



QUALITY AND MONITORING OF STRUCTURAL REHABILITATION MEASURES

Part 1: Description of Potential Defects

Henning Kaiser
Vistasp M. Karbhari

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1. INTRODUCTION

1.1 Materials:

For centuries, composite materials have been used extensively for a broad range of applications. Beginning with simple man-made substances like reinforced clay or ceramics, concrete soon became of interest for construction purposes due to its ease of production and generally low cost. Today, it is the most widely used composite construction material. From the 1970's onwards, polymer reinforced composite materials became increasingly popular, especially for use in the aerospace and defense industry. This interest was initiated by the demand for an extremely lightweight material, which would also be extremely resistant to most environmental factors and exhibit excellent strength and stiffness characteristics. Such materials typically consist of a load-bearing component (fibers) and a stress-transferring component (polymer matrix), which encapsulates the fibers. The two polymer families available are thermoplastics and thermosets. While thermoplastics contain long molecular chains, which have the capability of sliding over each other, thermosets incorporate a stiffer molecular structure consisting of a highly cross-linked three-dimensional network. Because of the molecular structure thermoplastics may be melted and reshaped, whereas once formed thermosets cannot be reshaped or reformed and suffer degradation at temperatures higher than their glass transition temperatures. Due to considerations of cost, processing ease and durability in specific environments, thermosetting resin systems are more widely used in civil infrastructure applications. This report, for the most part, therefore emphasizes only thermosetting resin systems and composites derived thereof.

Table 1-1: Mechanical Properties of Selected Resins [1]

Resin Type	Elastic modulus E [GPa]	Strength σ [MPa]	Cure shrinkage [%]	Strain to failure ϵ [%]
Polyester	3.1 – 4.6	50 – 75	5 – 12	1.0 – 6.5
Vinylester	3.1 – 3.3	70 – 81	2.1 – 3.5	3.0 – 8.0
Epoxy	2.6 – 3.8	60 - 85	1 - 5	1.5 – 8.0

As indicated, the matrix serves as the fiber-encapsulating media, which transfers stresses between fibers and, in addition, protects them from aggressive environmental factors, like water, chemicals, abrasion, etc. Examples of matrices commonly used in civil infrastructure applications are polyesters, vinylesters and epoxies, the latter generically having the least shrinkage and highest strength/stiffness properties, as depicted in Table 1-1. If desired, users may add diluents, pigments or fillers to modify resin viscosity or appearance. To initiate and control cure of the resin, carefully metered amounts of hardeners, catalysts, initiators and inhibitors are mixed into the resin. The time span over which resins remain in liquid form prior to gel and vitrification can vary significantly, depending on factors like resin system makeup, ambient temperature and bulk resin volume. An important property of thermoset polymers is their glass transition temperature T_g , which represents the range of temperatures (although usually specified as a single temperature level) over which the resin, or composite, changes response from a glassy, or elastic mode, to a rubbery, or viscoelastic mode. Consequently, a cured resin

system must not be exposed to temperatures close to T_g , as this will result in substantial changes in elastic response and matrix damage.

The vast majority of fibers used in current applications belong to the glass, aramid and carbon varieties. For applications that do not demand extremely high strength and stiffness, glass fibers are preferred. However, their use on concrete is limited due to the susceptibility of the fibers to moisture and especially alkali-induced degradation. Aramid fibers have found high appreciation in impact related applications, such as bulletproof vests, and in structural applications wherein impact or abrasion resistance is essential. A typically low bond between fibers and matrix allows for high-energy absorption, however, limits their use in structural applications. Carbon fibers are essentially inert to environmental influences and have the highest levels of stiffness. However, they are limited to fairly low levels of strain. Table 1-2 presents a comparison of mechanical properties of some representative fibers and structural steel. Commonly, carbon fibers are supplied in yarns (also referred to as bundles, strands or tows) by 3000, 6000, 12000, etc., indicating the amount of individual fibers included in each fiber tow. This high number indicates their extremely small diameter, usually in the order of $10\mu\text{m}$ [1]. Depending on manufacturing technique, fibers can be designed for either high-strength, high-modulus or a combination of both. Herein, notations like ‘HS’ or ‘HM’ represent ‘high-strength’ and ‘high-modulus’, respectively. These properties largely depend on the precursor type and heat treatment employed during manufacture of the fibers. Apart from high strength and stiffness, carbon fibers can tolerate high temperatures and most corrosive environments.

Table 1-2: Longitudinal Properties of Selected Reinforcement [1]

Material	Density ρ [kg/m^3]	Elastic modulus E [GPa]	Tensile Strength σ_t [MPa]
E-Glass	2570 – 2600	69 – 72	3.5 – 3.7
Kevlar 49	1440	131	3.6 – 4.1
Carbon (HS)	1700 – 1900	160 – 250	1.4 – 4.9
Carbon (HM)	1750 – 2000	338 – 436	1.9 – 5.5
Carbon Steel	7790	205	0.6

To promote good bond between fibers and the surrounding matrix, a suitable surface treatment (sizing) of the fibers is essential. The manufacturer typically provides information on resin/fiber compatibility.

To provide the user with a manageable fiber structure, yarns are arranged in specific reinforcement formations. Possible methods of integrating fiber tows include weaving, braiding, knitting or randomly oriented fiber mats. Depending on the intended use, fibers can be aligned in an almost infinite amount of variations to resist stresses in multiple directions. Some basic patterns include unidirectional (UD) or multidirectional weaves, schematically shown in Figure 1-1.

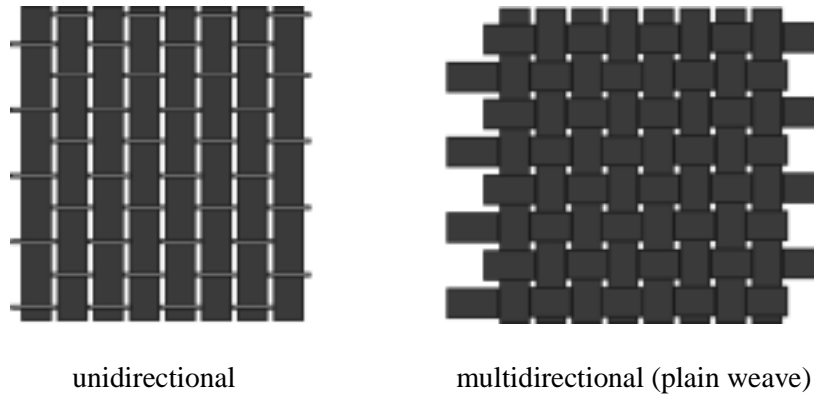


Figure 1-1: Geometry of Common Weave Patterns

1.2 Manufacturing Methods:

Successful incorporation of fibers within the resin can be obtained via a wide range of methods, including wet layup, spray-up, preimpregnated (prepreg) layup, liquid molding and others. Due to the simplicity and the flexibility of manual production, wet layup remains the most widely used process. In wet layup, dry sheets of fabric are typically placed inside a mold, and resin is added between each layer to ensure full saturation. Using rollers or squeegees, resin is then forced to penetrate the fabric and completely wet-out the fibers. The part may be left to cure at ambient conditions, however, enhanced mechanical properties may be obtained via application of vacuum pressure and external heat. While vacuum pressure leads to higher degrees of fiber compaction and saturation of the fibrous architecture by the resin system, lower part thickness and smaller resin voids, high temperature cure promotes crosslinking. Upon achieving sufficient “green strength”, which may actually be much lower than 100% cure, the composite is demolded. Degree of cure largely depends on the resin stoichiometry, as well as ambient conditions. Due to the chemical nature of polymer crosslinking, high moisture content can result in incomplete cure. Low temperatures cause a similar effect, which makes outdoor manufacturing of composites particularly susceptible to these effects.

Preimpregnated material typically contains unidirectional fibers that have been impregnated and partially cured prior to use. Prepreg is used for manufacturing of parts in the aerospace industry that demand a relatively high fiber volume fractions V_f , high dimensional stability, and high quality (see section 1.3). The material is much thinner compared to conventional fabric, thus a higher number of layers is required to form a composite with identical thickness. Prepreg sheets are supplied on rolls with a layer of backing paper (peel ply) between adjacent layers. Upon installation, the backing paper is removed and the plies are stacked to form the desired composite structure. Due to the preimpregnation with a partially cured resin system, prepreg rolls must be stored in a freezer to retard the steady progression of cure. Prior to installation, thawing should take place in the original container to prevent condensation.

