design interface

Part geometry, ply orientation, and stacking sequence are affected by the fabrication process.

In thick laminates, two competing objectives are:

- Minimizing process-induced residual stresses
- Maximizing production rates by reducing processing time required to achieve complete cure

Fast cure cycle times, involving steep heating and cooling rates, will generally lead to high process induced residual stresses.

Material properties are affected by fabrication processes and potential defects. Processing defects include:

- Porosity (micro-voids)
- Macro voids
- Delaminations
- Disbonds
- Fiber waviness
- Ply orientation (mis-laid plies)
- Inclusions
- Resin pockets
- Dry fibers

The strength and stiffness of a part can be significantly reduced by flaws induced by processing. For example, compression and shear strengths and stiffness can be affected by delaminations, disbonds, fiber waviness and dry fibers, and all strengths and stiffnesses can be affected by mis-laid plies.

Fabrication methods often dictate design guidelines to be used in practice to avoid surprises and to generate robust designs.

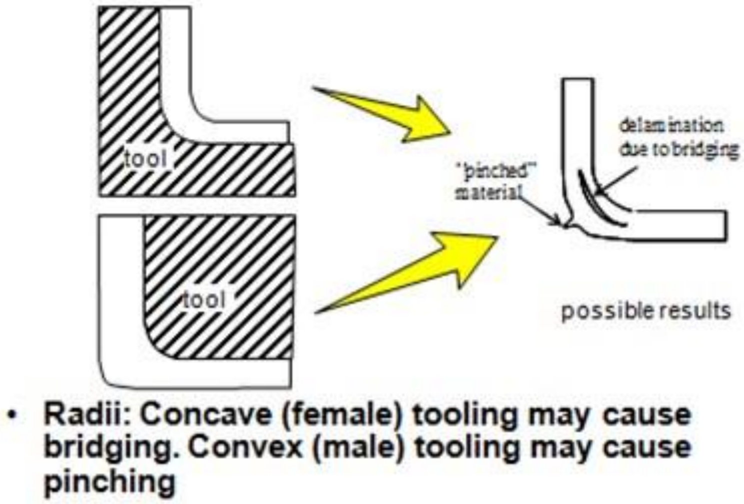
The effects of ply angle orientation must be considered. Unsymmetrical and/or unbalanced laminates can warp after the laminate has cured and cooled down. After cool-down, an unsymmetrical laminate is flat, but loading can cause coupling between extension, shear, bending, and twisting, resulting in a warped panel under loading. After loading, the laminate will return to its former flat shape. This can have serious implications in bonded and bolted assemblies and cause secondary loadings and delaminations, which may grow over time.

Some layup stacking sequence related rules that are designed to minimize micro-cracking, the effects of secondary loads, and improve laminate performance are:

- Minimize effect of micro-cracking: No more than 4 unidirectional plies of the same orientation next to each other in a layup. Micro-cracks can lead to delaminations under static and (especially) fatigue loads
- 10% rule: At least 10% of the fibers must be oriented in any of the principal directions 0, +45, -45, and 90 to protect against secondary loading cases
- Bending stiffness improvement can be obtained by placing 0-degree plies away from the mid-plane (e.g., increase column buckling load)
- Panel buckling, and crippling improvements can be made by placing 45/-45-degree plies away from mid-plane
- Place +45/-45 (or even better (±45) fabric) plies on the outside of a laminate for improved damage tolerance (i.e., loading carrying O and 90 plies are less likely to be damaged)
- Use laminates of “quasi-isotropic” (i.e., 50% of +45/-45 plies with 25% 0 plies and 25% 90 plies) layup to improve bearing strength in fastened joints
- In laminates where the thickness or ply stack must be changed, drop plies as close to mid-plane as possible to avoid ply separation issues, erosion, and damage effects
- Dropped plies should not be grouped together to minimize stress concentrations.

The selection of tooling is an important factor in reliable and repeatable fabrication of composite parts. Part configuration can have a significant effect on tooling complexity and cost. Size, shape, aerodynamic smoothness, and mating requirements for co-bonding or bonding surfaces are important considerations for tooling, and conversely tooling type (male, female, or closed). Flaws and induced thermal stresses due to thermal mismatch can affect part integrity.

Figure E40 shows the potential effects of tooling type on stiffening elements.



- **Radii: Concave (female) tooling may cause bridging. Convex (male) tooling may cause pinching**

Figure E40. Potential effects of tooling on stiffening elements

Thermal expansion during cure can be a significant factor in composite part fabrications. The CTE of composite laminates varies with fiber type, fiber orientation and resin type. The tool must be reasonably compatible with the parts being cured. Composite tools can be close in CTE with composite parts being processed and will result in lower residual thermal stresses in parts and tooling. Tools fabricated from steel will be more durable but may result in residual stresses, which may complicate secondary loadings. Some fabricators choose Invar steel tools due to Invar's closer CTE match with most composite parts, although this material is very expensive but is chosen for durability and ability to produce repeatable and reliable composite parts.

E.3.8 Composite joining practices

Joints represent one of the greatest challenges in the design of aircraft structures in composite aircraft structures by interrupting the geometry of the structure and create material discontinuities, which usually produce local highly stressed areas. Stress concentrations in mechanically fastened joints are particularly severe because the load transfer between elements of the joint take place over a fraction of the available area. In principle, adhesive joints are structurally more efficient than mechanically fastened joints because they provide better opportunities for eliminating stress concentrations and the reducing stress peaks due to the ductile response of the adhesive. Mechanically fastened joints use the available material inefficiently, and sizeable regions exist where the material near the fastener is nearly unloaded. This phenomenon must be compensated for by regions of high stress to achieve a required average load. Certain types of adhesive joints, scarf joints between components of similar stiffness, can achieve a nearly uniform stress state throughout the region of the joint.

E.3.8.1 Adhesively bonded joints

Adhesive joints are capable of high structural efficiency and constitute a resource for structural weight saving because of the potential for elimination of stress concentrations that cannot be achieved with mechanically fastened joints. Unfortunately, due to a lack of reliable inspection methods and a requirement for close dimensional tolerances in fabrication, aircraft designers avoid bonded construction in primary structure. However, exceptions include bonded step lap joints used in attachments for the F-14 and F-15 horizontal stabilizers and the F-18 wing root fitting, and a majority of the airframe components of the Lear Fan, the Beech Starship, Cirrus and Cessna aircraft, and helicopter rotor blades.

Polymer matrix composite adherends are much more affected by interlaminar shear stresses than metals, so there is a significant need to account for those effects in stress analyses of adhesively bonded composites. Transverse shear deformations of the adherends have an effect analogous to thickening of the bond layer and result in a lowering of both shear and peel stress peaks. In addition, because resins used for adherend matrices tend to be less ductile than typical adhesives and are also weakened by stress concentrations due to the presence of the fibers, the limiting element in the joint may be the interlaminar shear and transverse tensile strengths of the adherends rather than the adhesive strength. The effect of the stacking sequence of the laminates making up the adherends in composite joints is significant. For example, 900 layers of unidirectional material such as tape placed adjacent to the bond layer theoretically act largely as additional thicknesses of bond material, leading to lower peak stresses, while 00 layers next to the bond layer give stiffer adherend response with higher stress peaks. In practice, it has been observed that 900 layers next to the bond layer tend to seriously weaken the joint because of transverse cracking which develops in those layers, and an advantage cannot be taken of the reduced peak stresses.

In contrast with metal adherends, composite adherends are subject to moisture diffusion effects. As a result, moisture is more likely to be found over wide regions of the adhesive layer as opposed to confinement near the exposed edges of the joint, as in the case of metal adherends. The response of the adhesive to moisture may be an even more significant issue for composite joints than for joints between metallic adherends.

Stiffeners to Skin Bonded Joints

Adhesive bonding may also be used to attach various shapes of stiffeners onto flat or gently curved sheet material to produce stiff, strong structures. A problem with bonding stiffeners to skins is that to avoid eccentric loading, stiffeners require either two flanges bonded to the skin as shown in the closed hat stiffener in the illustration below or a centrally located flange or flanges. The two stiffeners shown with skin flanges offset from the shear web are not typically used in aircraft structures unless they are mechanically fastened to the skin. Even with centrally located or two skin flanges, skin-stiffener separation can occur due to peel stresses. These stresses can occur as skins are allowed to buckle or as stiffeners deflect under load.

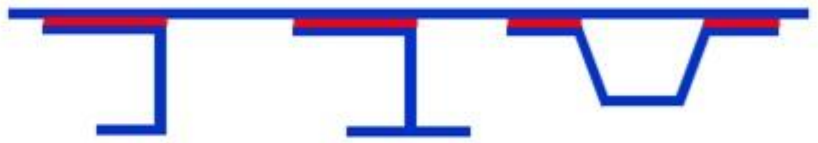


Figure E41. Stiffeners to skin-bonded joints

Sandwich Panel Bonds

Sandwich panel technology is highly dependent on adhesive bonding. An adhesive layer bonds the face sheet to the core and adhesive bonds the edge members to the face sheets. Core splices and core-to-edge member bonds are performed using expanding foam adhesives that fill the gaps in the core. Likewise, honeycomb core uses adhesive bonding to connect the cell walls at the honeycomb intersecting nodes. Bonds in sandwich panels are illustrated in Figure E42.

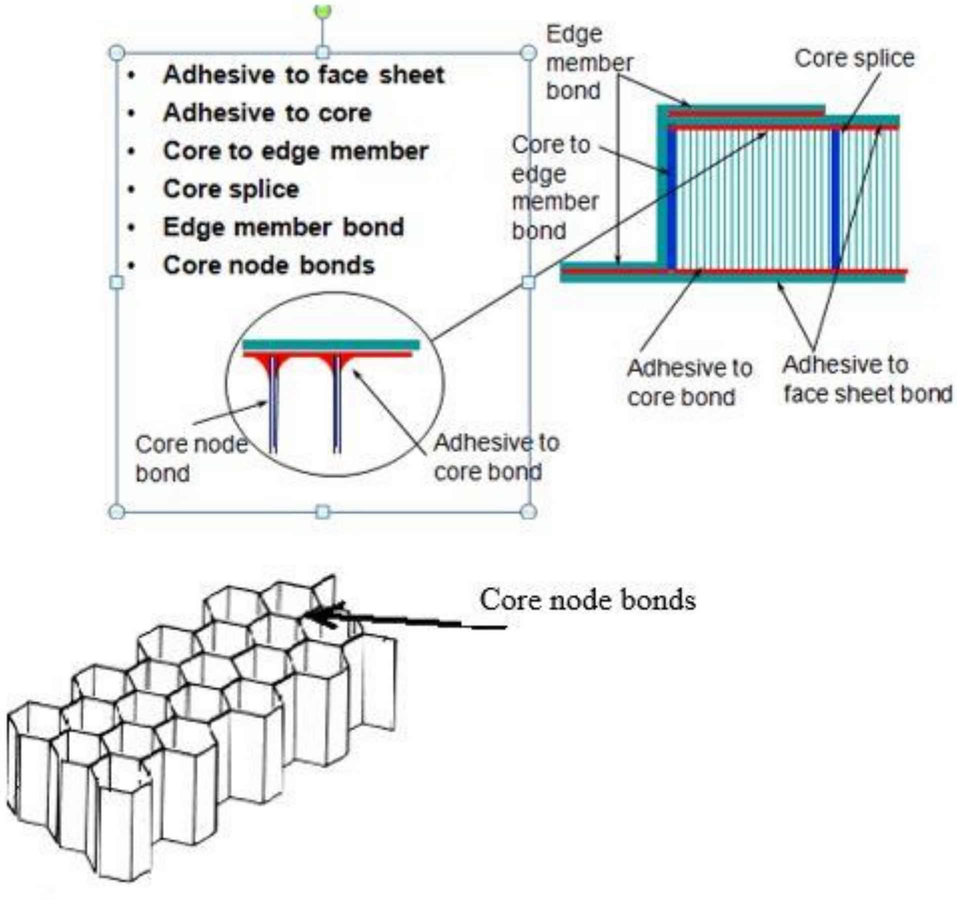


Figure E42. Sandwich panel bonds

Repair Bonds

Most bonded repairs of damaged composite structural components utilize the single lap or scarf joints. The single-lap joint is prone to peel stresses and is only used for lightly loaded parts. The scarf is used for more highly loaded structure and where aerodynamic smoothness is required. The double lap is often difficult to achieve due to the need to access both sides of the damaged part, and obviously cannot be used for repair of sandwich face sheets. The step joint is mainly used for thin laminates, such as 2-3 ply face sheets on sandwich structure, because of the difficulty with thicker parts of matching the steps of the repair plies with those of the base part.

