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Industry Survey on Thermal Loadings in Metallic-Composite Hybrid Structure

March 1, 2021

Final report

U.S. Department of Transportation
Federal Aviation Administration

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16. Abstract

The FAA and Industry have spent considerable effort in the Transport Airplane Metallic and Composite Structures Working Group (TAMCSWG) developing recommendations related to damage-tolerance and fatigue requirements and associated guidance for transport-category airplanes. The TAMCSWG recommended changes to Title 14a Code of Federal Regulations (14 CFR) 25.571 and associated guidance material to allow analysis that is supported by test evidence to evaluate thermal and environmental loads. Applying thermal loads to full-scale test articles is impractical and therefore the loads must be accounted for analytically. To assist the industry, information regarding the approach and issues of analyzing the effects of thermal loads in complex hybrid structures needs to be discussed to highlight areas where research, standardization, and available data can be provided to assist and standardize compliance.

The National Institute for Aviation Research (NIAR) conducted a survey of the industry to baseline practices used to certify hybrid structures, including approaches to address thermal cyclic loads. This report presents the results of that survey so it can be used to identify the needs and issues relative to hybrid aircraft structure. Additional industry engagement will be ongoing, as we continue to identify and discuss these issues with the goal of developing a roadmap addressing future research, test methodology, analysis and modeling techniques, and acceptable means of compliance relative to § 25.571 compliance.

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Contents

Acronyms

Acronym	Definition
CTE	Coefficient of Thermal Expansion
EMST	Emerging Metallic Structural Technology
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GREP	Graphite Reinforced Epoxy
NIAR	National Institute for Aviation Research
TAMCSWG	Transport Airplane Metallic and Composite Structures Working Group
14 CFR	Title 14 Code of Federal Regulations

Executive summary

The FAA and Industry have spent considerable effort in the Transport Airplane Metallic and Composite Structures Working Group (TAMCSWG) developing recommendations related to damage-tolerance and fatigue requirements and associated guidance for transport-category airplanes. This working group and the FAA examined all aspects of Title 14 Code of Federal Regulations (14 CFR) 25.571 and other related requirements and how they pertain to current and future technology. Specifically, they addressed the use of composites and hybrid structures. The TAMCSWG recommended changes to § 25.571 and associated guidance material to allow analysis that is supported by test evidence to evaluate thermal and environmental loads, which need to be included in the durability and damage tolerance assessments (TAMCSWG, 2018). Applying thermal loads to full-scale test articles is impractical and therefore the loads must be accounted for analytically. Special load factors may not always be conservative and may impose unnecessary performance penalties when they are arbitrarily applied. To assist the industry, information regarding the approach and issues of analyzing the effects of thermal loads in complex hybrid structures needs to be discussed to highlight areas where research, standardization, and available data can be provided to assist and standardize compliance.

The FAA's collaborative research initiative, Emerging Metallic Structural Technology (EMST), works in concert with industry and academia to provide fundamental research to address the potential technical gaps associated with new technologies, thus proactively supporting safety and continued airworthiness prior to their introduction.

The National Institute for Aviation Research (NIAR) conducted a survey of the industry to baseline practices used to certify hybrid structures, including approaches to address thermal cyclic loads. This report presents the results of that survey so it can be used to identify the needs and issues relative to hybrid aircraft structure. Industry engagement will be ongoing as we continue to identify and discuss these issues with the goal of developing a roadmap addressing future research, test methodology, analysis and modeling techniques, and acceptable means of compliance relative to § 25.571 compliance. This survey is seen as the start of a necessary dialogue to shape future discussions.

1 Introduction

Thermally-induced stresses in the joints of hybrid structures can contribute significantly to the overall assessment of the durability and damage tolerance of that assembly. Full-scale testing is required to show compliance to Title 14, Code of Federal Regulations (14 CFR) 25.571, but there are no practical means for applying the various cyclic thermal loads commensurate with typical aircraft spectrums. Multiple approaches have been investigated relative to measuring the resulting stress in the structure, but each approach has unique issues and limitations that further complicate uniform usage. To simplify the analysis, an applied thermal load or knockdown is sometimes universally applied to all the structures in a “conservative” approach to show compliance. Because thermal loading may be additive or relieving, depending on the assembly and particular flight segment, this approach may not always be conservative or may unduly penalize the entire structure.

Hybrid structures are becoming more prevalent and utilized through commercial transport aircraft and US Military platforms as designers strive to increase performance and reduce the overall cost of ownership. This report provides the results from the analysis of the hybrid structure survey that was conducted by the National Institute for Aviation Research (NIAR) sent to key people supporting the TAMCSWG. The intent of the survey is to provide a better understanding of the hybrid structure applications and methods used by industry to account for thermal loads when designing, constructing, and testing as part of the certification process and compliance with § 25.571.

2 Understanding key elements

Even in aircraft that use composite materials for primary structure, there is still a significant amount of metallic material utilized. Composites comprise 50% of the Boeing 787 (The Boeing Company) and 25% of the Airbus A380 (Airbus). Designers have come to understand that each material has specific applications where it is best suited for the loading and/or methods of manufacturing. As a result, hybrid structures incorporating both composite and metallic components are used for some structural elements.

The major focus of this research is the interface between those metallic and composite structural components, especially when there is a significant length where large thermal loads can be generated due to the differences between the Coefficient of Thermal Expansion (CTE) of the composite and metallic materials. This study is not focused on the potential interlaminar stresses that may be present in a composite laminate.

Research has revealed that the preferred structural composite material is Graphite Reinforced Epoxy (GREP). GREP is utilized as unidirectional tape and woven fabric, and can be processed at various pressures and temperatures to achieve the desired cured properties. Metals utilized are aluminum, titanium, and steel. The interfaces between the various components in a structural assembly are co-cured, bonded, or are bolted and bonded joints.