1.3 Mechanical and Thermal Properties:

Both mechanical and thermal properties of composite materials are governed by the properties of the individual components. Unlike steel, composites are anisotropic materials as they show significantly different properties in longitudinal and transverse directions, with respect to the fiber axis. Figure 1-2 indicates the rapid decrease of tensile stiffness with increasing off-axis angles for unidirectional and woven composite materials. A quasi-isotropic material, i.e. with similar properties in all directions, can only be obtained by using chopped strand mats with randomly oriented fibers, however, chopped fiber materials are not nearly as stiff and strong as their continuous counterparts. Although fibers are the main contributors to strength and stiffness, good adhesion between fibers and matrix as well as stress transfer between adjacent fibers is an absolute necessity for high material performance. In composite design, mechanical properties are mostly governed by the ratio of fiber volume to overall material volume, V_f . An increase in V_f results in a composite with higher strength and stiffness. Nevertheless, in practical applications, V_f is limited to roughly 55-65% for prepreg material and only 30 to 55% for wet layup, depending on weave geometry, resin viscosity, stacking order, degree of layer compaction as well as cure conditions.

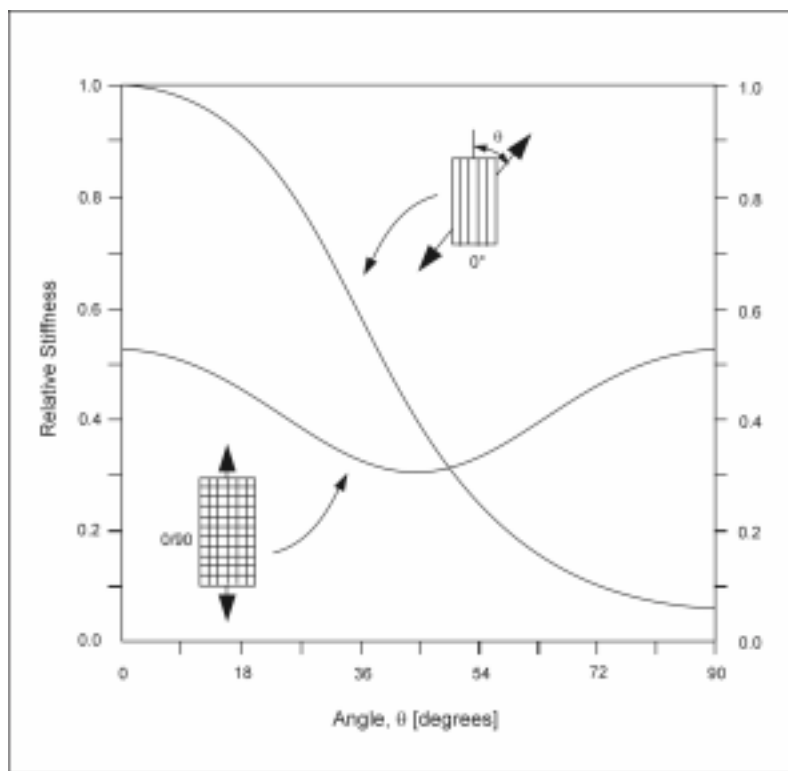


Figure 1-2: Effect of Test Angle upon In-Plane Stiffness of Unidirectional and Biaxial Laminates [2]

Due to the anisotropic nature of composites, thermal properties are often different in multiple directions. Under normal ambient conditions, the coefficient of thermal expansion of carbon fibers is positive in the transverse direction and negative in the

longitudinal direction, resulting in a longitudinal contraction of the composite material upon temperature increase. Most so-called ‘room-temperature’ epoxy resins have a T_g in the order of 60-80°C, indicating the maximum operating temperature of the composite. These resin systems are often available ‘off-the-shelf’ and the previously mentioned temperature limit must be considered prior to installation in hot environments.

1.4 Structural Applications:

A steadily increasing number of deteriorating infrastructure has forced civil engineers to develop viable rehabilitation methods, capable of significantly extending the service lifetime of a structure. While many concrete structures, such as bridges or dams were designed and constructed during the mid-20th century, continuously increasing traffic along with the exposure to harsh environments over more than 50 years has led to an unexpected degree of physical and chemical damage, experienced in substantial amounts of cracking, spalling and deterioration of internal steel reinforcement.

To date, a large number of concrete rehabilitation measures have involved the application of external reinforcement schemes, typically in form of epoxy bonded steel plates [3,4]. Recently, researchers have focused on using fiber reinforced polymer (FRP) composites for external strengthening, to make use of their high strength and stiffness as well as excellent environmental resistance [5-7]. Figure 1-3 depicts a typical application scheme for composite materials on concrete surfaces.



Figure 1-3: Strengthening of Concrete Bridge Deck

External strengthening is typically applied to account for structural degradation due to in-service conditions as well as additional flexural and shear loads, which were not included in the initial design of a structure. Furthermore, long-term exposure to the environment might have caused substantial damage in form of concrete cracking, spalling and exposure of corroded steel reinforcement. Through external bonding of composite materials, flexural and shear capacities of members such as columns, bridge girders or floor slabs may be significantly increased. Herein, the material is bonded to the concrete substrate using appropriate resin systems. To ensure adequate bonding, the concrete

substrate is sandblasted serving two main purposes. Firstly, the weak cement paste layer is removed and secondly, exposure of aggregate enhances mechanical interlock between adhesive and substrate.

While strength and stiffness of the composite material are important to the systems overall efficiency, the composite-substrate adhesive layer must primarily provide adequate stress transfers capabilities. Unless the adhesive material is specifically designed for adhesion, stress transfer and environmental resistance, the rehabilitation will lack performance and eventually undergo rapid degradation. Special resin formulations are available for these purposes, some of which are specifically designed as adhesives and others that are suitable for substrate bonding and saturation of fibers simultaneously.

If the composite element is bonded onto a concrete substrate, the efficacy of the method depends on the combined action of the entire system with emphasis on the integrity of the bond and the interface layers. The composite-adhesive/resin-concrete system must be considered as a complete system and material aspects of each of the constituents, and interactions thereof between themselves and the external environment can have a significant effect on overall efficiency and durability. The external reinforcement can be fabricated in three generic ways namely

- Adhesive bonding of a prefabricated element
- Wet layup of fabric
- Resin infusion

Of these methods, pre-manufactured elements show the highest degree of uniformity and quality control, since processing is done under controlled conditions. The composite strip/plate/panel is prefabricated manually or by automated processes (i.e. pultrusion) and then bonded to the concrete surface using an adhesive under pressure. Application is rapid but the efficiency is predicated by the use of an appropriate adhesive and through the achievement of a good bond between the concrete substrate and the adherent. Care must be taken to ensure that the adhesive is chosen to match as closely as possible both concrete and composite in regards to their elastic moduli and coefficients of thermal expansion, while providing an interlayer to reduce mismatch induced stresses. Commercially available strips are currently fabricated using unidirectional carbon fiber reinforcement, which is pultruded to preset thickness and widths. While this ensures uniformity of the material, preset dimensions often restrict the use of prefabricated material on structures with a more complex geometry.

As in other industries, the wet layup process is perhaps the most used currently and gives the maximum flexibility for field application. Moreover, it is probably the least costly alternative. However, it presents the most variability and necessitates the use of excessive resin and could result in wrinkling or shear deformation of the fabric used, decreasing its designed efficiency. The process entails application of resin to the concrete substrate followed by the impregnation of layers of fabric, which are bonded onto the substrate using the resin itself. Both the composite and the bond are formed at the same time in the field. The process affords the maximum flexibility in the field but

has the disadvantage of field mixing and fabrication along with a high potential for absorption of moisture and/or inclusions and impurities. Once applied, the composite is left to cure under ambient conditions. At present, both plain weave and unidirectional fabrics are commercially available for rehabilitation means.

The in situ resin infusion method is a fairly new variant and is capable of achieving uniformity and good fabric compaction, while making it easier for the reinforcement to be placed without excessive unintended deformation. However, this scheme is difficult to apply over large areas and necessitates application of vacuum. In the infusion process, the reinforcing fabric is first formed into a preform, which is attached to the substrate using a vacuum bag. Resin is infused into the fibrous assembly under vacuum to form the composite. As in wet layup, the composite and bond are formed at the same time.

Despite the high potential of composite materials, when compared to conventional building materials like steel and concrete, the physical nature of composites yields a much higher potential for introduction of material defects. In addition, composite materials represent a construction material that is relatively new to the civil industry. Consequently, contractors and field workers are still unfamiliar with the appropriate material handling, storage and installation procedures involved. Processing of composite materials, unless performed by highly automated processes like pultrusion or filament winding, typically necessitates a certain degree of human involvement, providing room for errors, such as non-uniformity or matrix flaws, to name only a few. Other examples include air pockets, debonding, fiber misalignment or poor resin quality. As shown by several researchers, the above-mentioned defects in composite materials are capable of reducing performance and long-term durability of composite materials [8-11].

Structural rehabilitation methods have already encountered several of the previously addressed material flaws, which have led to a substantial amount of material degradation as well as deterioration of the entire rehabilitation scheme. A typical example is shown in Figure 1-4, where moisture, propagating from inside the concrete, has become entrapped at the concrete/composite interface. The result was loss of intimate bond over a large area in the externally strengthened deck slab. Here, encapsulation of an entire area without incorporation of ventilation gaps has restricted the escape of moisture.