E.3.8.2 Mechanically fastened joints

In many cases, mechanically fastened joints cannot be avoided because of criticality, such as the presence of high load transfer between critical components, requirements for disassembly of joints, replacement of damaged structure, or the need to have access to underlying structure. Adhesive joints tend to lack structural redundancy and are highly sensitive to manufacturing deficiencies, and this includes poor bonding technique, poor fit of mating parts, and sensitivity of the adhesive to temperature and environmental effects such as moisture. Assurance of bond quality has been a continuing problem in adhesive joints, and while ultrasonic and X-ray inspection may reveal gaps in the bond, there is no present technique, which can guarantee that a bond that appears to be intact has adequate load transfer capability.

The behavior of composites in bolted joints differs greatly from that of metals. The brittle nature of composites requires more detailed analysis to quantify the level of various stress peaks because stress concentrations control static strength to a greater extent than with metals due to no local yielding. This affects joint design as the edge distances and hole spacing must be increased over those that are common in metal designs. For critical joints, local build-up of the parts is usually required for good bearing strength and a lay-up of 50% ±45plies is generally used for efficient bolted joint design. Low through-the-thickness strength of composite laminates has led to specialized titanium fasteners for composites. These special fasteners feature larger tail footprint areas, which have improved efficiency of composite joints. Two examples of these special fasteners are shown below. Although Figure E43 shows 1300 countersunk heads, most use 1000 head fasteners for flush applications due to poor pull through capability of composite laminates and the fragility of the 1300 heads when installing them.

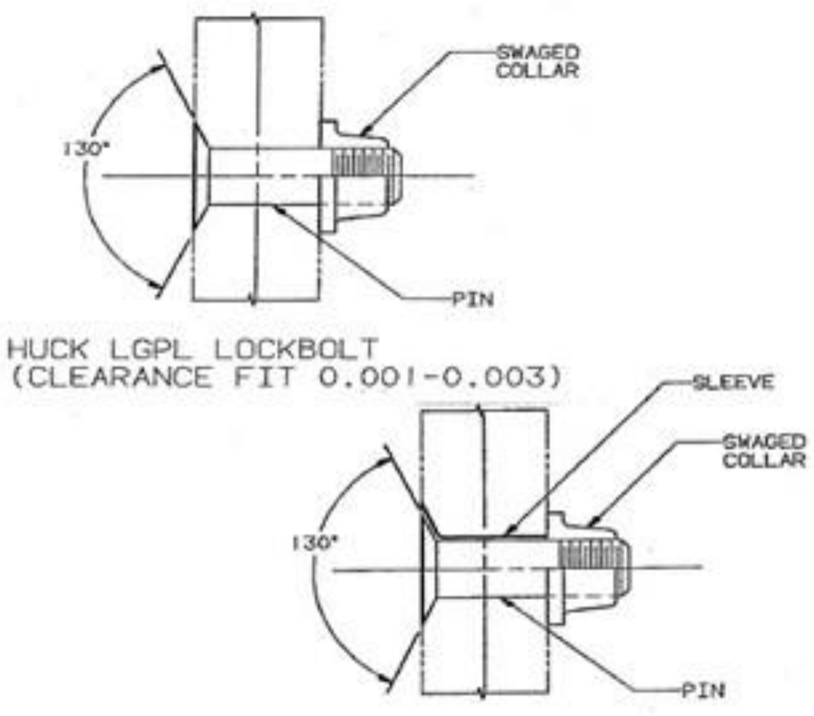


Figure E43. Examples of mechanical fasteners

Understanding the behavior of a composite bolted joint has concentrated on analysis to predict failure of a single bolt joint, supported by test results. This is because the problem of load sharing between bolts in a multi-fastener joint is similar to that of metal joints. Load sharing in mechanically fastened joints is strongly dependent on the number, diameter, and material of the bolts, and the stiffness of joining members. For a single in-line row of bolts, the first and last bolt will be more highly loaded if the plates are of uniform stiffness. This is illustrated in Figure 44. In addition to the equal stiffness members (configuration 2), other combinations of fastener diameters/plate configurations are shown, which can alter the bolt distributions appreciably. Hole/fastener fit is another important issue. Analysis methods rely on all hole/fasteners in a joint being the same close fit. A close fit for fasteners in composite joints is more difficult to achieve compared to metal joints. Typical hole/fastener fit for metal joints ranges from interference fit (driven rivets) to transition or close tolerance fit for bolts. Since composite laminates are prone to damage and delaminations, the hole/fastener fit cannot be close tolerance, and after many tests designers have come to use a hole/fastener fit that is between close tolerance and Class 1. This lack of close hole/fastener fit can make analysis of mechanically fastened composite joints difficult.

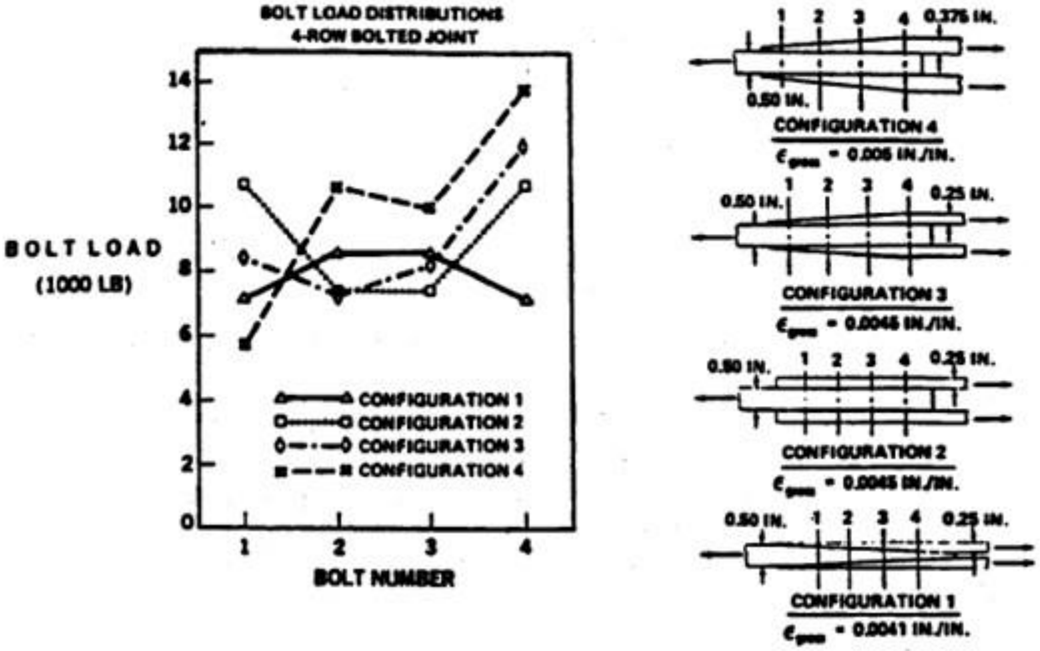


Figure E44. Bolt loads due to various configurations

Once the load sharing analysis has been performed, bolted joint analysis evolves to modeling a single bolt in a composite plate. Several analysis codes have been developed that perform stress analysis and provide useful failure predictions. Analysis must be supported by test, and the design of any bolted composite joint will entail an extensive test program involving various joint configurations, laminates, and bearing/bypass ratios.

Multiple failure modes must be considered. The first is net section failure of the composite. Alternatively, the laminate may fail immediately ahead of the bolt due to bearing pressure or the specimen will fail by pull-through. Depending on fastener spacing, edge distances, or lay-up, shear-out may occur before bearing failure is reached. Finally, failure of the fastener must be considered.

E.3.9 Protection of structure

Composite materials are sensitive to a greater variety of environmental threats compared to metallic materials, which requires different types and levels of protection.

- Relative to metals, polymer matrix composites are more vulnerable to moisture uptake, are sensitive to ultraviolet radiation if unprotected, are susceptible to impact damage, and typically need lightning protection provisions.
- Composite parts do not themselves corrode like aluminum or steel. However, carbon composites must be isolated from aluminum to prevent galvanic corrosion of the metal. Typically, a ply of GFRP fabric is used as an isolator in cases where aluminum fittings are used in conjunction with carbon composite components.
- Composite structure is not electrically conductive. Conductive material must be added for lightning strike protection and other electrical bonding considerations

Based on an assessment of the typical aircraft service environment, composite materials for structural applications should be selected such that they have little sensitivity to aircraft fluids exposure, such as hydraulic oils, Skydrol™, and de-icing fluids. Other characteristics to consider are good impact, abrasion, and erosion damage resistance, good damage visibility characteristics, good resistance to micro-cracking, matrix degradation over range of design environments, and sufficiently high T_g to avoid excessive property reductions at the upper end of design temperatures. There are often trades-off in material selection, so the “best” material will likely vary with the structural application.

Composites are more susceptible to temperature than aircraft quality metals, and part temperature is related to paint reflectance and emissivity. The industry standard maximum operating temperature is 180°F for most commercial aircraft structure, accounting for aerodynamic cooling during taxi and takeoff, and MOT generally does not require a limitation on paint color, although this assumption should be validated with specific thermal analyses, particularly for a thick or unique structure. Selecting a lower max operating temperature to achieve better mechanical properties may require limiting paint colors to lighter shades.

Non-structural surface layers are often used for a variety of reasons. Fiberglass plies prevent galvanic corrosion by providing a barrier between carbon composites and aluminum. Tedlar® film may be applied during layup and left adhered to the inside of the structure for protection, which replaces the need for painting the interior surfaces. Specific wear protection coatings are often required in high abrasion areas for economic reasons. Teflon® coatings for wear surfaces are sometimes used to protect surfaces from abrasion damage, and bonded metal strips to protect from airstream erosion.

Lighting protection schemes are a significant complication for composite design and structural substantiation. They typically require a building block test program for validation, especially with regard to in-service repair/refurbishment of the lightning protection after in-service impact damage or lightning strike events. Different levels of protection are required depending on the location (or strike zone) and underlying systems, such as those related to electrical and fuel. Interwoven wire fabrics, including bronze, copper, aluminum, metal-coated-fiber fabrics such as nickel, and copper. Some of these are often used as outer layers of laminates in addition to metal lightning diverter strips.

The aircraft service environment is harsh, and coatings typically have a finite life. The structural repair manual should address how/when to restore coatings.

E.3.10 Maintenance-design interface

Consideration of supportability issues during the design process can help minimize maintenance costs**.** Since the operating and support cost of an airframe continues to escalate throughout its life, it is important to select and optimize designs that maximize supportability. During early designs involving composites, lost airline revenue and reduced wartime readiness were quite often a result of designs that did not incorporate supportability early in the design process. Long-term durability requirements of parts originally constructed of aluminum were not fully accounted for when these composite parts were originally designed. Current design philosophy includes the concept of life cycle cost, which involves acquisition, operations and support, and disposal costs. Life cycle product cost is an important customer consideration for commercial transport or military aircraft acquisition. Design changes that enhance producibility, improve vehicle availability, and reduce operational and support costs, often outweigh any short-term increases in acquisition costs.

- Inspection methods available to both the manufacturer and the customer are important during the design of composite structural components. Design should minimize the need for NDI and should allow for easy backside/internal visual inspection.
- Most composite structural components include metal fittings or interfaces with metal parts. Metal parts should be visually inspected for corrosion and/or fatigue cracking. All composite components should be designed to ensure visual accessibility of external surfaces**.**
- Designing for maintainability and repair is essential during the development of composite aircraft structures. Supportability is the collection of attributes of a structure that affect the ease or difficulty in providing maintenance or support. Examples of these attributes are ease of inspection, material selection, damage resistance and tolerance, durability, and ease of repair.
- The design team should make large repairs a high priority, considering the damage threats. Effective repairs to weight-optimized structures can be difficult.

Typical design criteria for composite structure should include requirements to address issues that influence maintenance.

- Structural configurations may affect the amount, type, and degree of hidden damage and inspection for these damages. Stiffened skin panels may incorporate bonded stiffeners with difficult-to-inspect features such as webs or fillet noodles of T- or I-section stiffeners that may be cracked or delaminated due to an external impact. Closed hat stringers have two fillets that may be difficult to assess for damage.
- The base material type can affect visibility of impact damage. Toughened epoxies and thermoplastics may show little visible damage, and interior delamination damage and back-side damage may be hidden. However, toughened epoxy and thermoplastic resins exhibit better resist delaminations, so this may not be a serious drawback to the use of these damage-resistant materials. Although co-bonded, co-cured, or even fastened stiffeners substructures may be damaged due to an external impact.
- The base-material fabrication process may be difficult to replicate in a maintenance depot, and repair of structures using the original base toughened material may require additional steps to the bonded repair procedure. As an example, the toughened material system used for the primary structure of the Boeing 787 requires a debulk or compaction cycle for each stack

of 8 or so plies in each thick laminate layup before bagging and cure. This material also needs the additional pressure provided by an autoclave, and many components cannot be removed to accomplish this. In cases like this, non-toughened repair materials are required for vacuum cure, resulting in potential reductions in repair properties such as damage resistance and strength.