The interface is at a zero induced thermal load when the structure is at the same temperature as when the interface was assembled, called the reference temperature. That could be the temperature when the rivets or bolts were installed, or it could be the elevated temperature when a bond line was cured. A significant complication is that a full aircraft assembly could have multiple interfaces, each with a different reference temperature. The assessment of thermal loadings may also be equally complex when considering a typical ground-air-ground flight cycle and the dynamics of each piece of structure changing temperature throughout the flight. Consider a fuselage where the inside is at room temperature and the outside surfaces could be -65F when in flight, or +180F when sitting on a hot tarmac, creating a gradient across the structure. This is then further complicated by the cyclic nature of those thermal loads as the aircraft cycles through many environments during the course of typical flight operations. How those thermal cycles affect any damage initiation or growth assessment must be determined analytically without the ability to apply the loads during a full-scale fatigue test for compliance with § 25.571.

3 Problem statement

In the assessment of the primary structure, the determination of the flight and thermal load spectrums is a critical and complex task. Because composite structures tend to be sensitive to damage with compressive loads, whereas metals are sensitive to fracture and crack growth associated with tensile loadings, the two can sometimes conflict when analyzing or testing the structure. The sequence of the application of the high loads in the test spectrums may influence the outcome of the test (Seneviratne et al., 2013). The application of the high loads associated with a compression dominated spectrum affecting composites may contribute to a crack-propagation retardation in the metal structure, and to a reduction in the fatigue life for composites (Seneviratne et al., 2013). One means of addressing this issue is the utilization of two separate test articles, one for metals and the other for composites. However, using two test articles may double the required test duration and cost, and may complicate the assessment at the metal/composite interfaces. If an applicant only uses one test article, then the generation of the hybrid loading spectrum becomes a critical part of the assessment. Since it is typically impractical to apply the environmental and thermal conditions during a full-scale fatigue test of a transport airplane, applicants usually perform an analytical assessment of the thermal loads on the life of the structure.

The applicant is then required to validate their analysis, which requires an understanding of the actual thermal loads and the spectrum of how those loads should be applied. With this complexity, applicants have developed their own methodologies and procedures for addressing the loads and spectrums.

NIAR developed a survey to baseline the applications of hybrid structures, and to understand the general approach to account for thermal loads in the damage-tolerance and fatigue evaluation of structure. The FAA may use this information to build a framework for future investigations and to eventually develop guidance material to address analytical challenges related to the assessment of thermal loads. This initial survey may result in additional dialogue on this topic, as some of the common and high priority issues become clear.

4 Data collection

NIAR created the Hybrid Structure Survey through the software package, Survey Monkey™, and distributed it on 27 May 2020 to 26 individuals from industry and civilian government agencies that are familiar with the application of hybrid structures and efforts of TAMCSWG. The survey closed and data was collected on 7 July 2020. The survey received various responses from 18 individuals with seven individuals supplying responses to every question. The survey is completely anonymous and contact information received and used for distribution is held in confidentiality.

The survey consisted of 55 questions divided into the following five sections: Types of Materials, Types of Hybrid Structures and Assembly, Test and Analysis, Continued Airworthiness, and Additional Discussion.

4.1 Section 1: Types of materials

Questions 1-8 fall under this section. This section queries the use and application of hybrid structure in current and future applications.

4.2 Section 2: Types of hybrid structures and assembly

Questions 9-16 of this section covered the manufacturing methodology of hybrid structure focusing on fabrication and assembly with fasteners and bonding.

4.3 Section 3: Test and analysis

Questions 17-47 of this section requested information to understand industry approaches for applying load spectrums and test methods, when accounting for thermal loads. In addition, this section solicited for potential future research for FAA and industry participation.

4.4 Section 4: Continued airworthiness

Questions 48-51 inquired about the hybrid structure repair and inspection process. One question addressed the determination of inspection intervals and how thermal loads affected that assessment.

4.5 Section 5: Additional discussion

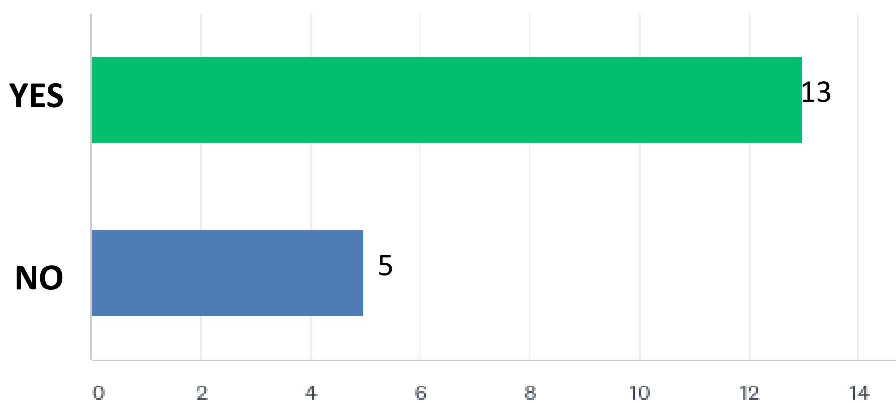
Questions 52-55 provided an opportunity for individuals to request and identify further discussions they would like to have concerning their topics.

5 Survey results

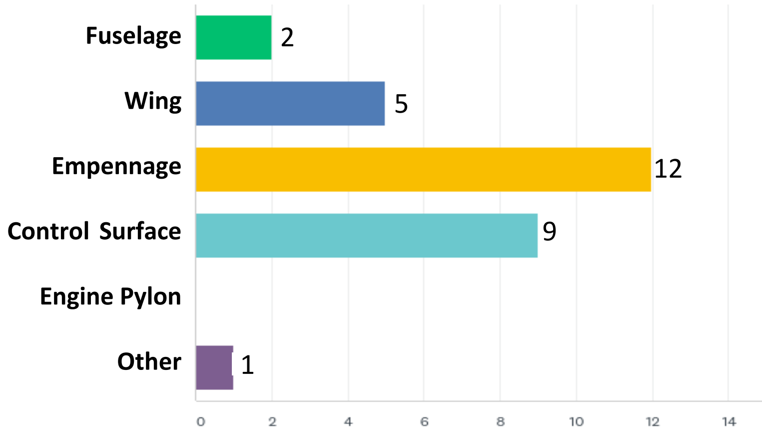
The survey results presented here correspond to the same five topics noted in section 4. Each section includes the individual questions asked in the survey and the responding results. Note that not every person provided responses to every question, so the total responses vary from question to question.