This report is the first of a series of reports discussing the typical appearance, identification, characterization and effect of defects in structurally rehabilitated members. Part 1 focuses on defect identification in composite materials, based on knowledge and results acquired from numerous research investigations conducted by the aerospace industry. This knowledge is projected onto common structural rehabilitation methods to provide a basis for identification of defects and assessment of their criticality in the external strengthening of concrete components. Subsequent parts will focus on defect detection, criticality and their effect on structural systems. While a range of materials can be used for external strengthening, this assessment will focus on composites using the wet lay-up process and external bonding of prefabricated strips. Since use of prepreg in structural rehabilitation has been rare, mainly due to the need for cure at elevated temperature and the difficulty to obtain adequate bond without the use of additional resin,

it will not be included in the further discussion. Apart from the installation process, material quality, site and material preparation and service conditions will be addressed. These stages are schematically shown in Figure 1-5. They will be discussed in further detail in the following chapters of this report.



Figure 1-4: Delamination Due to Entrapped Moisture

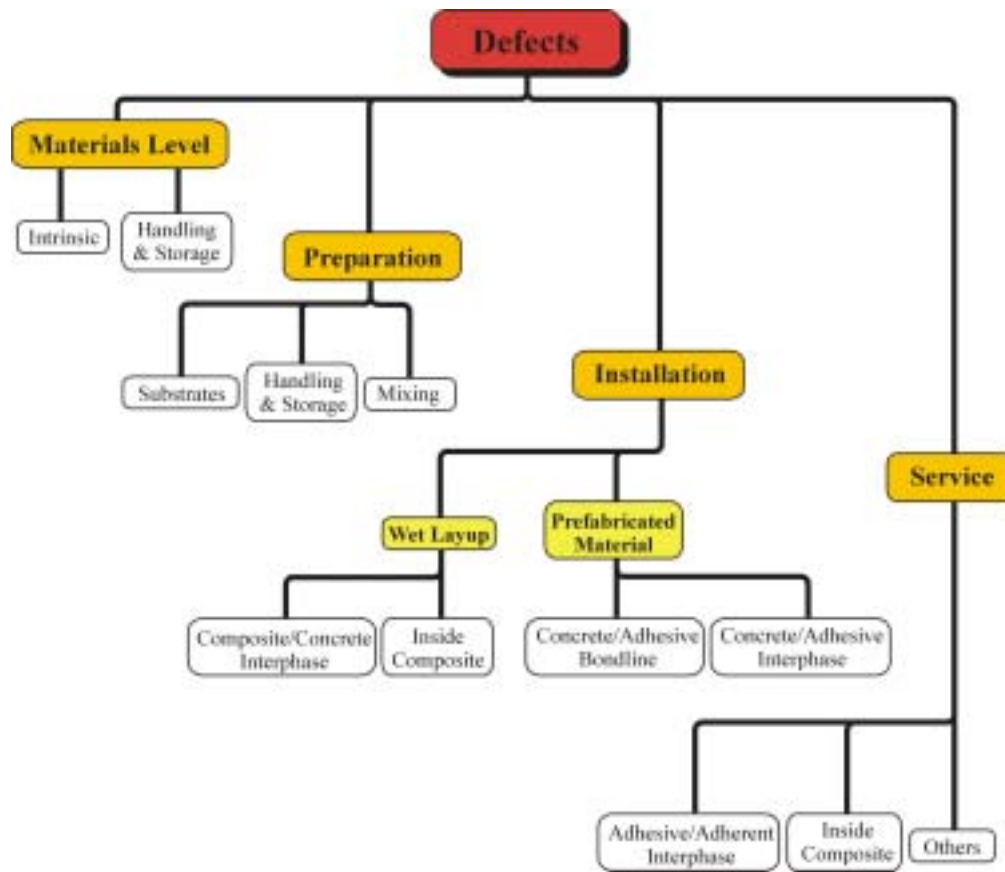


Figure 1-5: Schematic Diagram of Defect-Initiating Stages

2. DEFECTS IN COMPOSITE MATERIALS

The performance of composite materials depends on the successful incorporation of high strength and stiffness fibers in a surrounding matrix material. While fibers are the main contributors to strength and stiffness, the matrix serves as a medium for transferring stresses between adjacent fibers. Thus, an ideal unidirectional fiber reinforced composite material would have straight fibers running exactly parallel to each other, with fibers completely embedded in a strongly adhering, uniform matrix material. However, due to several factors, which will be addressed in the following, uniformity of the material may be disturbed. Such imperfections can occur in the fiber material, the matrix, as well as at the interface between both materials. If two materials are bonded together to form a composite (e.g. two composite strips), high quality of the interface is crucial, since it ensures stress transfer between layers. Bonding can be achieved using a resin system identical to that used for fiber infiltration or by application of special adhesives. These materials are preferably high-viscosity polymeric systems, particularly in cases where one material shows a significant amount of surface irregularities (i.e. when bonding composites to concrete).

Apart from knowledge on common defect types encountered in composite materials, their initiating factors (why and when is a defect introduced) must be studied. For most applications, two distinct stages can be identified, namely:

- Defects produced during manufacture
- In-service damage

A large body of research has already been conducted by the aerospace industry, a sector where high material uniformity and performance are an absolute necessity [9-15]. In the following, results of the extensive knowledge from the aerospace and marine industry are used to provide a basis for defect identification and assessment for the specific application under consideration in this document. Due care is however taken to assure applicability and appropriateness for the materials set and processing conditions that would be used in a civil engineering context.

Depending on size, defects can be classified as either microscopic or macroscopic. The former includes material flaws such as hollow, cracked or otherwise damaged or degraded fibers as well as variation in fiber diameter, as well as fiber-matrix debonds and/or non-uniform and poor fiber wet-out, while the latter is mostly related to matrix voids, misorientation, wrinkling or shearing of fabric, as well as delamination or separation of reinforcing fabric layers. It has been shown that microscopic defects in the form of existing defects on fibers occur even in the best laminates and that their effect on material performance is mostly negligible. Consequently, it has been suggested that, whilst causing slight reductions in material strength, micro-defect should be regarded as a material property [12]. However, effects of environmental exposure induced fiber degradation, fiber-matrix bond non-uniformity, and non-uniformity in wet-out can be significant and cannot be neglected. However, most of these effects can be avoided through the judicious and appropriate selection of constituent materials (fiber and resin)

and adherence to rigid processing standards. The use of prefabricated components is one means of ensuring a reasonable level of quality control and assurance. Classification of defects in wet layup systems is, however, more complicated. Here, the ratio of defective material over good material seems more deterministic towards defect criticality than the actual type of flaw encountered. As such, the isolated local existence of microscopic traces of contaminants such as moisture may be significantly less important for durability than the larger agglomeration of inclusions or global effects of moisture or solvent uptake.

At the macroscopic level, defects are often associated with certain structural features. For example, voids and kinking of fibers is more likely to occur in concave regions, since the laminate must be forced into this shape, resulting in poor material consolidation [12]. Other researchers have suggested further dividing the initiating factors of defects [13], including the following:

- Fibers
- Matrix and fiber-matrix bond
- Stacking or layup
- In-service defects

Generally, it may be assumed that the manufacturer controls quality of constituent materials (fibers, resin system components) to a sufficient degree. Nevertheless, poor manufacturing, handling or storage of the material during production/transportation can result in fiber damage, distorted alignment of fibers within the fabric, contaminations or surface moisture accumulation. Small debris, dirt, or other objects that adhere to single fiber bundles typically contaminate fibrous reinforcement [13]. While resin systems are less susceptible to physical damage, the vast majority of systems can be degraded by impurities. Contaminations in resins occur in form of foreign chemicals, moisture or fine particles, altering its chemical consistency and reactivity. Furthermore, their limited shelf life provides the chance of using overaged material that has lower reactivity along with an increase of viscosity to a point where processing becomes virtually impossible. Also, fiber-matrix bond is substantially lower if the resin system lacks reactivity or if contaminations are deposited on the fiber surface.

Prefabricated material designed for installation in the field typically possesses a higher degree of material uniformity. Since cutting of fabric and/or tensioning of individual tows in unidirectional pultruded elements, infiltration and cure of the part are performed by automated processes as well as in a controlled environment, most of the previously addressed material flaws can be ruled out in this form of material. It can thus be assumed that these materials possess a relatively low amount of internal defects. Nevertheless, handling damage remains as a potential initiator for material flaws.

Another important aspect in material quality is related to moisture accumulation. Resin systems are capable of moisture absorption, generally resulting in inferior material properties, including loss in shear strength, reduction in modulus, and depression in level of glass transition temperature. Further, moisture absorption can cause significant

physical and chemical changes in the resin leading to irreversible changes through hydrolysis, saponification, and other such phenomena. While the strength and modulus of carbon fibers is not influenced by moisture, a significant decrease in bond strength in the composite can occur if moisture is accumulated on their surface. However, both glass and aramid fibers can be severely degraded by the presence of moisture next to the bare fiber. Material properties can further be influenced by storage conditions. Resins and fibrous material should therefore be stored in a cool and dry environment, to prevent moisture accumulation and unintended gel.