- Critical bolted joints must be accessible for inspection and removal of fasteners.

While adhesive joints are in principle, more structurally efficient, mechanically fastened joints often cannot be avoided.

- Requirements must be specified for disassembly of the joint for replacement of damaged structure or to achieve access to underlying structure.
- Adhesive joints tend to lack structural redundancy and are highly sensitive to manufacturing deficiencies, including poor bonding technique, poor fit of mating parts, and sensitivity of the adhesive to temperature and environmental effects such as moisture.
- Bonded joints may create inspection challenges, and those bonded joints that are easily inspected may contain strength reductions that are not easily detected. Currently available NDI techniques are not able to detect “kissing” or weak bonds. It is essential that critical joints such as wing-side of body, empennage terminal joints, and wing spar-to skin joints are inspectable and repairable, and therefore employ mechanical fasteners.

E.4 Proof of structures

E.4.1 Structural reliability

Damage types are categorized from 1 to 5 for increased severity. Structure should be designed such that ultimate load, the highest load expected in service multiplied by a safety factor normally defined by the airworthiness standards, and which can be carried with impact damages that may go visually undetected. For small to larger damage that can be visually detected, structure should carry the maximum fleet design values, or limit load. Aircraft structure shall be designed to support all limit, ultimate load, and life goal requirements as defined in the Design Requirements and Objectives document and the Structural Certification Plan.

The reliability of the structure’s ability to support all limit and ultimate loads and life goals can be substantiated by test, analysis supported by test, or in some cases such as in derivative aircraft programs, by analysis only.

Structural reliability is commonly defined as "the probability of a structure performing its purpose adequately for the period of time intended under the operating conditions encountered." Structural reliability refers to the capability of a structure to operate without failure when put into service, and structural reliability includes events that are safety and non-safety related.

- Probability refers to the likelihood that a structural component will perform as designed. These terms imply acceptance of some degree of uncertainty.
- To determine whether a component has performed adequately, a standard is needed to define what is meant by adequate performance.
- Intended period of time is the mission endurance or lifetime of the structure under consideration.
- Operating and environmental conditions play a large role in reliability of composite materials, particularly polymer matrix composites.

Structural failure and, hence, reliability, is influenced by many factors. In its simplest form, the measure of reliability is made by comparing a component's stress to its strength. The gap between stress and strength, enforced by the factors-of-safety, generally produces adequate although unmeasured reliability. Failure occurs when the stress exceeds the strength. The larger this gap, greater reliability requires heavier structure. Conversely, a smaller gap allows lighter structure.

Factors affecting composite structural reliability are:

- Static strength
- Material variability
- Environmental effects
- Fatigue
- Damage tolerance
- Static strength

E.4.2 Building block test plan

When the material and processing variability of composite structure is greater than the variability of metallic structures, the difference shall be considered in the static strength substantiation by either:

- Deriving proper allowable or design values for use in the analysis and the analysis of the results of supporting tests
- Accounting for the difference in the static test when static proof of structure is accomplished by component test

The static test program is the basis for demonstrating that the airplane has the strength and stiffness necessary to meet the structural load bearing requirements and complies with the required airworthiness standards. The requirements for the static test program for an advanced composite structure are no different from a metallic structure. However, advanced composite materials are different from metallic materials and require that the test program address the unique aspects of structure fabricated from advanced composite material.

- For a metallic structure, which has a normally redundant or fail-safe design, a proof of strength demonstration consists of fabricating the test article from nominal materials and subjects it to ultimate load, the highest load expected in service multiplied by a safety factor normally defined by the airworthiness standards. For the basic airframe, this is performed under normal laboratory ambient conditions, which has been adequate to demonstrate strength throughout the normal airplane environmental design envelope. History and experience have demonstrated that this approach ensures safety for metallic structure.
- This approach is not adequate for a composite aircraft structure program. Recognizing that the metallic airplane has become the standard for an acceptable level of structural reliability, the requirement for an advanced composite airplane is to demonstrate the same level of structural reliability in the static test program as the metal airplane. This means that the significant effects of material variability and environmental effects should be compensated to achieve this.

A typical building-block certification plan is shown in Figure E45 below. The tests increase in complexity and reduce in number towards the apex of the triangle. Environmental effects are developed near the base of the triangle, allowing only room temperature non-conditioned tests to be performed in the sub-components and full-component tests. Data developed at the element and coupon level may be generic for the material and process specifications, and thus applicable to other airframes. It is extremely important that all structural specimens in the building block plan are manufactured using the same mature material and process specifications that are used in production airframe structure. The substantiation of static strength must begin by establishing material properties and design values utilizing the coupon, element, and structural detail data in the lower levels of the building-block test plan. This data also supports the development of semi-empirical methods of analysis, which must be validated by tests higher in the building block test plan.

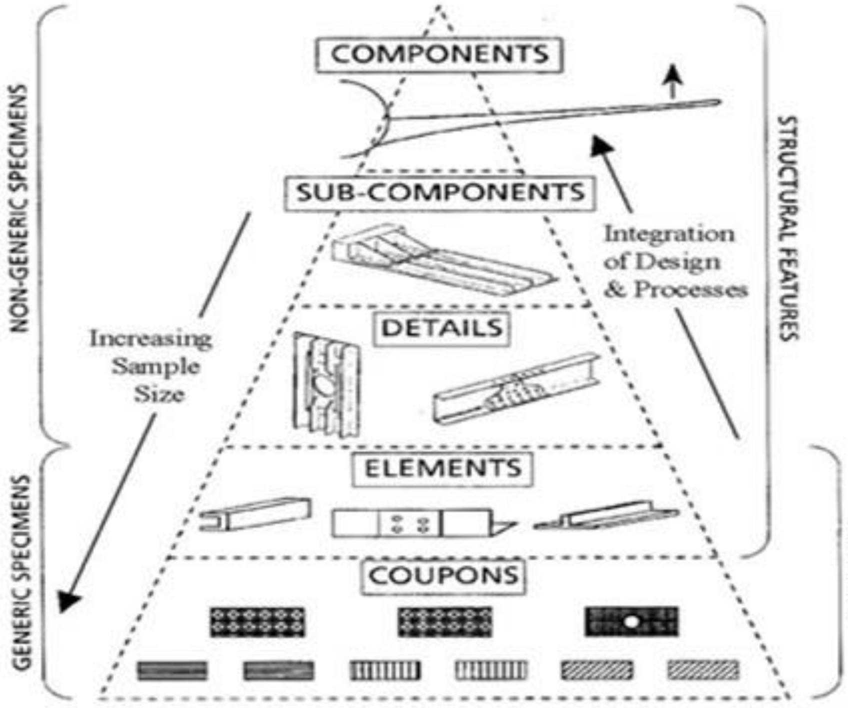


Figure E45. Building block certification illustration

The following is a brief description of the testing and objectives at each level in the building-block test plan:

Coupons: At this level, material properties and design values are developed and the total number of tests can be in the hundreds for smaller, simpler designs or modifications or in the thousands for certification of a large, complex aircraft. These tests also include material and process specification development coupons. These are relatively small uniaxial-loaded coupons, and hence allow the scope for the important study of failure modes, critical environments, and statistical variability. The effect of material and process variability and critical environments upon strength and stiffness properties must be established.

Structural Elements: These are small detail tests such as bolted joints, column stability, and crippling of stiffening sections, frame sections (e.g., radius bends), sandwich structures, structural discontinuities, and skin stiffener pull-off. Point design values can be developed from these tests, and these must include values addressing out-of-plane failure modes. These tests also support the development of semi-empirical analysis methods, with bearing-bypass analysis being a good example. In some cases, multiple replicates are tested to establish a degree of material and process variability. The elements are often representative of many parts of the airframe. Critical environmental effects will also be evaluated at this level.

Structural Details: These are generally much larger structures than in the “element” tests and are representative of only one or limited locations on the airframe. Typical examples are stiffened panels, large cutouts, complex beams, and frames. In many cases, the specimens are subjected to biaxial loading. These tests also verify design methodology, such as cut-out and post-buckled strength analyses. Tests are normally performed at room temperature on non-moisture preconditioned specimens. However, in some cases it may be necessary to develop environmental correction factors for these tests.

Sub-Components: These being one level down from the full component test are large tests. Examples are major joints, such as wing side-of-body joint, vertical stabilizer root attachment, major wing, and empennage torque boxes, etc. These tests must be used to confirm load distribution and deflection predictions. Tests are typically performed at room temperature on non-moisture preconditioned structures. Critical failure modes must be established from these tests and from ultimate load capability demonstrated using the environmental correction factors developed in lower levels, as necessary.

Components: Examples of these are the wing, empennage, and full airframe structure. These tests should validate load distribution predictions up to limit load, confirm deflection predictions, and demonstrate ultimate load capability. Choice of the applied loading conditions is important for ultimate load capability demonstration. It may be necessary to apply several critical loading conditions, due to the differing environmental correction factors of composite failure modes.

E.4.3 Fatigue and damage tolerance

Federal Aviation Regulations (FAR) such as FAR 25.571 require that the airplane structure be designed such that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage will be avoided throughout the life of the airplane.

For metallic airframe structure, compliance with these requirements is supported by a long history of development and use, and many generations of metallic airplanes have been introduced into service and have been retired at the end of their useful life. This has resulted in a large experiential database which has been used as part of the basis for the demonstration of compliance with these requirements.

The metallic airframe experience does not exist for airplanes that have a high content of advanced composite structure. In addition, the response of composite structure to fatigue, defects, and damage is dependent not only on the gross design characteristics of the airframe, such as stringer spacing, frame spacing, and design details, but also on the design of the composite components considering reinforcement and matrix selection, fiber form (tape, fabric), laminate definition, and environment. Thus, for a composite airframe structure, analysis and/or testing will become a significant part of the certification program.

Fatigue and damage tolerance substantiation is demonstrated by test or by analysis supported by test evidence. A new composite airplane program will generally include a full-scale test article, used to demonstrate the fatigue life and damage tolerance capability of the composite structure. Most OEMs developing composite airframes will use just one full-scale test article for substantiating first static strength, followed by damage tolerance with defects and damages, repairs, and ending with fatigue cycling with allowable defects and repairs to demonstrate life goals.

Composite materials exhibit higher fatigue threshold stresses than metals. Once this threshold is exceeded, composites show more scatter in fatigue than metals and might tend toward lower reliability performance if the composite structures were highly stressed. Design criteria, such as damage tolerance, limit the stress levels in composite structures to such low values that fatigue does not generally represent a design constraint, although this is not necessarily true for high-cycle fatigue dynamic system components in rotorcraft.

Damage tolerance is defined as a measure of a structure's ability to sustain a level of damage or presence of a defect, and yet be able to safely perform its operating functions. Damage to composite structures can occur during manufacturing or operational usage. Consequently, the concern with damage tolerance is ultimately with the damaged structure having adequate residual strength and stiffness to continue in service safely until the damage can be detected by scheduled maintenance inspection or malfunction, and either be repaired or until the life limit is reached. The extent of damage and detectability determines the required load level to be sustained. Thus, safety is the primary goal of damage tolerance.

Damage tolerance methodologies are most mature in the military and civil aircraft industry. They were initially developed and used for metallic materials but have more recently been extended and applied to composite structure. The damage tolerance philosophy has been included in regulations since the 1970s and evolved out of the “Safe Life” and “Fail Safe” approaches.

- The safe-life approach ensures adequate fatigue life of a structural member by limiting its allowed operational life. During its application to commercial aircraft in the 1950’s, this approach was found to be uneconomical in achieving acceptable safety, since a combination of material scatter and inadequate fatigue analyses resulted in the premature retirement of healthy components. The approach is still used today in such structures as high-strength steel landing gear. Due to the damage sensitivities and relatively flat fatigue curves of composite materials, a safe-life approach is not considered appropriate.
- The fail-safe approach assumes members will fail but forces the structure to contain multiple load paths by requiring specific load-carrying capability with assumed failures of one or more structural elements. This approach achieved acceptable safety levels more economically and, due to the relative severity of the assumed failures, was generally effective at providing sufficient opportunity for timely detection of structural damage. Its redundant-load-path approach also effectively addressed accidental damage and corrosion. However, the method does not allow for explicit limits on the maximum risk of structural failure, and it does not demonstrate that all partial failures with insufficient residual strength are obvious. Moreover, structural redundancy is not always efficient in addressing fatigue damage, where similar elements under similar loading would be expected to have similar fatigue-induced damage.