5.1 Section 1: Types of materials

Q1: Do you plan on building a hybrid primary structure?

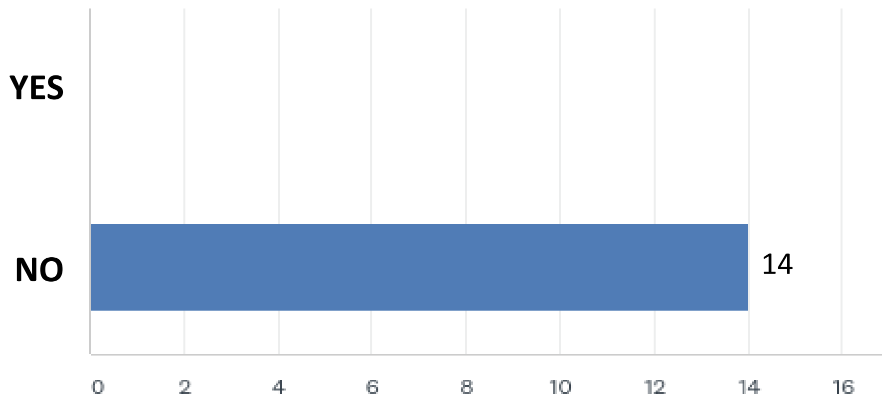


Q2: If “Yes”, what will that structure be (check all that apply)?



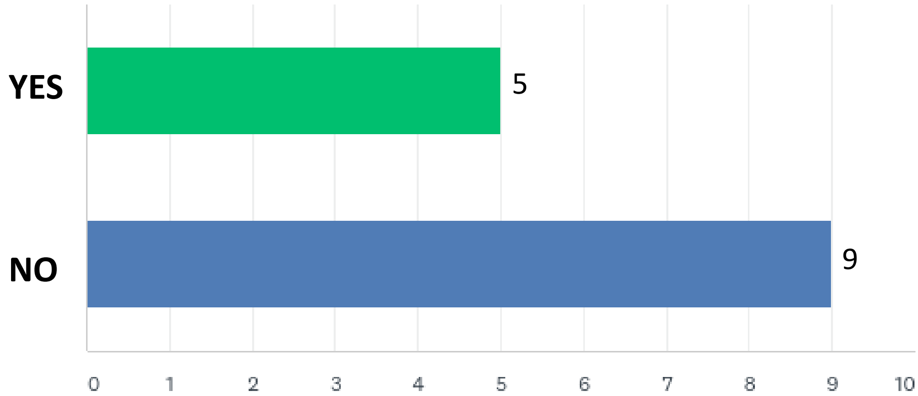
One participant responded, “pressure bulkheads” under “other”.

Q3: Do you plan on using FML’s (Fiber Metal Laminates)?

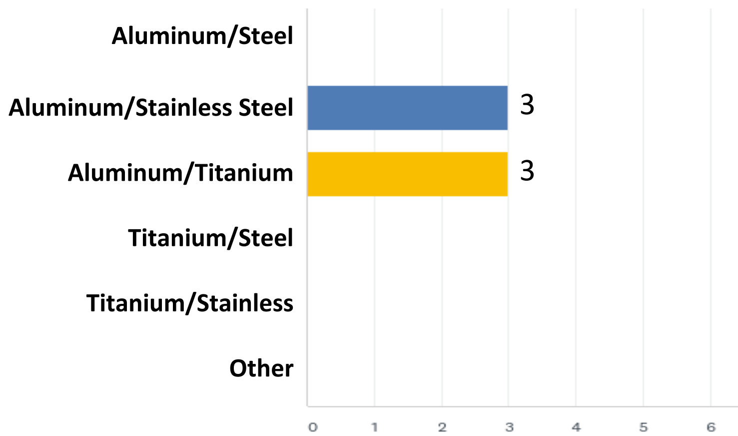


Question 4 asked “If "Yes" - Please define the FML's:”, and zero responses were confirmed.

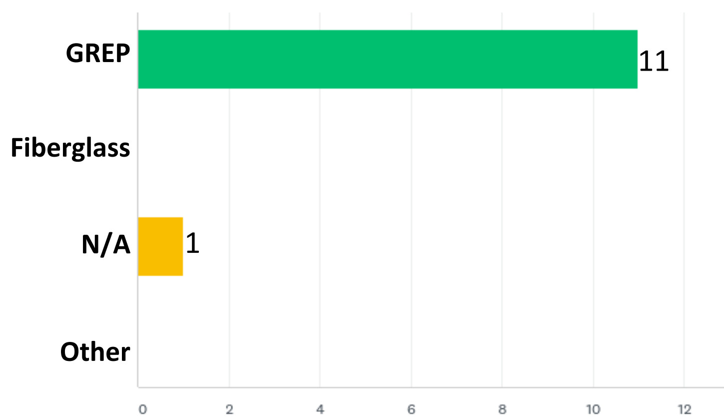
Q5: Do you utilize metals with different CTE's in your structural assemblies? (Note that this is referring to something like Titanium frames on an Aluminum skin, or a large steel doubler around a door cutout on an Aluminum skin, etc.)



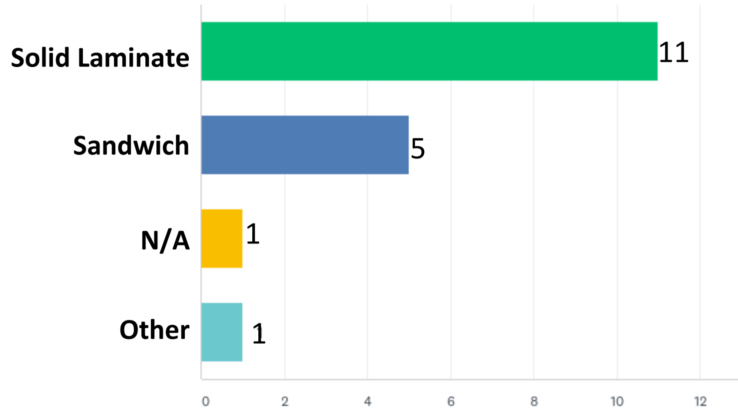
Q6: If "Yes" - Define the materials.