One of the main reasons for variations in material properties is the manufacturing process, i.e. the procedure used to develop the desired combination of resin and fibers to form the composite material. Since a small degree of human involvement always remains, even the most automated processes are susceptible to human errors. Naturally, composite material defects occur more frequently in parts manufactured by hand layup than in most other automatically processed components. Common types of defects include porosity, voids (air pockets), incorrect fiber orientation, resin richness/poorness, poor mixing, incorrect cure, inclusions and dirt, as well as wrong stacking sequences and delaminations [9-13]. Air pockets typically become entrapped when stacking multiple sheets of lamina and must be removed via use of rollers. Although this provides a means to remove most of the entrapped air, small amounts always remain inside the matrix. Porosity, a microscopic defect, can also be caused by volatiles given off during the curing cycle. In regions where porosity shows a high occurrence, these microscopic defects may join together to form a large void [13].

In-service defects have drawn the attention of many researchers [14,15], especially in the aerospace field. High-localized loading, such as impact of an object, causes one of the most common in-service defects. The exposure to runway debris often induces subsurface delaminations that are not visible on the surface yet significantly reduce material performance. Material defects induced during manufacturing, such as voids or excess resin often weaken the plane between two layers of fibrous reinforcement. Under high loading conditions, interlaminar cracks can form. Furthermore, moisture penetration remains critical even in the cured state. Over time, water and other liquids can penetrate the material and accumulate in porous matrix regions.

Similar to the composite material itself, quality and performance of adhesive bonds can be influenced by a number of material flaws. Depending on the substrate material, adhesives must be chosen to match the surface structure. The two main phases involved in adhesive bonding are:

- Adhesive
- Adhesive/adherent interface

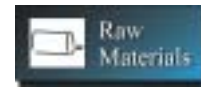
Similar to the matrix in composite materials, porosity, voids, incorrect or incomplete curing and application of incorrect amounts can be found in the application of polymeric adhesives. Moreover, the adhesive/adherent interfaces can experience weak bonding due to chemical deposits or material inclusions. Here, adherent refers to both prefabricated-

as well as substrate material. Sufficient abrasion followed by cleaning and, in the case of a concrete substrate, application of adequate surface primers, often results in a high-quality bond. During service, moisture penetration can lower the material properties and cause the loss of bond, resulting in separation of the bonded materials.

3. DEFECTS IN STRUCTURAL REHABILITATION

During rehabilitation of structural elements, defects may be induced at different stages of the process. A structurally significant defect can be defined as a material flaw which, within the lifetime of a structure, reduces its load carrying capabilities to a level less than or equal to the design values. Once a defect has been induced, elimination may become difficult, if not impossible. Furthermore, criticality can vary significantly among defects, depending on their type, location, density and size. The following discussion aims at describing those defects most likely to be encountered during structural renewal of concrete structures using FRP composites. Examples from defects already encountered in rehabilitated structures will be described and evaluated. While most defects can be related to a specific stage of the rehabilitation process, some may be induced at several, if not all stages of the process. According to the preceding discussion, the following four stages were chosen for closer evaluation:

- Incoming raw or constituent materials,
- Site preparation and on site processing,
- Installation in the field, and
- Service



3.1. Incoming Raw or Constituent Materials:

Incoming raw materials can be of inferior quality and unsuitable for structural applications. Quality control should be performed, in order to detect such defects before the materials are used in the field. Generally, resin, fabric, preimpregnated material (prepreg), and prefabricated material are considered as the primary components. In the following, potential defects of each material are listed, illustrated, and discussed.

3.1.1 Resin System:

Generally, any variation from the manufacturer's specifications should be reported and considered carefully. While a large number of resin systems are commercially available, they generally cannot be used interchangeably. If the resin system is not suitable for the desired purpose, it must not be used. Material variations caused by improper storage or production, such as chemical inconsistency or impurities are typically inspected visually on a pass/no-pass basis, typically through viscosity tests. More sophisticated techniques of material testing are mostly unavailable in the field since they generally require laboratory equipment. Consequently, control has to be performed in compliance with a specification sheet, as commonly supplied with most resin systems. While this may be used for some aspects, such as shelf life, it does not provide any information on impurities or moisture absorption during storage.

3.1.1.1 Overaged Material: Resin, hardener, catalyst or additives may be beyond their specified shelf life. Most cans bear a label, showing the date of expiration of the contents

(Figure 3-1). Typically, resin shelf life ranges between 3 to 8 months. If stored in warm environments, resin tends to pre-cure inside the container, thus decreasing shelf life. Although reactive agents have not been introduced to the resin, the constituents slowly cure, as the material is stored. If expired, resins should not be used. An overaged resin system shows lower reactivity, resulting in lower strength and elastic modulus. Also, viscosity increases with time, leading to difficulties during fiber infiltration. These properties can be checked through use of viscosity tests and differential scanning calorimetry (DSC).

3.1.1.2 Contaminations/Inclusions: Resin inclusions may be present in the form of small particles, such as dirt, sand, etc. If worked into the fabric, fibers may be damaged. Also, chemical consistency may be altered, depending on the type of inclusion. If oils or silicones are mixed within the resin, they may serve as potential initiators for debonding or delamination. These material flaws can be detected through viscosity tests since additions cause an increase in viscosity. Moisture can be detected through DSC or differential mechanical thermal analysis (DMTA) of cured materials, and in extreme cases, FTIR spectroscopy can be used to assess the state of the resin system itself.



Figure 3-1: Resin Label

3.1.1.3 Moisture Entrapment: Improper storage of sealed containers over extended periods of time may induce moisture to the resin, leading to poor reactivity and incomplete cure. Also, resealing of containers may result in moisture contamination of the remaining resin. If large quantities of resin have been stored in a humid environment, a DSC or FTIR test may be used to check for increased moisture content. Although time consuming due to additional off-field laboratory time, it can ascertain the quality of the resin and prevent long-term effects. Introduction of moisture into resin can lead to premature gelation, degradation through saponification, hydrolysis or other chemical reactions.

3.1.2 *Fibrous Material:*

Fibers are supplied in different forms with varying fibrous assembly geometries (unidirectional and multidirectional) to provide strength in one or multiple directions. For most rehabilitation applications, unidirectional or a woven fabric is preferable. Supplied on rolls, damage to fibers may not be detected until immediately prior to installation. The primary quality control objectives for fibers are:

- Mechanical properties
- Bond to matrix

3.1.2.1 Incorrect Fiber Type: Prior to installation, fiber type, structure and weave geometry has to be inspected. The material must meet the design specifications (type, strength and stiffness properties) in all aspects. If the material appears different in geometry, it most likely possesses strength and stiffness properties that vary from those required. Although this control process is visual and rather unsophisticated, it requires the installer to have basic knowledge of fiber geometry and appearance of different fiber types.

3.1.2.2 Kinked or Wavy Bundles: Fibers inside a fabric may be kinked or wavy, as shown in Figure 3-2. If kinked, fibers may easily break during handling or installation. Wavy fiber bundles do not run in the principle loading direction, hence they are not capable of resisting equally high loads along this direction. As a result, adjacent, straight fiber bundles have to account for higher stresses (stress concentrations). Also, a loss in stiffness is likely to be encountered.



Figure 3-2: Kinked Fibers

3.1.2.3 Broken Fibers: While a single broken fiber is difficult to detect, broken fiber strands (Figure 3-3) are more critical and should be noticed. Although each fiber bundle contains a large number of fiber discontinuities (due to the manufacturing process), these discontinuities differ in location throughout a bundle. Therefore, stress concentrations

from one broken fiber may be easily adopted by adjacent fibers. In case of a ruptured bundle, however, stress concentrations are significantly higher and weaken the fabric to an enormous extent.

3.1.2.4 Contaminations/Inclusions: The fiber surface may contain impurities in form of chemicals or small objects, as depicted in Figure 3-4, which can harm both fiber- and bond strength. While carbon fibers are rather inert to chemicals, glass fibers are highly susceptible to alkali attack. Sizing chemistry, a measure for resin/fabric bond capability, can be affected by certain chemicals and thus reduce bond strength. Small objects are likely to be trapped near the fiber surface to form a void and serve as a potential debond. In case of sharp-edged inclusions, fibers may be severely damaged upon infiltration.