In many instances, uncertainties associated with existing damage as well as economic considerations necessitate a reliance on inspection programs to ensure the required structural capability is maintained. The location and/or severity of manufacturing flaws and in-service damage can be difficult to anticipate for a variety of reasons. Complex loading and/or structural configurations result in secondary load paths that are not accurately predicted during the design process. Some manufacturing flaws may not be detectable until the structure is exposed to the service environment. For example, joints with contaminated surfaces during bonding may not be detectable until the weak bond further deteriorates in service.

The numerous variables associated with damage threats such as severity, frequency, and geometry are rarely well defined until service data is collected. Moreover, established engineering tools for predicting damage caused by well-defined damage events often do not exist. Economic issues can include both non-recurring and recurring costs. The large number of external events, combined with the interdependence of structural state, structural response, and external event history, can result in prohibitive non-recurring engineering or test costs associated with explicitly validating structural capability under all anticipated conditions. Moreover, large weight-related recurring costs associated with many applications rule out the use of overly conservative, but simpler approaches.

Damage tolerance is the combining of an inspection plan with knowledge of damage threats, damage growth rates and residual strength. Specifically, damage tolerance is the ability of a structure to sustain design loads in the presence of damage caused by fatigue, corrosion, environment, accidental events, and other sources until such damage is detected through inspections or malfunctions, and then repaired.

The goal in developing an inspection plan is to detect, with an acceptable level of reliability, any damage before it can reduce structural capability below the required level. To accomplish this, inspection techniques and intervals for each location in the structure must be selected with a good understanding of damage threats, how quickly damage will grow, the likelihood of detection, and the damage sizes that will threaten structural safety. To avoid costs associated with excessive repairs, inspection methods should also quantify structural degradation to support accurate residual strength assessments.

Durability considerations are typically combined with damage tolerance to meet economic and functionality objectives. Specifically, durability is the ability of a structural application to retain adequate strength, stiffness, and environmental resistance throughout its life to the extent that any deterioration can be controlled and repaired, if there is a need, by economically acceptable maintenance practices.

- Durability addresses largely economic issues, while damage tolerance focuses on safety concerns. For example, durability often addresses the onset of damage from the operational environment. Under the principles of damage tolerance design, small damages associated with initiation may be difficult to detect, but do not threaten structural integrity.
- All structural applications should be designed to be damage tolerant and durable. In using composite materials, a typical design objective is to meet or exceed the design service and reliability objectives of the same structure made of other materials such as metals, without increasing the maintenance burden. The generally good fatigue resistance and corrosion suppression of composites help meet such objectives. However, the unique characteristics of composite materials also provide some significant challenges in developing a safe, durable structure.

The brittle nature of some polymer resins causes concern about their ability to resist damage and, if damaged, their ability to carry the required loads until the damage is detected. While the primary concerns in metal structure relate to tension crack growth and corrosion, other damages, such as delamination and fiber breakage resulting from impact events and environmental degradation, are more of a concern in polymer matrix composites. In addition, composites have unique damage sensitivities for compression and shear loading, as well as tension.

Damage resistance is a measure of the relationship between parameters that define an event, or envelope of events, such as impacts using a specified impactor and range of impact energies or forces, and the resulting damage size and type. In composite structure, the damage caused by an impact event may be more severe and can be less visible than in metal structure. As a result of the increased threat of an immediate degradation in properties, damage resistance, has been used for composite structures and material evaluation. Damage resistance and damage tolerance differ in that the former quantifies the damage caused by a specific damage event, while the latter addresses the ability of the structure to tolerate a specific damage condition. Damage resistance, like durability, largely addresses economic issues, such as how often a particular component needs repair, while damage tolerance addresses safe operation of a component.

E.4.4 Summary of requirements for composite structures with damage

The following summarize basic requirements for composite aircraft structures with damage:

- Structure containing likely damage or defects that are not detectable during manufacturing inspections and service inspections, must withstand ultimate load and not impair operation of the aircraft for its lifetime
- Structure containing damage that is detectable during maintenance inspections must withstand a once-per-lifetime load, which is applied following repeated service loads occurring during an inspection interval
- Structure damaged from an in-flight, discrete source that is evident to the crew must withstand loads that are consistent with continued safe flight
- All damage that lowers strength below ultimate load must be repaired
- All repairs must withstand ultimate load

E.5 Composite structure maintenance

E.5.1 Maintenance overview

Aircraft in service require maintenance to ensure they continue to perform as intended. For aircraft structure, maintenance is defined as the set of actions needed to ensure its continued airworthiness. An integral part of the damage tolerance approach is to preserving aircraft safety. Aircraft maintenance includes damage during service, damage detection, characterization, disposition, and repair.

Damage types in composite structure differ substantially from those in metallic structure. Accidental impact events can cause considerable damage with little or no visual indication to composite structural components. This has many implications, two of which are particularly important to maintenance.

- Damage that is detected visually often has accompanying non-visible damage. NDI methods such as the tap test, pulse echo, and thermography are required to characterize the extent of the damage more fully.
- Severe unexpected events such as high-energy service-vehicle collisions, flight excursions outside the design envelop can cause substantial damage a) without any visual indication, and/or b) in areas away from the visual indications. Procedures must be in place to ensure that these events are immediately reported, and that proper inspections are carried out to detect and quantify any associated damage prior to further flights.

E.5.2 Maintenance practices

Numerous maintenance-related documents are developed by the OEM to define proper maintenance practices. The **structural repair manual** (**SRM**) **or the aircraft maintenance manual** (**AMM**) defines the limits of acceptable damage as well as repair options and procedures.

Most OEMs issue SRMs/AMMs to operators to efficiently maintain and repair fleet aircraft. An SRM/AMM will contain:

- Allowable damage limits for specific components based on stress analysis of each component during component development.
- Repair material information, including strength and stiffness properties and design values for repair materials based on testing like that performed for the base materials.
- Repair process instructions to ensure an adequate repair result.
- Repair designs based on repair material properties and design values, and the base structure material design values.
- Inspection techniques commonly available to aircraft operators and MROs.

- Inspection requirements for specific component details are typically set down in an inspection manual.

E.5.2.1 Substantiation of repairs

Design of a substantiated repair can be difficult for organizations, other than the OEM, due to the complex nature of composite materials. Duplicating an existing repair from a comparable structure and normally without the aid of drawings, documentation, or computer modelling is known as reverse engineering a repair.

- Reverse engineering, such as those sometimes used to design repairs for metallic structure, are not sufficiently mature for composites to provide the required level of safety.
- Substantial data is necessary to design and substantiate a repair that meets all requirements of the original design. This data includes strength and stiffness properties and design values for the original and repair materials, internal loads, all design requirements, and test data that validate the analysis methods used to ensure integrity of the repair. OEMs are reluctant to divulge this information to outside organizations, due to the proprietary nature of this data and potential litigation that may result from misuse of the data.

Repairs, just as the original structure, must be substantiated by test, or by analysis with supporting test evidence, with the latter approach typically used. Testing includes characterization of the repair materials, characterization of the bolted or bonded attachment strength, and development and validation of overall repair design, comprised of topics in design concept, associated processes, internal loads, structural sizing methods, and repeated load capability.

E.5.2.2 Damage sources and types

Aircraft parts can be damaged on the ground or during flight operations. Damages can be the result of dropped tools, service vehicle impacts, aircraft handling accidents, impacts from maintenance stands, dropped parts, local pressure from being walked on, incorrectly installed removable fasteners, bird strikes, hail, lightning strikes, and debris thrown up during take-off and landing, referred to as foreign object damage (FOD). Damages from the above sources can range from minor to critical to flight safety, and detection before flight loads are imposed on the damaged structures is essential.

Solvents and other fluids can be absorbed by composites causing degradation of mechanical properties. Aircraft parts can be contacted by all manner of different fluids such as grease, fuels, oils, hydraulic fluids, water, cleaning and de-icing fluids, and salt spray. Property reductions due to fluid or moisture absorption into otherwise undamaged composite components are considered during part design, with the result that repair is not usually required when composite structures are subjected to these fluids.

Structural components located near engines or sources of aerodynamic noise are susceptible to sonic fatigue. Examples of composite components that may be subject to sonic fatigue are engine cowl, duct, and strut components, and may include trailing edge panels and flaps. The sonic environment is addressed during the design phase of these components, and since the sonic fatigue performance of any component is dependent on the actual structural configuration, analysis and test programs are performed to validate the designs. If high frequency noise produced by propulsion units and aerodynamic disturbance is higher than design limits, damage such as loosened or broken fasteners, disbonds, delaminations, and through thickness cracking emanating from attachment details may result.

High heat sources can affect composite parts. Some examples of high heat sources are thermal de-icing ducts, typically located in the leading edges of wings, power plants and APUs, hot air feed ducts, air-conditioning units, and hot air duct failures. Composite parts expected to be exposed to high heat sources are designed for these exposures. For example, some aircraft wing fixed leading edge panels are fabricated with sandwich materials cured at 350^0 F because of the presence of the thermal de-icing ducts, while the wing fixed trailing edge panels, in a lower heat environment, are typically fabricated with materials cured at 250^0 F. A composite part heated above its cure temperature compromise mechanical properties such as stiffness and compression, and the epoxy resin may burn which results in exposure of the fibers and cracking that can provide moisture or fluid ingression paths. Apart from obvious burn damage, discoloration of the part finish may indicate high temperature exposure.

Hail, lightning strikes, UV radiation, high intensity radiated fields, rain erosion, moisture ingression, and ground-air-ground cycles (temperature, pressure, and moisture excursions) can cause damage to composite components. Lightning strikes can inflict severe damage to composite components unless protection systems are employed. Composite materials are either not conductive or are significantly less conductive than aluminum.

Damaged composite parts can absorb fluids from surrounding environments. This ingression can result from a loss of protective paints, or impact damage to laminates or the face sheets of sandwich. On occasion, sealant systems break down on sandwich components and unforeseen damage occurs due to moisture or fluid ingression into the core. In the case of aluminum honeycomb core in metal bond parts, the moisture or fluid can lead to corrosion which results in loss of the core material. In non-metallic honeycomb cores of composite sandwich parts such as Nomex™, moisture or fluid can seriously degrade core mechanical properties such as stiffness and shear strength. Paint cracking, caused by temperature excursions can also provide paths for moisture ingression.

E.5.2.3 Damage detection and disposition

Damages or defects are initially detected either by a prescribed inspection plan, by knowledge of anomalous events by operations personnel, or through loss of form, fit, or function. Aircraft inspection plans generally rely on visual inspections for initial detection followed by other techniques for full characterization of the damage.

Structural components are designed to withstand impact damages and retain required ultimate load design load capability within the bounds of performance and cost. Damages outside of these constraints are typically addressed in the aircraft SRM, which provide appropriate repairs. The SRM/AMM will also direct the operator to NDI methods to accurately map the extent of the damage.

- If the damage is represented in the SRM, then an approved repair can be performed, and the aircraft returned to service.
- If the damage is outside the damage limitations described in the SRM, either a DER must design a repair, or the OEM must be contacted for repair disposition.
- Reverse engineering, which is duplicating an existing repair from a comparable structure and normally without the aid of drawings, documentation, or computer modelling is not recommended. Ensuring that a competent repair that will remain intact for the remainder of the aircraft life requires much data and only the OEM or OEM accredited DERs typically have access to that data.

E.5.2.4 Characterizing damage

Since damage in composites often contains subsurface anomalies, nonvisual inspection methods should be employed to determine the type and extent of damage. Numerous techniques are available, each with unique capabilities and limitations. Depending on damage disposition, the damage may be acceptable with non-structural repair, such as sealing, aerodynamic smoothing, or may require structural repair. This determination is typically based on information provided in maintenance documentation such as the SRM.

Visual inspection is the cornerstone of aircraft composite structural maintenance for the initial detection of damage, followed using various inspection techniques to characterize damage more fully. Some of these techniques are briefly discussed below:

- **Tap hammer:** After damage is detected visually in sandwich structure, OEM maintenance documentation will require a definition of the extent of the damage by utilizing the tap hammer or other NDI techniques. Many operator maintenance personnel are very proficient with the tap hammer for detecting the full extent of delamination and disbonds in sandwich components. This technique is inexpensive, with some maintenance personnel using a coin as the tap instrument. The method is impractical for large area inspection and for laminates with greater than four plies, for example. Limitations include operator variation, poorly defined procedures leading to inconsistent practice, and environment, such as attempting to detect damage while surrounded by noisy shop operations, can be factors that can reduce tap hammer proficiency.
- **Pulse echo (PE):** PE is an ultrasonic method for the detection and characterization of defects in composites. Pulses are transmitted and received on the same side of the test panel after being reflected from the opposite face. Defects cause a decrease in the reflection amplitude. Most operators and MROs use PE to characterize damage detected visually on the surface of laminate stiffened structures.
- **X-ray** can be useful for detecting core damage and moisture ingression in sandwich structure, and through-cracks in laminates. This technique can provide an accurate picture of damage if used with a radio opaque penetrant, but the use of the penetrant contaminates the component. This technique, while effective, is cumbersome, expensive, and potentially exposes operators to radiation hazards.
- **Thermography** is a technique used by some operators to inspect for water in sandwich core, and disbonds and delaminations in laminates and sandwich. Passive and active methods are two types of thermographic procedures in use. In both cases, the surface temperature of the structure is monitored using infrared imaging. Variations in the temperature distribution reveal the presence of defects.
- **Bond testers** are often used to detect delaminations and adhesive bond failures in laminates, and face sheet disbonds from core in sandwich. Bond testers measure the change in local impedance produced by a defect when the structure is excited at low frequencies, such as 1 to 10kHz. These instruments are easily portable and relatively inexpensive.