Q7: Please describe the composite materials utilized in your hybrid structure if applicable.

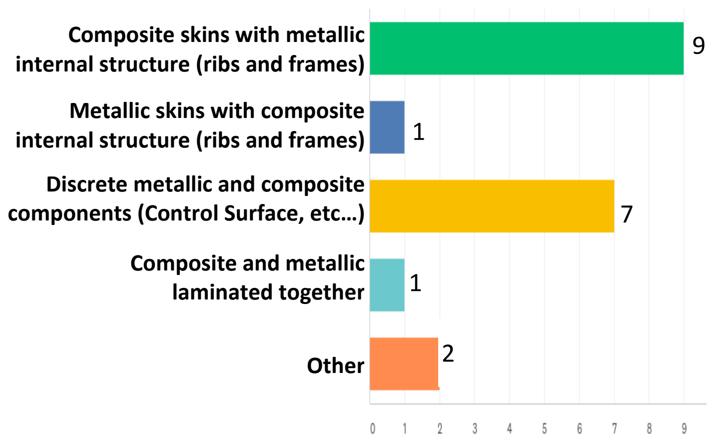


Q8: Please describe the composite construction utilized in your hybrid structure if applicable.

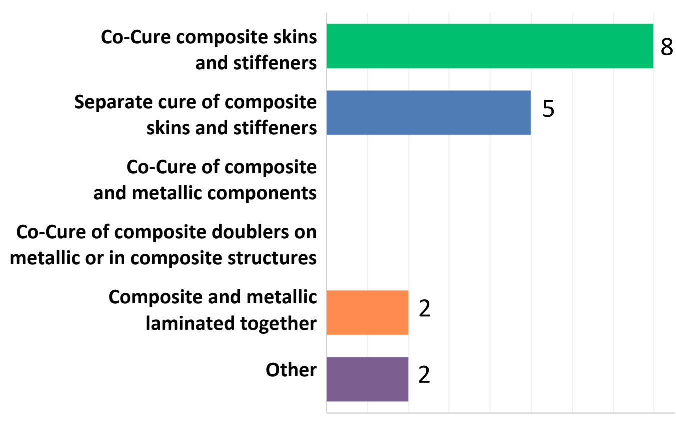


5.2 Section 2: Types of hybrid structures and assembly

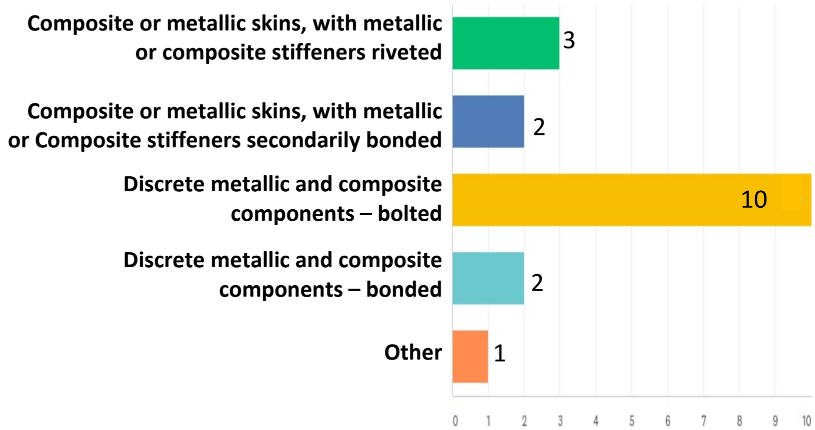
Q9: Please define how your structure is manufactured. Is your structure … (check all that apply).



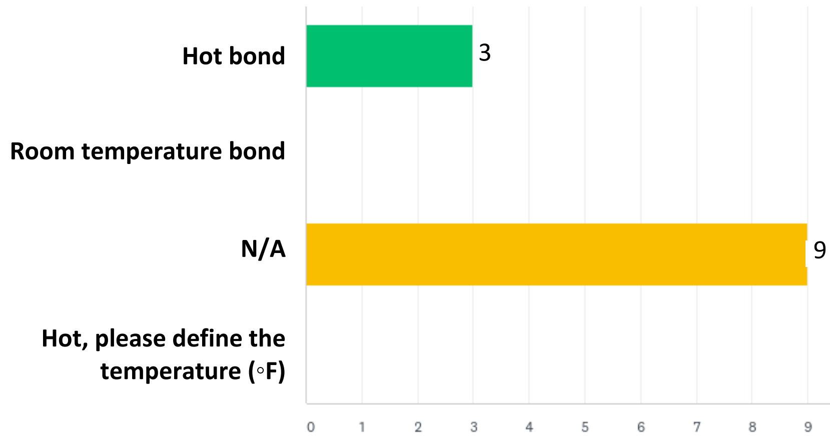
Q10: Please define how the hybrid structure is fabricated (check all that apply).



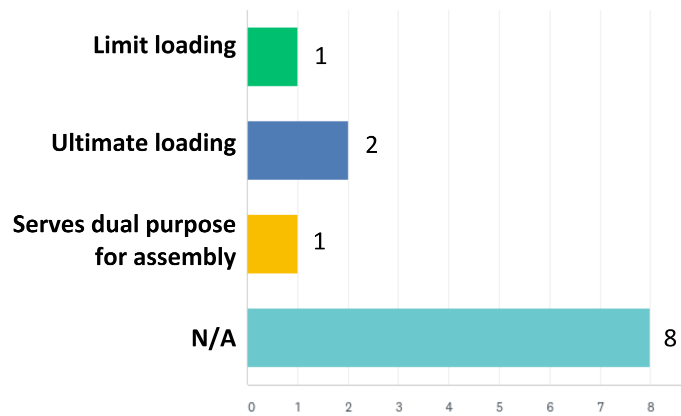
Q11: Please define how the hybrid structure is assembled (check all that apply).