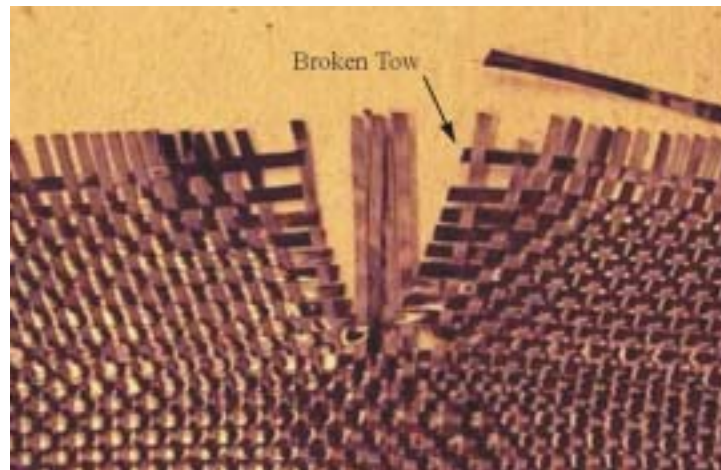


Figure 3-3: Broken Fiber Tows

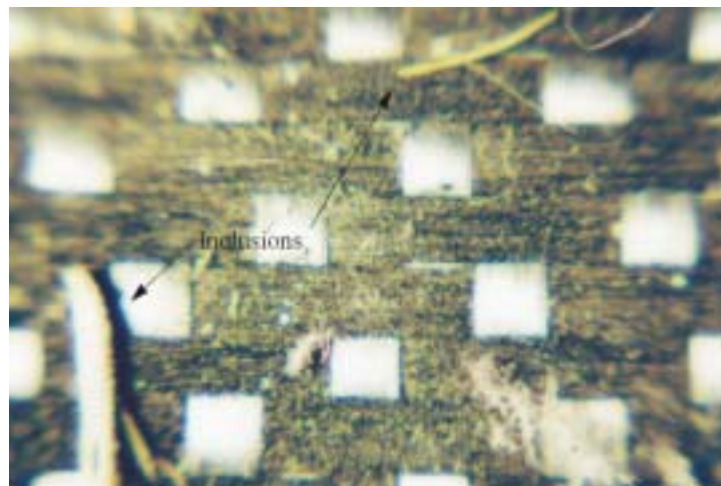


Figure 3-4: Fabric Inclusions

3.1.2.5 Fabric Wrinkles: During processing and handling of fabric, fiber wrinkles may be induced. Shown exaggerated in Figure 3-5, such wrinkles should be straightened as

much as possible without further disturbing fabric uniformity, before the fabric is infiltrated. On severely wrinkled material, fiber damage may occur. If a fabric has a wrinkle running along its entire width, strength and stiffness reduction may be a concern, especially if the wrinkle is not smoothed out during fabrication of the composite resulting in air entrapment, fiber misalignment, and local zones of weakness and points of crack/delamination initiation.

3.1.2.6 Sheared Fabric: If woven fabrics are exposed to shear forces during handling, fiber alignment can change to an undesirable off-axis direction. As such, a 0/90 fabric may end up as a 15/75, similar to the fabric shown in Figure 3-6. As a result, fibers no longer run along the principal axis and cannot develop their full potential in strength and stiffness.

3.1.2.7 Damage to Free Edges: During handling of fabric rolls, damage to free edges is likely to occur. Because a fabric structure does not exhibit the same integrity around edges as inside the woven area, edges are also more likely to decompose during resin infiltration. Material shown in Figure 3-7 utilizes additional rows of stitching along the material edges that are effective in preventing such decomposition. However, if the stitching is damaged or missing, as shown on the left, the affected portion must be discarded. In case of multiaxial fabrics, the removal or damage of tows can cause change in local reinforcement ratio.

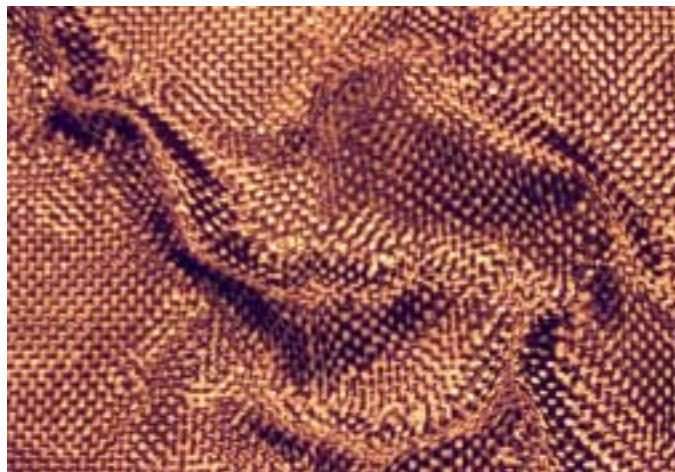


Figure 3-5: Wrinkled Fabric

3.1.2.8 Loose Fibers: Pullout of single fibers or fiber bundles (Figure 3-8) may occur during processing, as well as handling in the field. Loose material does not exhibit the same intermediate contact to nearby fibers and is more likely to be sheared during resin infiltration. Furthermore, resin rich areas tend to form in these regions, resulting in low stress transfer capabilities between adjacent fiber strands.

3.1.2.9 Fiber Gaps: Separation of fiber tows within a woven fabric or unidirectional tape can be experienced in form of gaps (Figure 3-9). Such gaps will disturb fiber integrity,

lower strength and stiffness, promote resin richness and serve as locations of low crack propagation resistance.

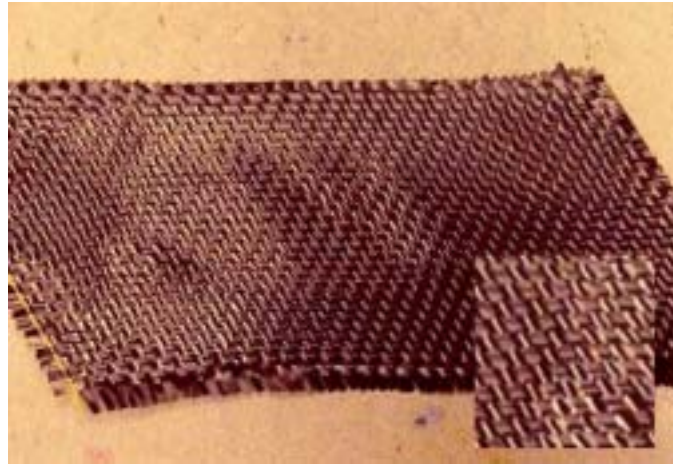


Figure 3-6: Sheared Fabric



Figure 3-7: Damaged Edges

3.1.2.10 Moisture Entrapment: Similar to resins, fibers may accumulate surface moisture if exposed to humidity for an extended period. Overnight storage should be performed under stable temperatures and in a moisture-controlled environment. If moisture is apparent, fabric should be discarded. Most fibers do not absorb moisture. However, surface moisture will lower bond strength to the resin matrix and present risk of large area delamination.

3.1.3 Prefabricated Material:

For some applications, prefabricated composite strips are preferred over wet lay-up of fabric. Manufactured under controlled conditions, prefabricated material is less likely to experience material strength degradation due to voids, non-uniform impregnation, or

moisture entrapment. A special adhesive is chosen to bond the reinforcement to the prepared concrete substrate. In most cases, long uniform strips are used to serve as additional flexural or shear reinforcement. These are commonly made via the pultrusion process. On more complex members, such as T-girders, the use of prefabricated material is likely to be limited due to the requirement of exact conformance with specific geometric configurations. Although L- and U-shaped sections are commercially available, their suitability must be confirmed for each individual member prior to attempting installation. A slight deviation in chamfer- or web dimensions along the girder length may therefore not allow the use of identically prefabricated parts. Nevertheless, prefabricated material has been used successfully in concrete rehabilitation.

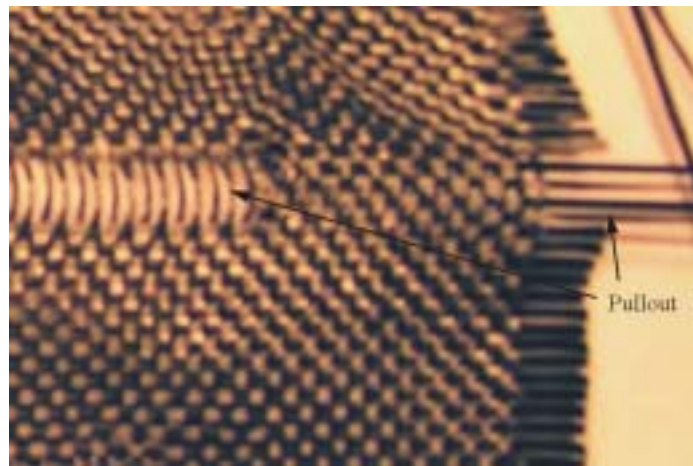


Figure 3-8: Fiber Pullout

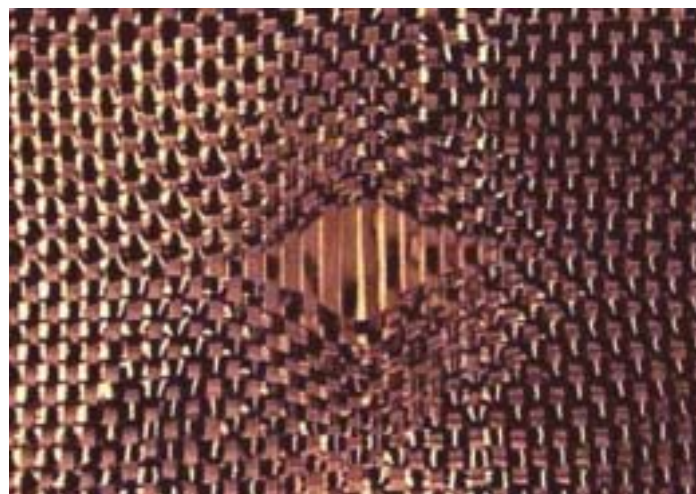


Figure 3-9: Large Fiber Gap

3.1.3.1 Voids and Process Induced Defects: Since prefabricated material is manufactured under controlled conditions, void content may be considered low. In most cases, quality

control of the supplier determines whether a part is acceptable or should be discarded. In addition, specification sheets of prefabricated material are based on average results and account for a typical void content.