- **Moisture meters** are useful for the detection of moisture in sandwich core. Moisture meters measure the increase in conductivity of the composite due to moisture absorption. This type of meter cannot be used with carbon or any other conductive fiber or in the presence of metal.

Effective use of the above techniques requires specialized and recurrent training to effectively characterize damage.

E.5.2.5 Repair design and quality

When repair is required, repair details and procedures must be determined and approved. The repaired structure must meet all regulatory requirements of the original structure, as well as several repair-specific criteria. Regulatory approval of the repair also requires that sufficient data exist to substantiate the repair performance. Characterization of the repair materials involves determining the stiffness and strength properties, property variability, and the effects of environment. The repair material design values should be generated using approved testing and data reduction methods that reflect the amount of testing completed, material and process controls in place, and the criticality of the structure. Associated testing is typically conducted at the coupon, detail, and sometimes sub-component level.

- The structural performance of repairs is highly dependent on the repair quality. Successful repair of composites requires attention to numerous key details. Procedures should be described in detail for fabrication, assembly, and quality assurance, and must be strictly followed in performing the repair. The SRM/AMM should contain sufficient information to enable the operator or MRO to perform adequate repairs.
- Bolted repairs are similar to those in metallic structure, but composites require higher rotational speeds and lower feed speeds than needed by metals. Differences from metals also include fastener types as well as unique installation procedures. Proper fastener selection and installation are critical to achieving the necessary joint strength and load transfer into the repair patch.

Bonded repair quality depends on material quality, surface preparation, and proper processing. Moreover, since post-repair inspection methods are not adequate to ensure the integrity of a bonded repair, it is important to strictly adhere to all prescribed procedures, including those for material control and in-process quality control. Specific requirements for purchasing, storing, handling, and, for wet layup, mixing materials ensure the material performs as required. Bondline defects are minimized by properly removing contaminants and adequately preparing the bonding surface for chemical adhesion. Detailed processing procedures that consider the unique aspects of the in-service repair environment will ensure the proper consolidation and cure of the repair materials, as well as attaining the necessary bond strength.

E.5.2.6 Maintenance teamwork

Safe maintenance of composite structure depends on a coordinated effort by several disciplines, including ground and flight personnel, inspectors, repair technicians, and engineers. The different steps in damage inspection, disposition, and repair require unique skills. Each member of the maintenance team should have the necessary training and acquired skills for their own roles, as well as an awareness of all areas of composite maintenance and the skills required of other team members. They should understand the limits of their expertise, and who to contact when the situation is beyond those limits. They should recognize that damage beyond that included in approved maintenance documents requires special inspection and repair instructions. Such cases may require other teammates with the necessary skills to determine the full extent of damage and to design and substantiate a repair that meets the airworthiness requirements for a given structure.

Most large airlines and MROs will employ maintenance teams that consist of technicians, inspectors, engineers, and a manager. Smaller aircraft operators may have maintenance technicians perform the duties of both the technician and the inspector, and only a few may employ engineers. In either case, the approved sources of technical data, maintenance and repair instructions, guidelines, and regulatory requirements contain information vital to proper aircraft maintenance and repair. Team members must be familiar with and have access to this information. Familiarity with the specific aircraft structure drawing system and SRM is essential to avoid the selection of inappropriate repair instructions including inspection and repair processes.

While inspectors and technicians may not be fully cognizant with the FARs, ACs, and ADs, it is appropriate that all members of the repair team be aware of regulatory requirements. Regulatory requirements should be understood by at least one person in the repair process. Any lack of understanding, or deviation from the approved data, maintenance and repair instructions, or regulatory requirements can produce a defective repair, and be detrimental to flight safety.

E.6 Other structural design issues

E.6.1 Flutter and aeroelastic instabilities

Airplane structures are not completely rigid, and aeroelastic phenomena arise when structural deformations induce changes on aerodynamic forces. The additional aerodynamic forces cause an increase in the structural deformations, which leads to greater aerodynamic forces in a feedback process. These interactions may become smaller until a condition of equilibrium is reached, or may diverge catastrophically if resonance occurs.

Aeroelasticity is the study of "mutual interaction that takes place within the triangle of the inertial, elastic, and aerodynamic forces acting on structural members exposed to an airstream, and the influence of this study on design". Aeroelasticity is divided into two categories: (1) steady and static, and (2) dynamic aeroelasticity.

1. Steady aeroelasticity is the interaction between aerodynamic and elastic forces on an elastic structure. Mass properties are not significant in the calculations of this type of phenomena. The two situations below are of particular concern for aircraft design/performance.
    - Divergence occurs when a lifting surface deflects under an aerodynamic load so as to increase the applied load or move the load so that the twisting effect on the structure is increased. The increased load deflects the structure further, which brings the structure beyond the design loads to failure.
    - Control surface reversal is the loss, or reversal, of the expected response of a control surface, due to structural deformation of the main lifting surface.
2. Dynamic aeroelasticity is the interaction among aerodynamic, elastic, and inertial forces. Flutter is a dynamic aeroelastic phenomenon and is a major concern of aircraft design/performance.

Flutter is a self-feeding and potentially destructive vibration where aerodynamic forces on a structure couple with the structure's natural mode of vibration to produce rapid periodic motion. Flutter can occur in any structure within a strong fluid flow, under the conditions that positive feedback occurs between the structure's natural vibration and the aerodynamic forces. That is, the vibrational movement of the structure increases an aerodynamic load, which in turn drives the structure to move further. If the energy input by the aerodynamic excitation in a cycle is larger than that dissipated by the damping in the system, the amplitude of vibration will increase, resulting in self-exciting oscillation. The amplitude can thus build up and is only limited when the energy dissipated by aerodynamic and mechanical damping matches the energy input, potentially resulting in large amplitude vibration and leading to rapid failure. Because of this, structures exposed to aerodynamic forces such as wings and other airfoils are designed carefully within known parameters to avoid flutter. In complex structures where both the aerodynamics and the mechanical properties of the structure are not fully understood, flutter can only be assessed through detailed testing. Changing the mass distribution of an aircraft or the stiffness of one component can induce flutter in an apparently unrelated aerodynamic component, possibly developing uncontrollable aircraft performance involving high speed, causing serious damage, or leading to the destruction of the aircraft.

Aeroelasticity involves not only the external aerodynamic loads and the way they change, but also the structural, damping, and mass characteristics of the aircraft. Prediction involves making a mathematical model, which represents the dynamic characteristics of the aircraft structure. The model should also include details of applied aerodynamic forces and how force variance.

For safe design/operation of the aircraft, aeroelastic evaluations are required. These evaluations include flutter, control reversal, divergence, and any undue loss of stability and control because of structural loading and resulting deformation. Flutter and other aeroelastic instabilities must be avoided through design, quality control, maintenance, and systems interaction.

E.6.2 Crashworthiness

As part of the overall aircraft safety requirement, airframe design should minimize the likelihood of fatalities and injuries under realistic and survivable crash impact conditions. Crashworthiness is the measure of the aircraft’s ability to achieve these goals. Five key areas address survivability during an aircraft crash described by the acronym CREEP:

- C – Container – maintain survivable occupant volume
- R – Restraint – provide adequate occupant restraint to limit injuries
- E – Energy absorption – manage the acceleration forces to limit loads transmitted to the occupants
- E – Environment – Remove lethal environment from the cabin environment, including overhead stowage bins and contents
- P – Post crash conditions - ensure that the occupants can egress the aircraft in the event of failed seats and unusable exit doors

Aircraft crash scenarios can be broadly divided into three categories:

1. **Ground-to-ground**, such as overrun and aborted take-off.

2. **Air-to-ground** such as hard landing and undershoot.
3. **Air-to-ground impact** such as ground collision, stall, or undershoot.

While air-to-ground hard landings are the most prevalent, it usually results in the fewest injuries and damage to the aircraft. Conversely, air-to-ground impacts typically result in the most severe injuries, damage to the aircraft, and greatest potential for fatalities. Ground-to-ground overruns have resulted in injuries, fatalities, and loss of aircraft.

Crashworthiness must be addressed at a systems level as it encompasses multiple areas and codependent responses. The following examples highlight areas that influence the crashworthiness of an aircraft: Aircraft seats, seat restraints, floor mounts, floor track strength, fuel tanks, fuel-line mountings, fuel-line location, cargo, cargo container and type, crushable space beneath cabin floor, fuselage stiffness, wing location, engine location, impact surface, and aircraft attitude at time of impact.

The crashworthiness of the aircraft is dominated by the impact response characteristics of the fuselage. Regulations, in general, have evolved based on experience gained through incidents and accidents of existing aircraft, or in anticipation of safety issues raised by new designs. For example, emergency load factors and passenger seat loads have been established to reflect dynamic conditions observed from fleet experience and from FAA and industry research. As a result, the regulations reflect the capabilities of traditional aluminum aircraft structure under survivable crash conditions. This approach was satisfactory, as aircraft have continued to be designed using traditional construction methods and materials. Each aircraft type, including transport, small airplane, and rotorcraft, has unique regulations governing the crashworthiness of aircraft-type structures.

With the advent of composite fuselage structure and/or the use of novel design, this historical approach may no longer be sufficient to substantiate the same level of protection for the passengers as provided by similar metallic designs. The impact response of a composite transport fuselage structure must be evaluated by test or analysis supported by test to ensure comparable levels of safety to that of a similar-sized aircraft fabricated from metallic materials. Impact loads and the resultant structural deformation of the supporting airframe and floor structures must be evaluated.

Physics and mechanics of the crashworthiness for composite structures involve several issues. The local strength, energy-absorbing characteristics, and multiple, competing failure modes need to be addressed for composite structure subjected to a survivable crash. As a result, the accelerations and loads experienced by passengers and equipment on a composite aircraft may differ significantly from that seen on a similar metallic aircraft unless specific considerations are designed into the composite structure.

E.6.3 Fire safety and fuel tank

In-flight fires and post-crash fires are main concerns regarding aircraft fire safety.

E.6.3.1 In-flight fires

Most in-flight fires are associated with engine and auxiliary power unit fires and are designed with required fire detection/suppression systems. In-flight fires that occur within the fuselage can occur in either accessible areas or inaccessible areas. Accessible areas are areas of the fuselage that can be accessed by the crew during flight and a handheld fire extinguisher can be used to extinguish the fire. Inaccessible areas cannot be accessed by the crew during flight. Inaccessible regions, for example, are in the below-floor cargo compartments, behind the cabin sidewall panels, above ceiling panels, below the floor panels and behind the aft pressure bulkhead. Fuselage fires in inaccessible areas pose a major threat to the safety of the passengers and crew, as the fires are difficult to locate or extinguish. Inaccessible areas contain large amounts of non-metallic, potentially combustible materials, including thermal/acoustic insulation, ducting, and electrical wiring. The FAA's approach to minimizing the threat posed by inaccessible area fires is to restrict the fire growth and flame propagation properties of the materials used in these locations.

Lessons learned from significant accidents have historically prompted regulation changes. An example of a significant and catastrophic in-flight fire was that of a Saudi Arabian Airlines L1011 in 1980. The aft cargo compartment smoke alarm sounded 7 minutes after take-off. Smoke and fire extended to the main cabin above the cargo compartment. The airplane returned to the airport and landed safely. Following the landing, and prior to initiation of an evacuation, the occupants were incapacitated by smoke and fire inside the airplane, and all 301 passengers and crew perished in the fire. This accident prompted regulatory changes, which included implementation of a new severe fire test method for cargo liner materials.

Another example of a significant and catastrophic in-flight fire was that of a Swissair MD-11. An in-flight fire ensued in the area above the flight deck ceiling, causing loss or malfunction of numerous airplane systems and instruments. As the fire progressed, electronic navigation equipment and communications radios stopped operating. Twenty minutes later, the airplane plunged into the ocean. This accident prompted a new rule that required specific flammability standards for thermal/acoustic insulation materials typically installed behind interior panels in transport category airplanes.