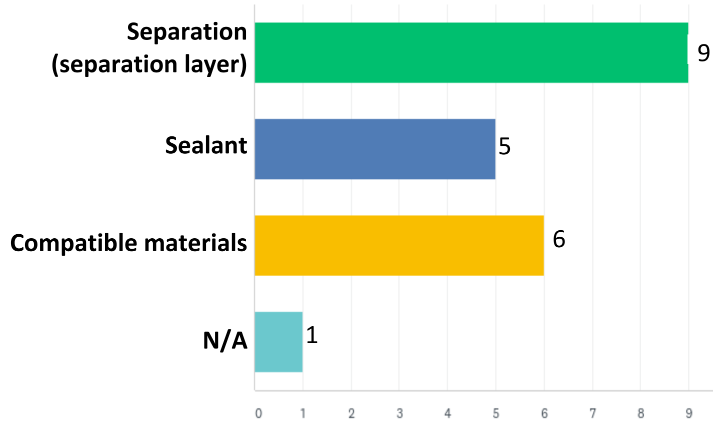
Q12: Please define how the hybrid structure is bonded.



Q13: Do you utilize fasteners in your bonded joints? If so, identify the application.



Q14: What is the primary means of any corrosion control? (check all that apply)



Q15: Please describe the special processes utilized to address issues with installing fasteners in hybrid structures.

As an issue that needs to be addressed, some responses were observed such as drilling, reaming, hole tolerance (CTE mismatch), and fastener interference.

As a solution to these issues, several notable answers were returned such as the following:

- Special procedures and inspection tools, differing hole tolerance, fastener isolation (3).
- Fastener fit for metallic and composite structure (1).
- GFRP cloth layer and wet installation with sealant (1).
- One-step drilling with further separation of parts for cleaning of drilling debris (1).
- Interference fit for sleeved fasteners (where required) and the use of compatible materials (1).

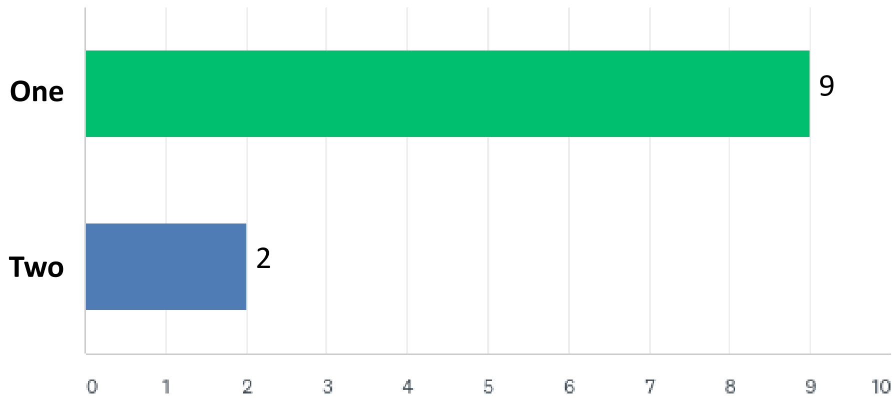
where the number in parentheses shows the number of responses.

Q16: Please define any other items about your construction and assembly that you would like to note.

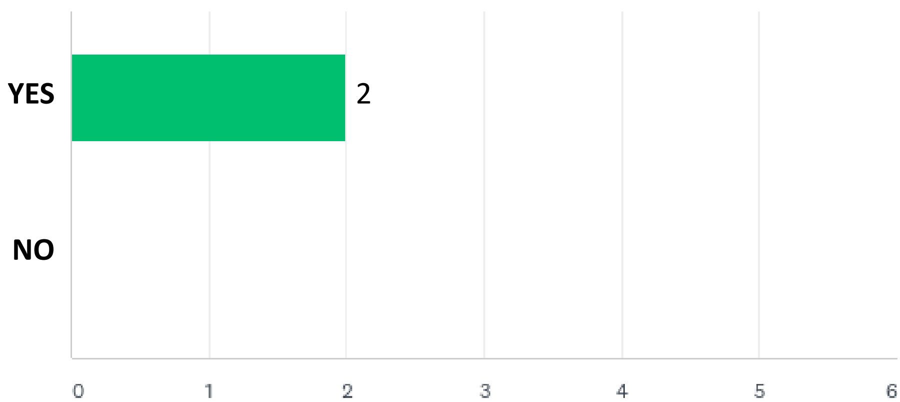
One response was found stating: "Careful selection of material, joint thicknesses and transitions to minimize effects of CTE mismatches."

5.3 Section 3: Test and analysis

Q17: Do you use one or two Durability and Damage Tolerance Articles?

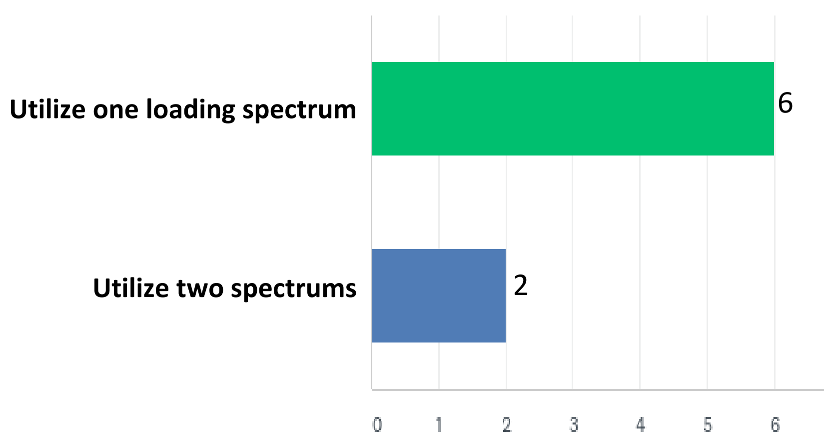


Q18: If two articles, are the articles tested differently?