3.1.3.2 Transportation/Handling Damage: Damage to prefabricated material may be induced during storage, transportation or handling. Typical defects include splitting, delamination, matrix cracking, scratched surfaces, etc. Once the material has left the processing facility, the installer must determine whether it has experienced additional damage and make assessments towards the suitability for installation. Figure 3-10 shows typical composite strips with delamination of several layers (top) as well as longitudinal splitting (bottom). It must be emphasized, however, that these forms of material damage are not a common occurrence.

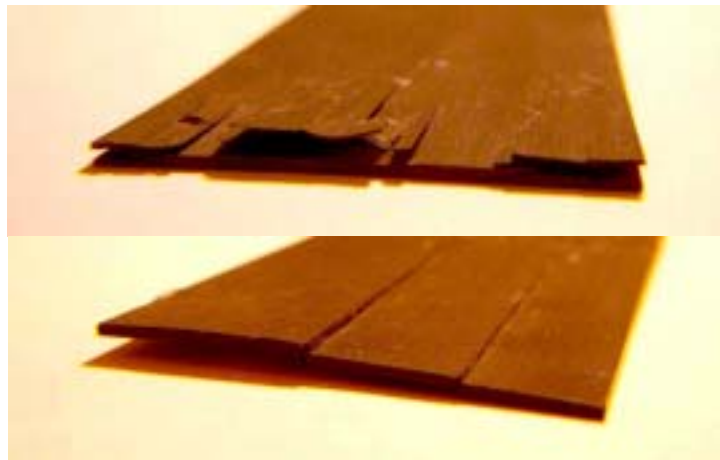


Figure 3-10: Damaged Prefabricated Material

3.2 Site Preparation and on Site Processing:

Any successful rehabilitation measure demands proper preparation of the structural element. This includes surface preparation, such as sandblasting, of the concrete to a desired degree, storage of fiber- and resin constituent materials as well as mixing of the resin system. On-site processing, if performed incorrectly, contains a high potential for flaw introduction. It further necessitates assessments in regards to the integrity and bond-capability of the concrete substrate. In some cases, cracked or split concrete sections may contain wide cracks that must be injected with resin prior to application of the composite strengthening system. Defects induced by preparation and site processing are listed in the following.

3.2.1 Resin System:

3.2.1.1 Storage: Improper storage of the resin system, as well as the hardener/catalyst, can lead to significant moisture absorption. If stored under inappropriate conditions, such as extreme cold, heat, or humidity, resin properties may change dramatically with time. In addition, as discussed previously, shelf life must be monitored to assure sufficient reactivity and viscosity.

3.2.1.2 Stoichiometry: Resin and hardener/catalyst must be compatible and of adequate mechanical and chemical properties for the job at stake. For all resin systems, the hardener/catalyst ratio must be determined very carefully to prevent premature gelling or loss of matrix strength.

3.2.1.3 Mixing: During mixing, several defects may be introduced to the system, and consequently, the laminate itself. Firstly, if using rotary mixers, air can be drawn into the resin and remain as small air bubbles, leading to laminate porosity. In some cases, this porosity may later result in the formation of air bubbles of much larger diameter (mm range). A high number of roller passes are thus required to remove porosity from laminates that have been infiltrated with air-rich resin systems, since it is known that in the range from zero to 5%, each 1% increase in void content decreases interlaminar shear strength by about 10% [16]. Consequently, mixing must be performed at a slow rate and without drawing an excessive amount of air into the matrix. In contrast, a low degree of mixing can result in chemical inconsistency, meaning that some regions contain high percentages of reactant, while others may contain no reactant at all, schematically illustrated in Figure 3-11. As a result, matrix strength and adhesion are low and due to lower levels of crosslinking there may be enhanced susceptibility to environmental degradation in areas of low polymer chain linkage. Secondly, the efficacy of the resin system depends on the appropriate use of mix ratio. Errors in mix ratio can result in undercure or no cure, premature gelling and even degradation due to excessive exotherm.

3.2.2 Fibrous Material:

Like resin, fibers are susceptible to moisture accumulation, however, accumulated moisture does not alter the performance of individual fiber tows. Instead, bond to the surrounding matrix is severely weakened. Since fibers can be directly exposed to the environment, i.e. torn plastic packaging, conditions must be monitored more closely than

in the case of a sealed resin container. If visual detection shows a significant amount of moisture accumulation on the fiber surface, they must be discarded. When a moist fabric is infiltrated, it will experience a weak bond to the surrounding matrix. Debonding and subsequent delamination are likely to be the result.

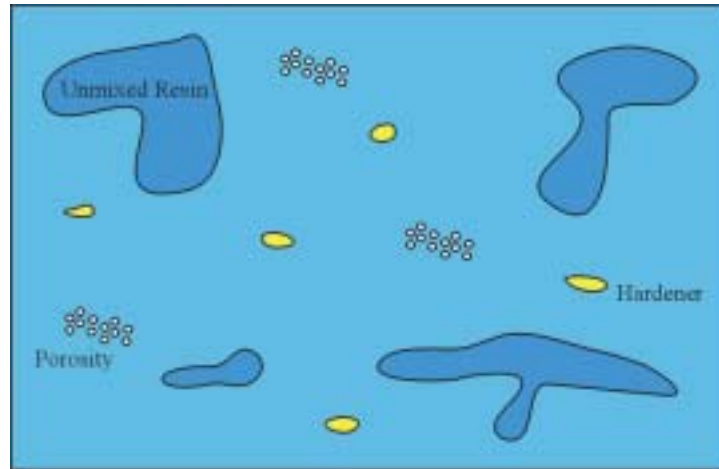


Figure 3-11: Results of Incorrect Mixing

3.2.3 Concrete Substrate:

To obtain adequate force transfer between the retrofit material and the concrete substrate, concrete preparation is essential. This includes thorough surface preparation to a specified degree and filling of concrete cracks. Large, deep cracks propagating into the concrete may contain water that can destroy the composite-concrete interface bond and should therefore be injected prior to rehabilitation (Figure 3-12). Cracks propagating at shallow depth can promote failure in the substrate. As such, the retrofit becomes ineffective.

3.2.3.1 Inadequate Primer Application: Concrete is a porous material and hence absorbs liquids. Moreover, due to abrasion of cement paste during sandblasting, a large number of small to medium diameter voids become exposed on the concrete surface, as shown in Figure 3-13. Prior to application of the composite overlay, regardless of type, a compatible primer coat should be applied. The role of this primer is to fill voids and quench the absorption so that the surface is prepared for the subsequently applied composite material. If primer coatings are omitted, the saturating resin would otherwise be to an extent absorbed. Also, the primer presents a “bondable” surface. To ensure an intimate bond between composite and concrete, thickness of the coating should be kept as thin as possible. If excessive amounts of primer are used, low stress transfer capabilities and resin dripping can result (Figure 3-14).

3.2.3.2 Disbonding in Marked Regions: Marking of areas that require strengthening is generally done using a chalk line. However, care must be taken not to cause separation between the layup and base material by applying a material, which cannot be penetrated by the resin/adhesive. A typical example is shown in Figure 3-15, where duct tape serves

as a “marker line”. Here, edge disbonding at the concrete/composite interface was more likely to be encountered.

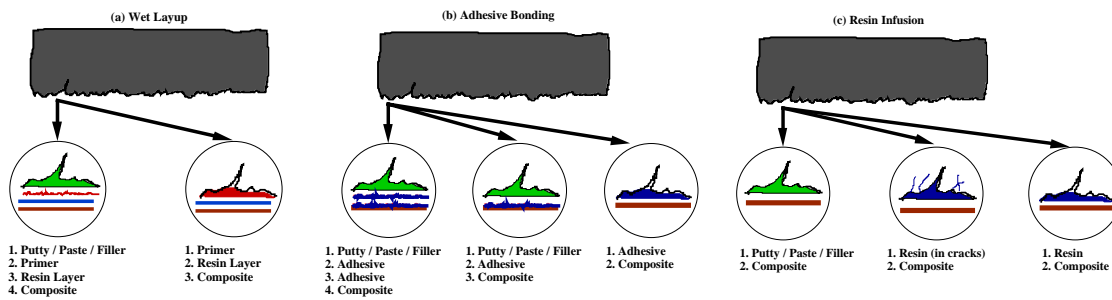


Figure 3-12: Common Surface Morphologies



Figure 3-13: Concrete Surface Irregularities



Figure 3-14: Primer Dripping



Figure 3-15: Fiber Placement over Duct Tape

3.2.3.3 Degradation at Imperfections: If the concrete substrate displays a high degree of microcracking at its surface, the composite overlay must bond to an initially weak base material. In extreme cases the poor cover material may need to be completely removed and replaced by appropriate fillers, prior to rehabilitation. Two forms of typical substrate degradation are depicted in Figure 3-16.