E.6.3.2 Fuel tanks

Since the beginning of commercial jet aviation, fuel tank explosions have been a threat to aircraft safety. Recent years have seen several fuel tank explosions in commercial aircraft, some with catastrophic results. The highest profile accident was TWA flight 800 in 1996. The flight took off normally when, suddenly during climb, an explosion occurred, breaking apart the aircraft, and causing the aircraft to fall into the ocean with no survivors. The subsequent NTSB investigation determined that the aircraft was broken apart by an explosion in the center wing fuel tank located in the wing box area of the aircraft.

Rules were changed to minimize ignition sources in fuel tanks. A secondary measure was initiated to preclude having a flammable mixture present in the unfilled space above the fuel, referred to as ullage. Utilizing nitrogen was successfully demonstrated as a viable method to accomplish this in transport aircraft. By displacing the flammable mixture with inert nitrogen gas, the fuel tank mixture becomes inert due to the lack of oxygen available for reaction with the fuel vapor. A rule was issued that mandated flammability reduction means for aircraft fuel tanks not meeting flammability requirements for Part 25 transport aircraft.

E.6.3.3 Post-crash fires

The post-crash fire scenarios, addressed by the FAA, are survivable accidents, whereby injuries sustained from trauma will not prevent occupants from evacuating the aircraft. Typical post-crash fire scenarios result from aborted takeoffs, landings, and uncontained engine failures. The fuselage remains largely intact, and passengers are generally unhurt after the incident. Fires in these accident scenarios are due to fuel tank rupture by debris or wing impact with ground or other structures, and ignition sources are usually abundant during the accident. The fuel forms a large pool adjacent to the fuselage and the fire impinges on the outer skin.

The fire-related FAA regulations rely on the assumption that, up to the present time, all commercial transport aircraft and most FAA Certified Part 23 aircraft have been constructed with aluminum alloys as the primary structure and skin. The fire properties of aluminum are well understood; when exposed to heat, the aluminum has excellent thermal conductance and will transfer heat away from the source readily, especially during flight when convective cooling is significant. During a post-crash fire, the aluminum melts in about 1-2 minutes, and for Part 25 aircraft, this assumption has been built into the thermal acoustic insulation burn through rule. This rule mandates that the insulation must withstand the flame for 4 minutes, but this is assumed to be after the skin has melted, giving passengers 5-6 minutes of evacuation time before the fire enters the cabin.

Increasing use of composites has changed the principal material of construction of the aircraft, and the aluminum assumptions may no longer be valid. Each regulation must be reviewed to determine if changing the structure/skin material will also modify the severity of the fire threat. If it is deemed worthy of investigation, experiments are designed to make a final judgment for a regulatory action.

E.6.3.4 Fire safety summary

The FAA objective is to provide through regulations and oversight for the safety of the passengers and crew. Protection from an in-flight fire is achieved by preventing flame propagation in inaccessible areas by mitigating fire growth and propagation by regulating the fire prevention worthiness of inaccessible area materials. The strategy to prevent fuel tank explosions is to reduce the vapor flammability levels of fuel tanks during all phases of flight, either by use of inert nitrogen or by other similarly effective method. Protecting against a postcrash fire requires increasing the time available for passengers to escape, by prolonging both the time it takes to burn through the fuselage cabin skins, and the time to flashover by limiting the cabin materials to those with low heat release rate, smoke emission, and flammability.

E.6.4 Lightning protection

The science of lightning protection design for aircraft began in the early 1930s when the air transport industry was in its infancy, and navigation aids were comparatively primitive. Since early aircraft were not able to fly over adverse weather well, navigation beneath or between areas of precipitation and thunderstorms was common practice, and thunderstorms were not easily identified. These encounters often resulted in accidents due to turbulence, icing, and lightning.

Lightning, like any natural phenomenon, is probabilistic in nature. The probability of a lightning strike to an aircraft depends on various parameters, including local climate, flight profile, and type of aircraft. The average probability of a lightning strike to a given aircraft is one strike between 1,000 and 20,000 flight hours. A lightning strike to an aircraft will be initiated by the presence of the aircraft in a strong electric field and will originate at the aircraft, or will occur because of the encounter with a naturally occurring leader strike that originated elsewhere.

Lightning effects on aircraft may be either direct or indirect.

Direct lightning effects are any physical damage to the aircraft and/or equipment due to the direct attachment of the lightning channel and/or conduction of the current. Damages include

- Dielectric puncture
- Blasting
- Bending, melting, burning and vaporization of aircraft structure or components
- Magnetic pinching
- Shock waves and overpressure
- Explosion of fuel vapors
- Electric shock and flash blindness to personnel
- Residual magnetism
- Directly injected voltages and currents in wiring, plumbing, control cables, and other conductive components

Indirect effects may include electrical transients induced by lightning in electrical/avionic wiring and systems.

Aircraft structure and components may be vulnerable to lightning hazards. Aluminum, an excellent electrical conductor, experiences less damage from lightning compared to composites, with damage restricted to holes burned in the trailing edges, for example. Composite materials are less electrically conductive than aluminum and usually suffer more physical damage due to lightning currents than do structures fabricated from aluminum. Composite fuselages, which are less conductive than metallic structures, allow significant portions of lightning currents to flow into onboard systems such as hydraulic lines, fuel and vent tubes, and electrical wiring. Composite skins sometimes provide less electromagnetic shielding of onboard systems from lightning electromagnetic fields.

For composite aircraft structures, three features of the lightning protection design are required to fulfill regulatory requirements:

1. Lightning protection for structural integrity: The composite structural design should incorporate lightning protection when appropriate for anticipated lightning attachment. Lightning protection features may include, but are not limited to, metal wires or mesh added to the outside surface of the composite structure where direct lightning contact is expected. Proper electrical bonding must be incorporated between structural parts.
2. Lightning protection for fuel systems: The fuel system lightning protection is especially important for an aircraft with integral fuel tanks in a composite structure. Transport airplane

regulations for fuel system ignition prevention require lightning protection that is failure tolerant.

3. Lightning protection for electrical and electronic systems: Lightning strike protection is required for composite structures to avoid inducing high lightning voltages and currents on the wiring for electrical and electronic systems, which could affect safe aircraft operation. Electrical shields over system wiring and robust circuit design of electrical and electronic equipment both provide some protection against system upset or damage due to lightning.

E.6.5 Regulations and guidance: other structural design issues

Regulations are listed in appendix 1 of AC20-107B “Composite Aircraft Structure”.

Guidance can be found in the following documents:

- AC20-107B
- AC20-53 “Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning”
- AC20-135 “Powerplant Installation and Propulsion System Component Fire Protection Test Methods, Standards and Criteria”
- AC20-136 provides certification guidance for aircraft electrical and electronic system lightning protection
- FAA Technical Report “Aircraft Lightning Protection Handbook” (DOT/FAA/CT-89/22)

F Terminology

This appendix lists the terminology utilized in this report and in the composite structural engineering technology (CSET).

Table F1. The CSET Terminology

Terminology	**Definition**
A-Basis	Statistically-based material property; a 95% lower confidence bound on the first percentile of a specified population of measurements. Also, a 95% lower tolerance bound for the upper 99% of a specified population.
ABD matrix	Stiffness matrices of a laminated fiber-reinforced composite: 1. The A matrix is the extensional stiffness matrix, relating extensional loads to extensional strains. 2. The B matrix is the coupling stiffness matrix that relates how much coupling there is between extensional loads and flexural strains (and vice versa). 3. The D matrix is the flexural stiffness matrix that relates flexural loads to flexural strains.
A-Stage	Early stage in the reaction of thermosetting resins in which the material is still soluble in certain liquids and may be liquid or capable of becoming liquid upon heating
Adherend	The surface that adheres to another by adhesion.
Absorption	Process in which one material (the absorbent) takes in or absorbs another (the absorbate)
Adhesion	State in which two surfaces are held together at an interface by forces, interlocking action, or both.
Adhesive	Substance capable of holding two materials together by surface attachment. In this course, the term is used specifically to designate structural adhesives, those which produce attachments capable of transmitting significant structural loads.
Aging	Effect, on materials, of exposure to an environment for a period; the process of exposing materials to an environment for an interval of time.
Ambient	Surrounding environmental conditions such as pressure or temperature.
Angle ply	Same as Cross ply
Anisotropic	Not isotropic; having mechanical and/or physical properties which vary with direction relative to natural reference axes inherent in the material.
Anisotropic laminate	Difference of the properties along the directions parallel to the length or width of the lamination planes and perpendicular to the lamination.
Aramid	Manufactured fiber in which the fiber-forming substance consisting of a long-chain synthetic aromatic polyamide in which at least 85% of the amide

Terminology	**Definition**
	(-CONH-) linkages are attached directly to two aromatic rings. Used primarily as a high-strength, high modulus fiber. Kevlar™ and Nomex™ are examples of aramids.
Areal weight of fiber	Weight of fiber per unit area of prepreg. This is often expressed as grams per square meter.
Autoclave	Closed vessel for producing an environment of fluid pressure, with or without heat, to an enclosed object which is undergoing a chemical reaction or other operation.
ADL	Allowable damage limit. This is typically the limit of damage, presented in structural repair manuals, that can be present in a specific composite structural component or specific area of a specific component, and is still capable of carrying regulatory loads (e.g., Ultimate Load) without failure.
APU	Auxiliary power unit. This provides power for air conditioning other ancillary devices when engines are not running and is usually located in the fuselage of commercial airplanes (in the belly or tail sections).
Advanced Technology Composite Aircraft Structure (ATCAS)	Research program performed by Boeing and funded by NASA to investigate the application of composite materials to pressurized commercial aircraft fuselage structure
B-basis	Statistically-based material property; a 95% lower confidence bound on the tenth percentile of a specified population of measurements. Also, a 95% lower tolerance bound for the upper 90% of a specified population.
B-stage	Intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells when in contact with certain liquids but does not entirely fuse or dissolve. Materials are usually precured to this stage to facilitate handling and processing prior to final cure.
Balanced laminate	Composite laminate in which all identical laminae at angles other than 0 degrees and 90 degrees occur only in ± pairs (not necessarily adjacent).
Batch	For fibers and resins, quantity of material formed during the same process and having identical characteristics throughout. For prepregs, laminae, and laminates, material made from one batch of fiber and one batch of resin (sometimes referred to as a Lot).
Bilinear	Of or referring to two lines.
Bismaleimide (BMI)	Class of polymer thermosetting resin which has better resistance to high temperatures than do epoxy and polyester resins.
Bleeder cloth	Nonstructural layer of material used in the manufacture of composite parts to allow the escape of excess gas and resin during cure. The bleeder cloth is removed after the curing process and is not part of the final composite.