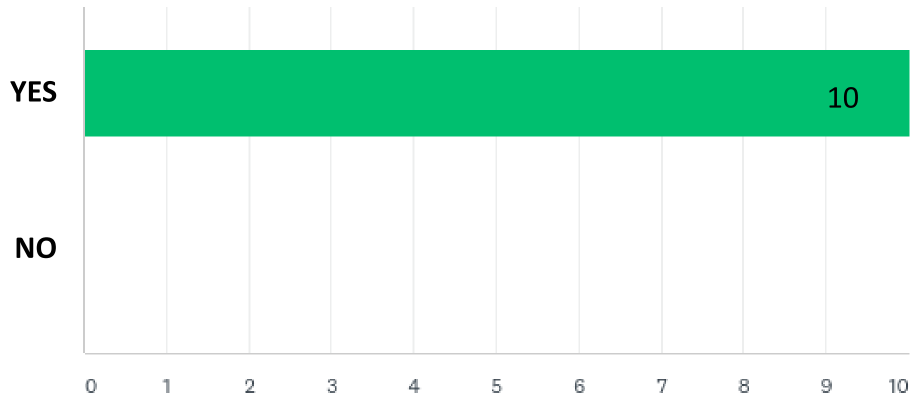


Q19 asked "If "Yes" - Please describe the differences:", and zero responses were provided.

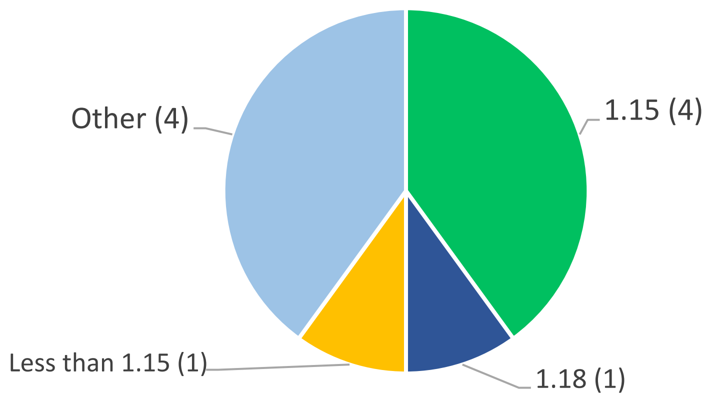
Q20: If you have one test article do you…



Q21: On your composite load spectrums do you utilize a Load Enhancement Factor (LEF)?



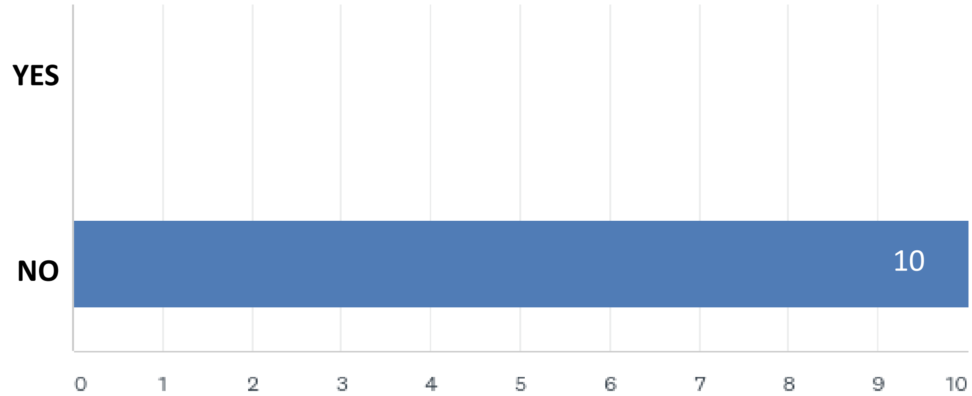
Q22: If "Yes" - Please describe the factor used.



Other responses stated the variation in LEF, including:

- "*Based on LEF testing*" (1)
- "*LEF is applied to account for composite material variability, and decided with coupon level test data and how many lifetimes applied to the component test, following CMH-17 descriptions.*" (1)
- "*Test-based LEF is an "overload" applied to the spectrum to account for composite fatigue scatter*." (1)
- "*LEF is allowed to test interrogate lower level of complexity structure (e.g. sub-component) with higher LEF to mitigate risks at the Aircraft Full Scale Testing Level.*" (1)

Q23: Do you account for thermal loads in your mechanical test loadings?



Question 24 through 27 received no responses. The questions are shown below:

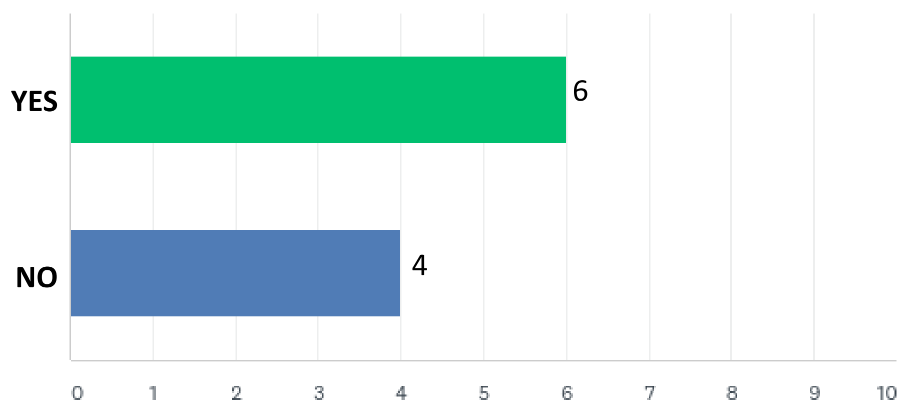
Q24: If "Yes" - Please describe how the loads are applied and how any unintended consequences (e.g., changing failure modes in a structural part may benefit from a particular test loading because it is reducing stress).