3.2.3.4 Inclusions at Imperfections: Naturally, many structures in need for rehabilitation already show a large number of cracks, which may have opened to a significant degree and thus accumulated moisture, dirt or other foreign material over time. By applying a primer coating, inclusions may become permanently encapsulated within the surface to serve as weak spots (Figure 3-17) for future crack initiation and propagation at the interface level. As a preventive measure, cracks should be cleaned and injected with appropriate filler materials, depending on depth and diameter of the crack.

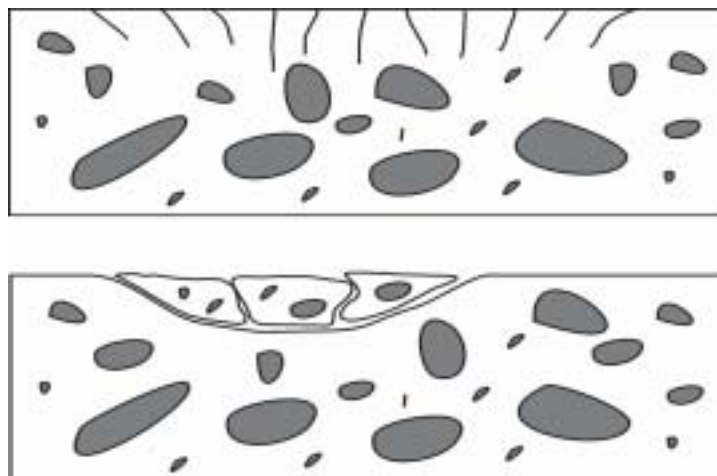


Figure 3-16: Microcracking and Spalling of Concrete Substrate

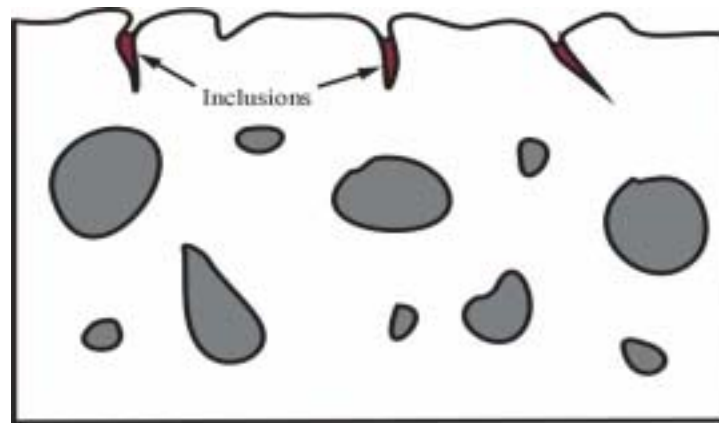


Figure 3-17: Inclusions at Imperfections

3.2.3.5 Inadequate Grinding of Substrate: To provide a smooth surface for bonding, any irregularities such as form lines or protruding aggregate should be ground down. If a composite laminate is applied to concrete surfaces that contain high spots, as depicted in Figure 3-18, the laminate will tend to form an air pocket. Similarly, large, hollow regions, which may result from high spots in the formwork, must be filled prior to composite application. Figure 3-19 illustrates the effect of composite placement over hollow regions.

3.2.3.6 Galvanic Corrosion: On spalled or otherwise heavily degraded members, the embedded steel reinforcement may be exposed to the environment. As a result, the composite strengthening system is likely to come into direct contact with the reinforcement (Figure 3-20). Due to the galvanic corrosion potential of carbon fibers, deterioration of the steel as well as the matrix material would be the result [17]. Thus, intimate contact between carbon composites and steel must be prevented, possible by application of suitable polymeric systems that serve as an insulator (e.g. GFRP, primer coating).



Figure 3-18: Air Entrapment over High Spots

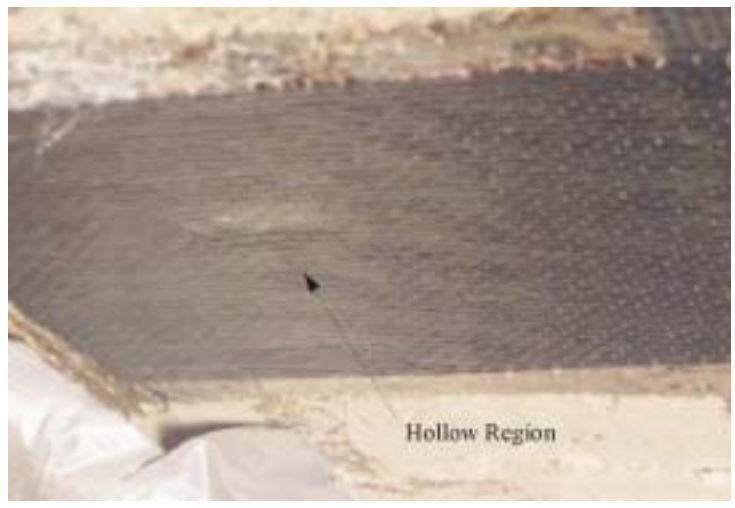


Figure 3-19: Air Entrapment over Hollow Regions

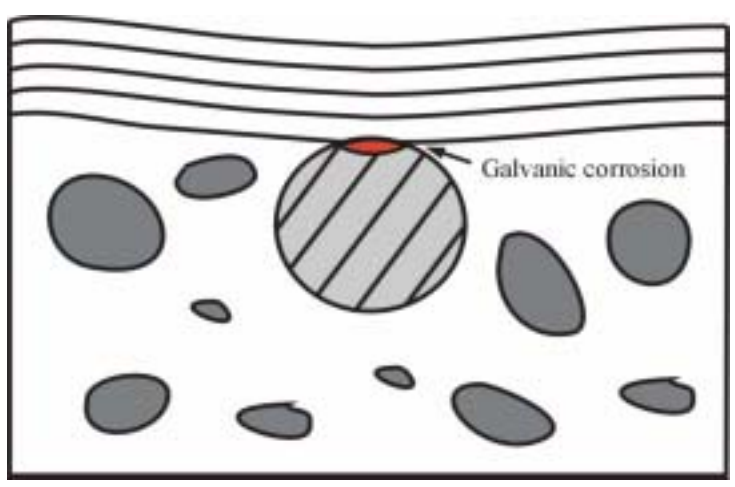


Figure 3-20: Galvanic Corrosion

3.3 *Installation in the Field:*

Among the four main stages of rehabilitation, field installation may be considered the most critical step in regards to quality assurance. A wide range of defects, classifiable from benign to severe can be introduced at this stage. Numerous research studies have been conducted that quantify the possible defects in composite materials. However, most research has been focused on aerospace applications [14,15]. Environmental conditions and material preparation are key elements to a successful installation of the material. For instance, many resin formulations do not cure at low ambient temperatures ($\approx 5^{\circ}\text{C}$) and develop significantly lower glass transition temperatures. In addition, a hot environment will cause premature gelling and make handling virtually impossible. Thus, installation must not be allowed to begin or be continued at temperatures below a critical threshold value. Furthermore, surface preparation and application procedures have to be followed closely to ensure proper interfacial bond strength as well as complete infiltration of the fibers. In the following, defects most likely to be encountered during installation of rehabilitation systems are addressed:

3.3.1 *At the Composite/Concrete Interface:*

3.3.1.1 *Sagging of Infiltrated Material:* Until the resin has developed adequate tackiness, i.e. turns into a gel, the infiltrated material tends to separate from the concrete, especially in vertical and overhead regions (Figure 3-21). To prevent large-scale debonding, the most susceptible areas must be rolled repeatedly until resin tack can be confirmed. If the material sags there is no bond or intimate contact between the composite and the substrate, thus stress transfer capabilities are severely reduced. Moreover, air pockets promote the accumulation of moisture as a long-term effect.



Figure 3-21: Sagging of Infiltrated Composite Material

3.3.1.2 *Non-uniform Concrete/Composite Interface:* Insufficient amounts of resin/adhesive can lead to a weak interfacial bond. While resin-rich regions experience low stress transfer, resin-starved areas tend to favor disbonding of the composite material

from the concrete substrate. Figure 3-22 illustrates a typical non-uniform interface thickness.

3.3.1.3 Porosity: Porosity is termed as the presence of a large number of microscopic air voids, typically in the range of $10\mu m$. It may be caused by volatiles and entrained gasses (air and water vapor) inside the resin/adhesive. While porosity can be considered a normal material property, it serves as a depository for diffused moisture. In certain areas, microvoids may combine to form a large void.