Terminology	**Definition**
Bond	Adhesion of one surface to another, with or without the use of an adhesive as a bonding agent.
Bonded repair size limit (BRSL)	Maximum size of damage that can be repaired in a specific structural component or specific area of a specific component.
Boron	Very high strength and high stiffness fiber produced by vapor deposition of elemental boron, usually onto a tungsten filament core, to impart strength and stiffness. Boron filaments are quite large in diameter compared to carbon or glass filaments. This, together with high stiffness, makes them difficult to twist into yarn or fabric.
Braid	System of three or more yarns which are interwoven in such a way that no two yarns are twisted around each other.
Braid, biaxial	Braided fabric with two-yarn systems, one running in the +θ direction, the other in the -θ direction as measured from the axis of braiding.
Braid, triaxial	Biaxial braided fabric with laid in yarns running in the axis of braiding.
Braiding	Textile process where two or more strands, yarns or tapes are intertwined in the bias direction to form an integrated structure.
Buckling	Mode of structural response characterized by an out-of-plane material deflection due to compressive action on the structural element involved. In advanced composites, buckling may take the form not only of conventional general instability and local instability but also micro-instability of individual fibers.
Barely visible impact damage (BVID)	Barely visible impact damage. This is impact damage which is on the threshold of being visible by the naked eye in good lighting conditions.
Bolted joint stress field model (BJSFM)	Bolted Joint Stress Field Model. The BJSFM program operates by computing the stress/strain field using Lekhnitskii's classical solution of holes through laminated plates (Lekhnitskii, S.G. "Anisotropic Plates", Gordon and Breach Science Publishers, 1968). This approach considers the angle of the bolt loading, biaxial and shear loads, and the effect of biaxial far field bypass loading.
C-Stage	Final stage of the curing reaction of a thermosetting resin in which the material has become practically infusible and insoluble.
CAI	Compression after impact (strength)
Carbon fibers	Fibers produced by the pyrolysis of organic precursor fibers such as rayon, polyacrylonitrile (PAN), and pitch in an inert atmosphere. The term is often used interchangeably with "graphite"; however, carbon fibers and graphite fibers differ in the temperature at which the fibers are made and heat-treated, and the amount of carbon produced. Carbon fibers typically are carbonized at about 2400°F (1300°C) and assay at 93 to 95% carbon, while

Terminology	Definition
	graphite fibers are graphitized at 3450° to 5450°F (1900° to 3000°C) and assay at more than 99% elemental carbon.
Catalyst	Substance that changes the rate of a chemical reaction without itself undergoing permanent change in composition or becoming a part of the molecular structure of the product. It is a substance that markedly speeds up the cure of a compound when added in minor quantity, as compared to the amounts of primary reactants. See also accelerator, curing agent, hardener, inhibitor, and promoter. See ASTM D 907 and ISO 472.
Cauls or caul plates	Smooth tooling plates (often metal), free of surface defects, the same size and shape as a composite lay-up, used immediately in contact with the lay-up during the curing process to transmit normal pressure and to provide a smooth surface on the finished laminate.
Chopped mat	Mat formed of strands or fibers cut to a short length, randomly distributed, without intentional orientation, and held together by a binder. It is the system for each of the constituents which have been separated.
Close reamed	Close tolerance hole where a reamer is used for the final hole size after initial hole drilling.
Close-tolerance	Hole diameter or shank diameter for typical holes and bolts used in critical bolted aircraft structural joints.
Cloth	See fabric.
Co-bonding	Act of bonding one or more cured composite pieces (e.g., stiffeners or stringers) to an uncured composite piece (e.g., a skin) during the same cure cycle (see co-curing and secondary bonding).
Co-curing	Act of curing a composite laminate and simultaneously bonding it to some other uncured composite piece (e.g., stiffener or stringer) during the same cure cycle (see co-bonding and secondary bonding).
Coefficient of linear thermal expansion (CTE)	Change in length per unit length resulting from a one-degree rise in temperature.
Coefficient of variation (CV)	Ratio of the population (or sample) standard deviation to the population (or sample) mean.
Composite material	Composites are combinations of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.
Constituent	Element of a larger grouping. In advanced composites, the principal constituents are the fibers and the matrix.
Continuous filament	Yarn or strand in which the individual filaments are substantially the same length as the strand.

Terminology	**Definition**
Code node	Adhesively bonded junction of honeycomb core cells.
Crazing	Apparent fine cracks at or under the surface of an organic matrix.
Creep	Time dependent part of strain resulting from an applied stress.
Creep, rate of	Slope of the creep-time curve at a given time.
Crimp	Undulations induced into a braided fabric via the braiding process.
Cross ply	Any filamentary laminate which is not uniaxial. Same as Angle ply. In some references, the term cross ply is used to designate only those laminates in which the laminae are at right angles to one another, while the term angle ply is used for all others. In the course, the two terms are used synonymously. The reservation of a separate terminology for only one of several basic orientations is unwarranted because a laminate orientation code is used.
Cure	Changes the properties of a thermosetting resin irreversibly by a chemical reaction (i.e., condensation, ring closure, or addition). Cure may be accomplished by the addition of curing (cross-linking) agents, with or without catalyst, and with or without heat. Cure may occur also by addition, such as occurs with anhydride cures for epoxy resin systems.
Cure cycle	Schedule of time periods at specified conditions to which a reacting thermosetting material is subjected to reach a specified property level.
Cure stress	Residual internal stress produced during the curing cycle of composite structures. Normally, these stresses originate when different components of a lay-up have different thermal coefficients of expansion.
Damage tolerance	1. Design measure of crack growth rate. Cracks in damage tolerant designed structures are not permitted to grow to critical size during expected service life. 2. Ability of a structure to withstand damage, as by impact, and still perform acceptably.
Debond	Deliberate separation of a bonded joint or interface, usually for repair or rework purposes. (See Disbond, Unbond).
Double debulk	Double vacuum debulk (DVD). Air and volatiles are normally removed from composite laminates by applying vacuum and pressure at an elevated temperature. Removing gasses from higher ply count laminates and laminates made from materials using a toughened resin, however, may be inadequate. The double vacuum system facilitates the escape of volatiles by removing pressure on the laminate during debulking. This greatly reduces the risk of porosity, improves fiber compaction, and ensures the level of strength required for thick structural laminates and repair patches.
Deformation	Change in shape of a specimen caused by the application of a load or force.
Degradation	Detrimental change in chemical structure, physical properties, or appearance.

Terminology	**Definition**
Delamination	Separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes.
Density	Mass per unit volume.
Deviation	Variation from a specified dimension or requirement, usually defining the upper and lower limits.
Disbond	Area within a bonded interface between two adherends in which an adhesion failure or separation has occurred. It may occur at any time during the life of the structure and may arise from a wide variety of causes. Also, colloquially, an area of separation between two laminae in a finished laminate, normally referred to as "delamination". (Other terms utilized are Debond, Unbond, Delamination).
Distribution	Formula which gives the probability that a value will fall within prescribed limits. (See Normal, Weibull, and Lognormal Distributions).
Dry	Material condition of moisture equilibrium with a surrounding environment at 5% or lower relative humidity.
Dry fiber area	Area of fiber not totally encapsulated by resin.
Ductility	Ability of a material to deform plastically before fracturing.
Elasticity	Property of a material which allows it to recover its original size and shape immediately after removal of the force causing deformation.
Electron-beam (E-beam) curing	Curing process employing electron beam energy.
Elongation	Increase in gage length or extension of a specimen during a tension test, usually expressed as a percentage of the original gage length.
Epoxy resin	Resins which may be of widely different structures but are characterized by the presence of the epoxy group. (The epoxy or epoxide group is usually present as glycidyl ether, glycidyl amine, or as part of an aliphatic ring system. The aromatic type of epoxy resins are normally used in composites).
Extension modulus	See Young’s modulus.
Fabric, woven	Generic material construction consisting of interlaced yarns or fibers, usually a planar structure. Specifically, as used in this handbook, a cloth woven in an established weave pattern from advanced fiber yarns and used as the fibrous constituent in an advanced composite lamina. In a fabric lamina, the warp direction is considered the longitudinal direction, analogous to the filament direction in a filamentary lamina.
Face sheet	See Facings
Fiber	General term used to refer to filamentary materials. Often, fiber is used synonymously with filament. It is a general term for a filament of finite

Terminology	**Definition**
	length. A unit of matter, either natural or manmade, which forms the basic element of fabrics and other textile structures.
Fiber content	Amount of fiber present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.
Fiber direction	Orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.
Fiber volume (fraction)	See Fiber Content.
Filament	Smallest unit of a fibrous material. The basic units formed during spinning, and which are gathered into strands of fiber (for use in composites). Filaments usually are of extreme length and of very small diameter. Filaments normally are not used individually. Some textile filaments can function as a yarn when they are of sufficient strength and flexibility.
Filament winding	See Winding.
Filament wound	Pertaining to an object created by the filament winding method of fabrication.
Fill (filling)	In a woven fabric, the yarn running from selvage to selvage at right angles to the warp.
Filler	Relatively inert substance added to a material to alter its physical, mechanical, thermal, electrical, and other properties or to lower cost. Sometimes the term is used specifically to mean particulate additives.
Finish (or size system)	Material, with which filaments are treated, which contains a coupling agent to improve the bond between the filament surface and the resin matrix in a composite material. In addition, finishes often contain ingredients which provide lubricity to the filament surface, preventing abrasive damage during handling, and a binder which promotes strand integrity and facilitates packing of the filaments.
Flash	Excess material which forms at the parting line of a mold or die, or which is extruded from a closed mold.
Galvanic corrosion	Corrosion associated with the current of a galvanic cell made up of dissimilar electrodes (typically occurs when carbon fibers are in contact with a metal such as aluminum).
Gel coat	Quick-setting resin used in molding processes to provide an improved surface for the composite; it is the first resin applied to the mold after the mold-release agent.
Glass fibers	Fiber spun from an inorganic product of fusion which has cooled to a rigid condition without crystallizing.

Terminology	**Definition**
Glass transition	Reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.
Glass transition temperature (T_g)	Approximate midpoint of the temperature range over which the glass transition takes place.
Graphite fibers	See carbon fibers.
Hand layup	Process in which components are applied either to a mold or a working surface, and the successive plies are built up and worked by hand.
Heterogeneous	Descriptive term for a material consisting of dissimilar constituents separately identifiable; a medium consisting of regions of unlike properties separated by internal boundaries. (Note that all non-homogeneous materials are not necessarily heterogeneous).
Homogeneous	Descriptive term for a material of uniform composition throughout; a medium which has no internal physical boundaries; a material whose properties are constant at every point, in other words, constant with respect to spatial coordinates (but not necessarily with respect to directional coordinates).
Honeycomb	Manufactured product of resin-impregnated sheet material (paper, glass fabric, and so on) or metal (aluminum, titanium) foil, formed into hexagonal-shaped cells. Other cell shapes are produced. Used as a core material in sandwich construction. See also sandwich constructions.
Hot Bonders	Hot bonders apply, control, and document, heat and pressure required for composite repairs and adhesive bonding. Hot bonders use heat blankets and vacuum bags.
Humidity, relative	Ratio of the pressure of water vapor present to the pressure of saturated water vapor at the same temperature.
Hybrid	1. Composite laminate comprised of laminae of two or more composite material systems. 2. Combination of two or more different fibers such as carbon and glass or carbon and aramid into a structure (tapes, fabrics, and other forms may be combined).
IBOLT	Composite bolted joint static strength prediction tool.
Impact damage	Damage from a foreign object striking the composite structure.
Inclusion	Physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but in a noticeably different manner from the parent material.
Interface	Boundary between the individual, physically distinguishable constituents of a composite.
Interlaminar	Between the laminae of a laminate.

Terminology	**Definition**
Interlaminar shear	Shearing force tending to produce a relative displacement between two laminae in a laminate along the plane of their interface.
Intralaminar	Within the laminae of a laminate. Used when describing objects (for example, voids), event (for example, fracture), or fields (for example, stress).
Isotropic	Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.
Lamina	Single ply or layer in a laminate. Discussion: For filament winding, a lamina is a layer.
Laminate	Consolidated collection of plies with one or more orientations with respect to some reference direction.
Laminate orientation	Configuration of a cross-plied composite laminate regarding the angles of cross-plying, the number of laminae at each angle, and the exact sequence of the lamina lay-up.
Lay-up	Process of fabrication involving the assembly of successive layers of resin-impregnated material.
Leading edge	Classification of assembled aircraft parts which includes wing or vertical and horizontal stabilizers.
Load enhancement factor (LEF)	To avoid excessive test duration for composite fatigue tests, the applied loads in the fatigue spectrum are increased so that the same level of reliability can be achieved with a shorter test duration. This approach is referred to as the load enhancement factor (LEF) approach.
Macro	Gross properties of a composite as a structural element but does not consider the individual properties or identity of the constituents.
Macroscopic	Macroscopic scale is the length scale on which objects or processes are of a size that is measurable and observable by the naked eye.
Mandrel	Form fixture or male mold used for the base in the production of a part by lay-up, filament winding, or braiding.
Marcelling	Regular, continuous, or in-plane waviness of fibers or tows that can result from various aspects of the manufacturing process. Fiber waviness or marcelling may reduce structural strength and stiffness.
Material acceptance	Testing of incoming material to ensure that it meets requirements.
Material qualification	Testing of incoming material to ensure that it meets requirements.
Material review board (MRB)	Organization and/or system for dispositioning rejected parts as use-as-is, rework/repair, or scrap.
Material system	Composite material made from specifically identified constituents in specific geometric proportions and arrangements and possessed of numerically defined properties.