Q25: Please describe what data do you need to accomplish a hybrid structure thermal analysis; ergo, CTE's material and/or bond line, flight strain values, thermal loads, strain surveys, etc.

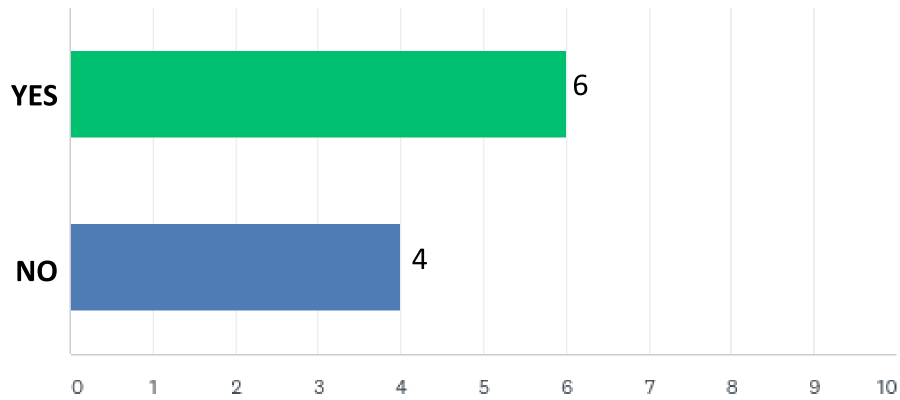
Q26: How is the data you use for your analysis validated?

Q27: In your analysis how are the thermal loadings applied?

Q28: Has your organization already certified hybrid structures for commercial transport aircraft?



Q29: Does your company already have documented procedures for determining thermal loadings and how they are accounted for in FAR 25.571 analysis?



Q30: What standards should be developed that would assist in future Hybrid Certifications?

Three participants responded to this question as listed below:

- "*As for Composite-Metal joint with multiple fasteners, static and FDT substantiation can be assumed as necessary depends on their importance. Practical test standard for analysis validation can help future certification activity and in-service support, such as 1)Strain gauge location to monitor the bypass strain for the prediction of fastener load and bypass load and 2)Design features needs to be stimulated by the test specimen. The establishment of an analysis model also can be helpful*." (1)
- *"Internal loads generated by temperature differentials in complex structures cannot be represented by tests at room temperature, which provides FE modeling, calibrated with building block tests at details/panels levels, as the most effective way for quantifying these effects. Any standardization of recognized tests and analysis parameters would be very useful*." (1)
- "*Analytical methods addressing impracticality of testing by applying both thermal and mechanical loading, Spectra analysis, acceptable methods for inspection intervals definitions, including cross-referencing ICA and MSG-3 for example*." (1)

Q31: Please describe any areas where dedicated FAA/Industry research would aid in the development of standards or make hybrid certifications more robust:

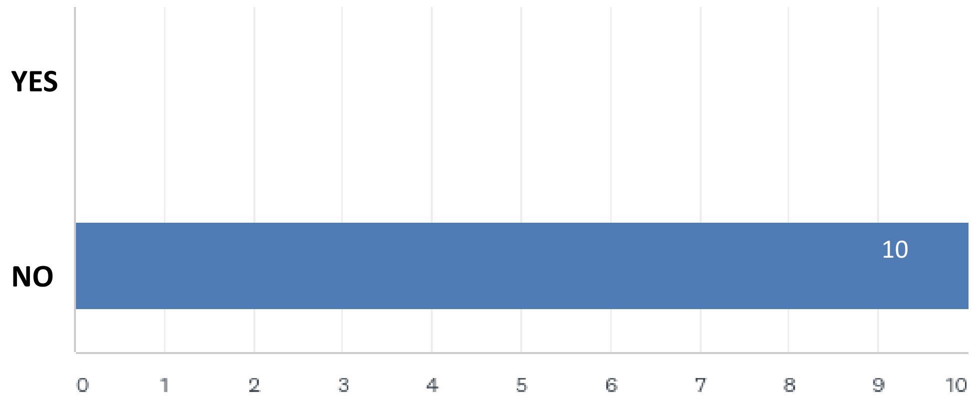
As a response to this question, the following suggestions were found:

1. Establishment of an analysis method.

   "*Specifically with test standard for FDT analysis of hybrid joint and with WFD rule for thermal and mechanical load interactions.*"
2. Review of corrosion-resistant design with fleet data.
3. Dedicated research in support of acceptable parameters for modeling and corroboration.

   "Since certification of Hybrid structures, is heavily based on FE modeling."

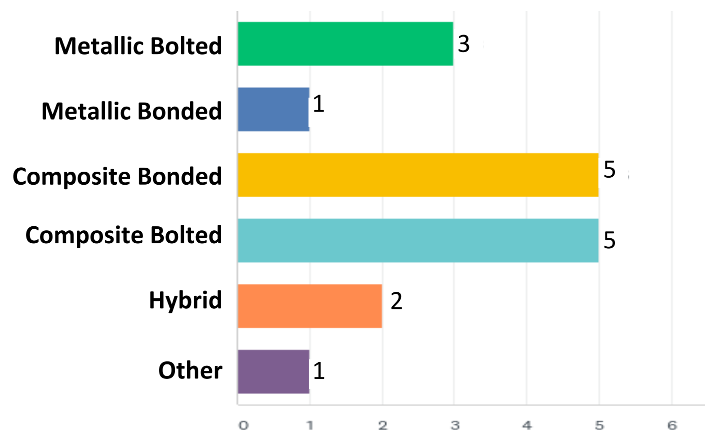
Q32: Would you like to provide additional information?



Question 33-47 asked if there is any additional topic that should be addressed; no responses were provided.