Terminology	**Definition**
Material variability	Source of variability due to the spatial and consistency variations of the material itself and due to variation in its processing.
Matrix	Homogeneous material (e.g., resin) in which the fiber system of a composite is embedded.
Mean	See Sample Mean and Population Mean.
Mechanical properties	Properties of a material that are associated with elastic and inelastic reaction when force is applied, or the properties involving the relationship between stress and strain.
Metallic properties development and standardization (MMPDS)	MPDS handbook is the preeminent source for aerospace component design allowables relating to metal alloys and fasteners (formerly MIL HBK-5).
Metal bond	Metal to metal bonding. This can be two or more metal parts bonded to each other, or metal sandwich in which metal face sheets are bonded to a metal honeycomb core. Typical metals employed in metal bond are aluminum and titanium.
Micro	Denotes the properties of the constituents (i.e., matrix and reinforcement and interface only, as well as their effects on the composite properties).
Microscopic	Scale of size or length used to describe objects smaller than those that can easily be seen by the naked eye, and which require a lens or microscope to see them clearly.
Microcracks	Cracks formed in composites when thermal or mechanical stresses locally exceed the strength of the matrix. Since most microcracks do not penetrate the reinforcing fibers, microcracks in a cross-plied tape laminate or in a laminate made from cloth prepreg are usually limited to the thickness of a single ply.
Microstrain	Strain over a gage length comparable to the material's inter-atomic distance.
Modulus, initial	Slope of the initial straight portion of a stress-strain curve.
Modulus, Young's	Ratio of change in stress to change in strain below the elastic limit of a material. Applicable to tension and compression loads.
Modulus of rigidity	Also known as Shear Modulus or Torsional Modulus. Ratio of stress to strain below the proportional limit for shear or torsional stress.
Moisture content	Amount of moisture in a material determined under prescribed condition and expressed as a percentage of the mass of the moist specimen (i.e., the mass of the dry substance plus the moisture present).
Moisture equilibrium	Condition reached by a sample when it no longer takes up moisture from, or gives up moisture to, the surrounding environment.

Terminology	**Definition**
Mold	Cavity into or on which the plastic composition is placed and from which it takes form. To shape plastic parts of finished articles by heat and pressure. Also see Mandrel.
Mold release agent	Lubricant applied to mold surfaces to facilitate release of the molded article.
Molding	Forming of a polymer or composite into a solid mass of prescribed shape and size by the application of pressure and heat.
Monolithic	Made of one piece. Examples of monolithic composite structural components are laminate ribs, spars, and skins which are made in one piece unlike many equivalent metal components which have separate parts fastened together.
Nomex™	Aramid fiber or paper. Paper form is used to make honeycomb. Nomex has good resistance to fire and flames and emits low amounts of smoke when burning.
Nondestructive inspection (NDI)	Process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties. Often used as synonymous with nondestructive evaluation (NDE) and nondestructive testing (NDT).
Nonlinear	Not of, in, along, or relating to a straight line.
Normal distribution	Two parameter (μ, σ) family of probability distributions for which the probability that an observation will fall between a and b is given by the area under the curve: f√2 /2σ2]
Normalization	Mathematical procedure for adjusting raw test values for fiber-dominated properties to single (specified) fiber volume content.
Normalized stress	Stress value adjusted to a specified fiber volume content by multiplying the measured stress value by the ratio of specimen fiber volume to the specified fiber volume. This ratio may be obtained directly by experimentally measuring fiber volume, or indirectly by calculation using specimen thickness and fiber areal weight.
Orthotropic	Having three mutually perpendicular planes of elastic symmetry.
Peel ply	Layer of resin free material used to protect a laminate for later secondary bonding.
Plastic	Material that contains one or more organic polymers of large molecular weight is solid in its finished state and, at some state in its manufacture or processing into finished articles, can be shaped by flow.
Ply	1. In general, fabrics or felts consisting of one or more layers. 2. Layers that make up a stack. 3. Yarn resulting from twisting operations (three ply yarn, etc.). 4. Single layer of prepreg. 5. Single pass in filament winding (two plies forming one layer).

Terminology	Definition
	6. Sheet or layer that is one discrete piece of manufactured material such as fabric, tape or adhesive film etc. A discrete piece may consist of just one piece or of adjoining pieces of the same material.
Poisson’s ratio	Absolute value of the ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material.
Polymer	Organic material composed of molecules characterized by the repetition of one or more types of monomeric units.
Polymerization	Chemical reaction in which the molecules of monomers are linked together to form polymers via two principal reaction mechanisms. Addition polymerizations preceded by chain growth and most condensation polymerizations through step growth.
Porosity	Condition of trapped pockets of air, gas, or vacuum within a solid material, usually expressed as a percentage of the total nonsolid volume to the total volume (solid plus nonsolid) of a unit quantity of material.
Post cure	Additional elevated temperature cure, usually without pressure, to increase the glass transition temperature, to improve final properties, or to complete the cure.
Pot life	Period during which a reacting thermosetting composition remains suitable for its intended processing after mixing with a reaction initiating agent.
Preform	Assembly of dry fabric and fibers which has been prepared for one of several different wet resin injection processes. A preform may be stitched or stabilized in some other way to hold its shape. A commingled preform may contain thermoplastic fibers and may be consolidated by elevated temperature and pressure without resin injection.
Preimpregnation	Practice of mixing resin and reinforcement and effecting partial cure before use or shipment to the user. See also Prepreg.
Preply	Layers of prepreg material, which have been assembled according to a user specified stacking sequence.
Prepreg	Ready to mold or cure material in sheet form which may be tow, tape, cloth, or mat impregnated with resin. It may be stored before use.
Pressure	Force or load per unit area.
proportional limit	Maximum stress that a material is capable of sustaining without any deviation from the proportionality of stress to strain (also known as Hooke's Law).
Quasi-isotropic laminate	Balanced and symmetric laminate for which a constitutive property of interest, at a given point, displays isotropic behavior in the plane of the laminate. Common quasi-isotropic laminates are (0/±60)s and (0/±45/90)s.
Quality assurance (QA)	Function of evaluating product quality and the procedures taken to ensure that the final product conforms to the specification requirements.

Terminology	**Definition**
Reinforced plastic	Plastic with relatively high stiffness or very high strength fibers embedded in the composition. This improves some mechanical properties over that of the base resin.
Release agent	See Mold Release Agent.
Repair	Airplane repairs of damage can be classified as either "major" or "minor." This assessment is based on the scope and complexity of the repair and the experience and capability of the operator. The responsibility for determining whether a repair is major or minor rests with operators, repair stations, and holders of an inspection or maintenance authorization. Because the classification of a repair as either major or minor is not a 14 CFR Part 23,25, 27, or 29 requirements, this classification is outside the scope of FAA authority delegated to OEMs.
Resin	Organic polymer or prepolymer used as a matrix to contain the fibrous reinforcement in a composite material or as an adhesive. This organic matrix may be a thermoset or a thermoplastic and may contain a wide variety of components or additives to influence handleability, processing behavior, and ultimate properties.
Resin content	See Matrix Content.
Resin starved area	Area of composite part where the resin has a non-continuous smooth coverage of the fiber.
Resin system	Mixture of resin, with ingredients such as catalyst, initiator, diluents, etc. required for the intended processing and final product.
Room temperature ambient (RTA)	1. Environmental condition of 73±5°F (23±3°C) at ambient laboratory relative humidity. 2. Material condition where, immediately following consolidation/cure, the material is stored at 73±5°F (23±3°C) and at a maximum relative humidity of 60%.
Run-out	Fatigue cycling of a test specimen produces no failure after a significant number of cycles and the test is stopped.
Sample	Small portion of a material or product intended to be representative of the whole. Statistically, a sample is the collection of measurements taken from a specified population.
Sample standard deviation	Square root of the sample variance.
Sandwich construction	Structural panel concept consisting in its simplest form of two relatively thin, parallel sheets of structural material bonded to, and separated by, a relatively thick, light-weight core.
Saturation	Equilibrium condition in which the net rate of absorption under prescribed conditions falls essentially to zero.

Terminology	**Definition**
Scarf Joint	Joint made by cutting away similar angular segments on two adherents and bonding the adherents with the cut areas fitted together.
Scrim	Also known as Glass Cloth, Carrier. Low-cost fabric woven into an open mesh construction, used in the processing of tape or other B-stage material to facilitate handling.
Secondary bonding	Joining together, by the process of adhesive bonding, of two or more already-cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself.
Shelf life	Length of time a material, substance, product, or reagent can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended function.
Sizing	Generic term for compounds which are applied to yarns to bind the fiber together and stiffen the yarn to provide abrasion-resistance during weaving. Starch, gelatin, oil, wax, and man-made polymers such as polyvinyl alcohol, polystyrene, polyacrylic acid, and polyacetatates are employed.
Skydrol™	Hydraulic fluid which is fire resistant unlike hydraulic oils used in military aircraft.
S-N curve	Curve in which data is presented as a plot of stress (S) against the number of cycles to failure (N). A log scale is almost always used for N.
Specific gravity	Ratio of the weight of any volume of a substance to the weight of an equal volume of another substance taken as standard at a constant or stated temperature. Solids and liquids are usually compared with water at 39°F (4°C).
Specific heat	Quantity of heat required to raise the temperature of a unit mass of a substance one degree under specified conditions.
Specimen	Piece or portion of a sample or other material taken to be tested. Specimens normally are prepared to conform to the applicable test method.
Stacking sequence	Description of a laminate that details the ply orientations and their sequence in the laminate.
Statistical process control (SPC)	Method of quality control which uses statistical methods. SPC is applied to monitor and control a process. Monitoring and controlling the process ensures that it operates at its full potential.
Standard deviation	See Sample Standard Deviation.
Strain	Per unit change, due to force, in the size or shape of a body related to its original size or shape. Strain is a non-dimensional quantity, and usually expressed in inches per inch, meters per meter, or percent.
Stress relaxation	Time dependent decrease in stress in a solid under given constraint conditions.

Terminology	**Definition**
Stress-strain curve (diagram)	Graphical representation showing the relationship between the change in dimension of the specimen in the direction of the externally applied stress and the magnitude of the applied stress. Values of stress usually are plotted as ordinates (vertically) and strain values as abscissa (horizontally).
Structural element	Generic element of a more complex structural member (for example, skin, stringer, shear panels, sandwich panels, joints, or splices).
Symmetrical laminate	Composite laminate in which the sequence of plies below the laminate midplane is a mirror image of the stacking sequence above the midplane.
Tack	Stickiness of the prepreg.
Tape	Prepreg fabricated in widths of up to 12 inches for carbon and 3 inches for boron. Cross stitched carbon tapes up to 60 inches wide are available commercially in some cases.
Tedlar™ film	Polyvinyl fluoride film. 1. Release film for wrapping composite tooling. 2. Intermediate de-bulking wrap whereby ply compaction is required between prepreg layers.
Thermal conductivity	Ability of a material to conduct heat. The physical constant for quantity of heat that passes through unit cube of a substance in unit time when the difference in temperature of two faces is one degree.
Thermoplastic	Plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and when in the softened stage, can be shaped by flow into articles by molding or extrusion.
Thermoset	Class of polymers that, when cured using heat, chemical, or other means, changes into a substantially infusible and insoluble material.
Toughness	Measure of ability to absorb work, or the actual work per unit volume or unit mass of material that is required to rupture it. Toughness is proportional to the area under the load elongation curve from the origin to the breaking point.
Tow	Untwisted bundle of continuous filaments. Commonly used in referring to man-made fibers, particularly carbon (or graphite) fibers, in the composites industry.
Transition fit	Fastener hole fit that can range from a small interference to a small clearance.
Traveler	Small piece of the same product (panel, tube, etc.) as the test specimen used, for example, to measure moisture content as a result of conditioning.
Ullage	Unfilled portion of fuel tank above the fuel.
Unidirectional fiber composite (UDC)	Any fiber-reinforced composite with all fibers aligned in a single direction.

Terminology	**Definition**
Vacuum bag	Plastic or rubber layer used to cover the part so that a vacuum can be drawn.
Vacuum bag molding	Process in which the lay-up is cured under pressure generated by drawing a vacuum in the space between the lay-up and a flexible sheet placed over it which is sealed at the edges.
Variance	See Sample Variance.
Virtual crack closure technique (VCCT)	Technology that Boeing developed for predicting fracture and failure in laminated composite materials.
Visible impact damage (VID)	Visible impact damage. This is impact damage which is considered easily visible by the naked eye in good lighting conditions.
Viscosity	Property of resistance to flow exhibited within the body of a material.
Void	Any pocket of enclosed gas or near-vacuum within a composite.
Warp	Longitudinally oriented yarn in a woven fabric (see Fill); a group of yarns in long lengths and approximately parallel.
Wet lay-up	Method of making a reinforced product by applying a liquid resin system while, or after, the reinforcement is put in place.
Winding	Process in which continuous material is applied under controlled tension to a form in a predetermined geometric relationship to make a structure. Filament winding is the most common type.
Work life	Period during which a compound, after mixing with a catalyst, solvent, or other compounding ingredient, remains suitable for its intended use.
Yield strength	Stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. (The deviation is expressed in terms of strain such as 0.2 percent for the Offset Method or 0.5 percent for the Total Extension Under Load Method.)
X-axis	In composite laminates, an axis in the plane of the laminate which is used as the 0-degree reference for designating the angle of a lamina.
X-Y plane	In composite laminates, the reference plane parallel to the plane of the laminate.
Y-axis	In composite laminates, the axis in the plane of the laminate which is perpendicular to the x-axis.
Z-axis	In composite laminates, the reference axis normal to the plane of the laminate