5.4 Section 4: Continued airworthiness

Q48: Generally, describe your hybrid structure repair process. Are your structural repairs of interest… (Check all that apply)



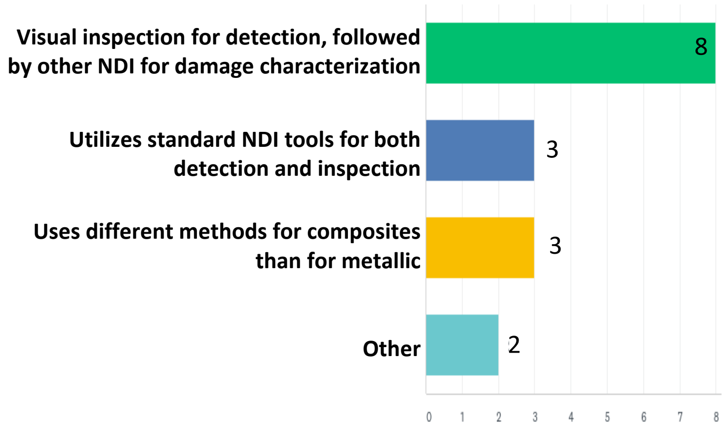
One participant answered with "Very limited reliance on bonding (sandwich primarily)."

Q49: If "Hybrid" - Please describe your process for repair.

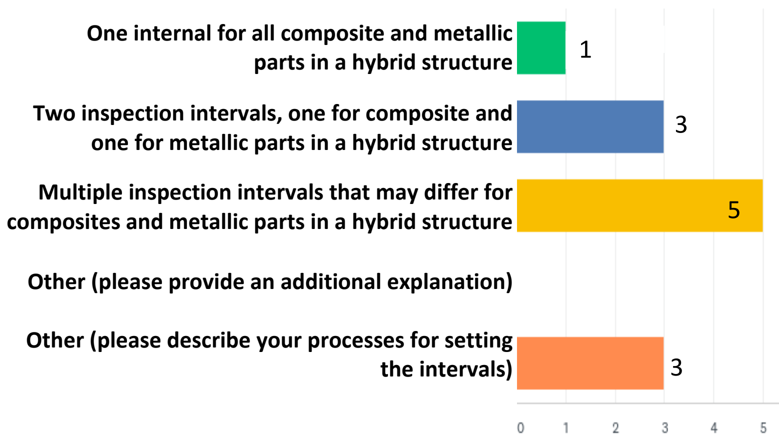
Two responses were provided to this question.

1. Metallic doubler repair onto Composite plate (1)
2. Metallic bolted repairs. It could be composite bolted repair depending on the configuration (1)

Q50: Please describe your process for field detection or inspection.



Q51: Please describe your methodology for determining inspection intervals and the issues that hybrid structures and thermal loads have on that determination. Please describe your process for setting the inspection interval(s).



The three other responses include:

- "*Not determined yet since the study is still on-going*." (1)
- "*Usually, one inspection at midlife for composites since the full-scale static and fatigue test is inflicted with category two damages at its beginning. For Metals, the inspection is based on crack propagation*." (1)
- "*Harmonized two inspection intervals to lower maintenance cost*." (1)

5.5 Section 5: Additional discussion

Questions 52 through 55 asked participants to indicate their level of interest in any follow-on discussion or workshop. Responses to questions in this section are held in confidentiality. The current plan is to provide future opportunities for anyone to engage in discussions on hybrid structures and their certifications.

6 Findings

The objective of this survey was to baseline industry practices used to certify transport airplanes with hybrid structures. Additionally, information was gathered to understand how thermal loads are applied and assessed. Early in this research, we found that companies were already working on or have worked on addressing these issues. What we found, based on responses, was that each company's approach, although similar, varied from each other. Because the data on their approaches was limited, it is not possible to generalize an overall approach or identify specific issues for the analysis of thermal loads on hybrid structure at this time. Likewise, there was no evidence of any standards or training used to address thermal loads in the hybrid structure.

Specific to this survey the following findings were observed:

- The data revealed high interest in the use of hybrid structures in primary and secondary structures. The data also affirmed the increasing trend in the use of GREP as the primary composite material. The survey highlighted that both solid laminate and sandwich structure designs would be used where applicable.
- Responses indicated that the most commonly used method of fabricating hybrid structure is Co-Curing composite skins and stiffeners, followed by a separate cure of composite skins and stiffeners. Data also revealed the high usage of bolts and fasteners on metallic and composite components assembly instead of bonding.
- A separation layer was selected as the most utilized feature to control corrosion and dissimilar materials, with faying surface sealing as the second. Most of the time a separation layer and sealant are used together.
- A high degree of development, precision, and care is required for proper drilling and hole preparation in hybrid structures.
- No respondents indicated that they applied thermal loads to their full-scale test articles. No indication was given that any coupons or sub-components had both load and thermal cycles applied.
- A majority of the respondents indicated that they used or intended to use only one test article for their durability and damage tolerance assessment. For those who chose one article, more than half indicated that they were using one load spectrum, while the others utilized two spectrums: one for the metals and the other for the composites.
- All participants indicated that they used a Load Enhancement Factor (LEF) on their composite load spectrum. There was little consensus on the load factor but most centered on a LEF of 1.15.
- Responses indicated that the most commonly used repair processes in a hybrid structure are the procured composite bonded and bolted followed by bolted metallic.

- The most used NDI for field-level inspections was visual for finding damage, followed by other NDI for damage characterization.
- In determining inspection intervals, a majority of the responses indicated the usage of two or more inspection intervals, which may differ for composites and metallic parts. It was also noted for the cases where inspections differed there was ongoing work to align these intervals to lower maintenance cost.

7 Conclusions and recommendations

The following conclusions/recommendations can be drawn from the results of this survey:

- The use of hybrid structures in commercial transport aircraft will continue to grow in frequency and complexity.
- There is a need for additional research relative to adequate means to validate the thermal loads in a hybrid structure.
- The lack of available data on thermal interactions of bonded and bolted joints has driven the industry to develop its own data and methodology for showing compliance.
- Additional information is needed from industry before any recommendations can be made on changes to industry or regulatory standards and associated guidance materials. This information should be gathered through individual discussions and public workshops.
- Any assessment of available training could not be made at this time.

8 References

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