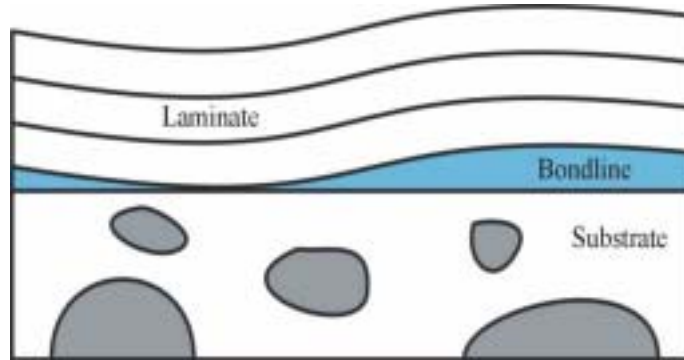


Figure 3-22: Resin-rich and Resin-starved Interface Regions

3.3.1.4 Voids: Voids are typically caused by air entrapment during the lay-up process. Other factors contributing to void formation are entrapped air from mixing, volatiles/gasses, an insufficient amount of resin applied, and inclusion of foreign particles. Also, if laminate is placed over high spots, which can occur as a result of formwork irregularities, air is likely to become entrapped around it. Thus, careful grinding of irregularities after sandblasting is advisable. Both porosity and voids cause internal stress concentrations. Examples of voids at the concrete/composite interface are shown in Figure 3-23.

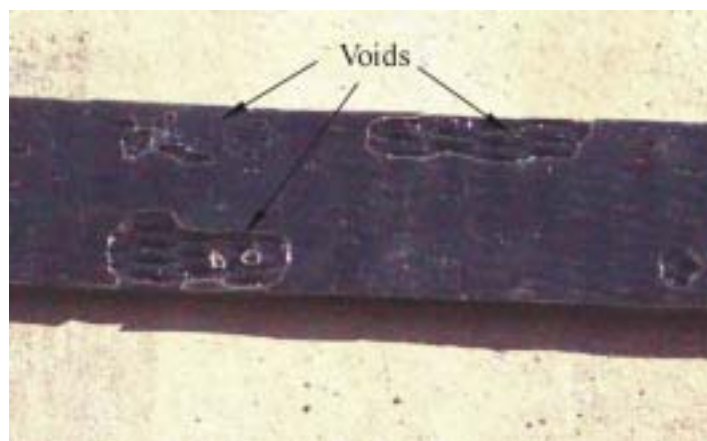


Figure 3-23: Typical Voids at the Concrete/Composite Interface

3.3.2 *Intrinsic to the Composite Material:*

3.3.2.1 *Porosity:* Similar to porosity at the concrete/composite interface, this flaw can occur inside the composite material. Initiating factors include volatiles given off during resin cure.

3.3.2.2 *Voids:* If multiple layers of fabric are placed on top of each other, air usually becomes entrapped between them. Rollers can be used to ‘work out’ most of the air. In addition, overlapping of layers promotes the formation of voids, since additional resin is needed to fill the gap formed at the overlap. For instance, voids in unidirectional composites exist as tubular pores, which run along adjacent fiber direction, almost exclusively at the fiber/matrix interface. Figure 3-24 shows the common forms of air entrapment inside the matrix material.

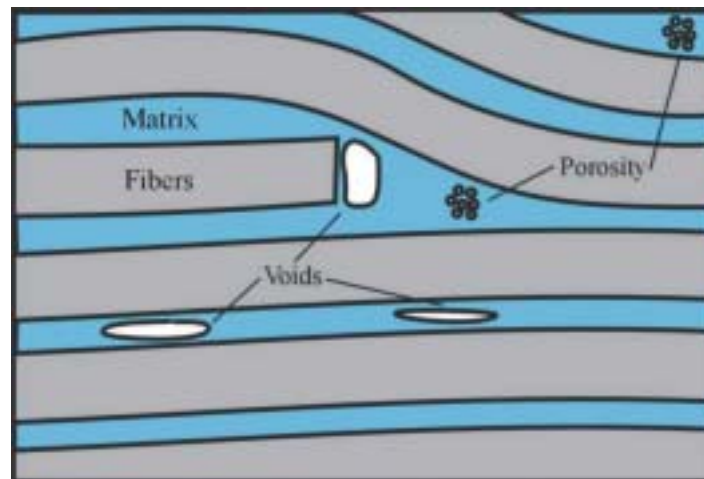


Figure 3-24: *Voids and Porosity Inside Composite Laminates*

3.3.2.3 *Debonding:* In the case of moisture accumulation on the fiber surface, deficiencies in bond strength between fibers and the surrounding matrix may occur. Depending on the amount and location of moisture accumulation, this can mean lack of bond formation during cure or debonding of the fibers from the matrix at a later stage. Generally, debonding results in loss of composite strength in transverse tension, interlaminar shear, and impact. Unlike delamination, debonding occurs in localized areas.

3.3.2.4 *Delamination:* Wrinkles, in which air is entrapped between layers, inclusions of non-adherent foreign objects or an inadvertent use of moist material may cause a delamination. In most cases, delamination is present over a fairly large area and severely reduces shear transfer capacity. Figure 3-25 shows certain types of delamination and their initiating factors.

3.3.2.5 *Fabric Waviness:* Performance of a strengthening system is in part dependent on fiber orientation. Fabric waviness in localized regions, as presented in Figure 3-26, can

lower the elastic modulus and result in inferior properties (compare Figure 1-2). Waviness originates from improper rolling in opposite directions towards one point of the laminate. Instead, rolling should be performed from mid-length towards both ends of a strengthening strip.

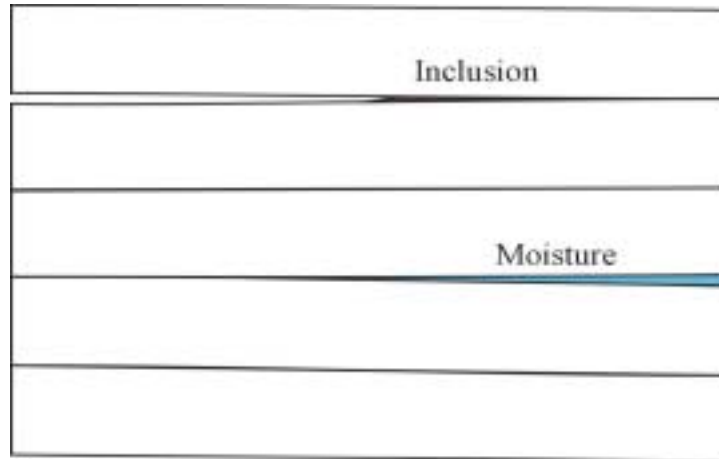


Figure 3-25: Delamination in Laminates



Figure 3-26: Waviness Caused by Improper Rolling

3.3.2.6 Resin Richness/Poorness: Resin rich areas result from the use of excessive amounts of resin during fiber infiltration. Proper rolling/squeezing of the fibers may contribute to lower void volume, higher uniformity, and removal of resin rich areas. Resin starved areas (resin poorness) are caused by an insufficient amount of resin. Consequently, no interlaminar bond will be present in those areas. Also, resin poor areas serve as a potential initiator for delamination. This material flaw is illustrated in Figure 3-27.

3.3.2.7 *Indentations:* Although mainly an in-service defect, indentations, presented in Figure 3-28, can occur during installation. Careless handling of prefabricated material can result in deep scratches that propagate into the material and cause damage to fibers. On wet lay-up, indentations can be caused by harsh use of infiltration tools.

3.3.2.8 *Damaged Edges:* Damage to edges mostly occurs in regions where fibers have already been pulled out of the fabric in the dry state. Upon infiltration, the weave loosens and allows fibers to be pulled from the fabric, as shown in Figure 3-29. This will cause reduction in strength and stiffness and increase the likeliness of material separation at the concrete/composite interface.

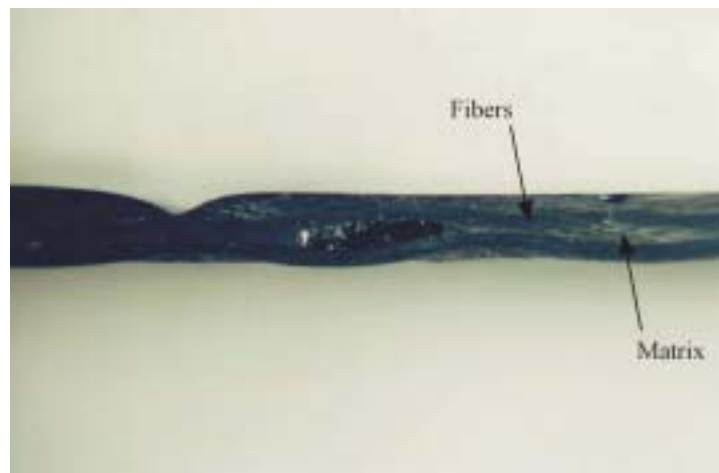


Figure 3-27: Variation in Matrix Thickness

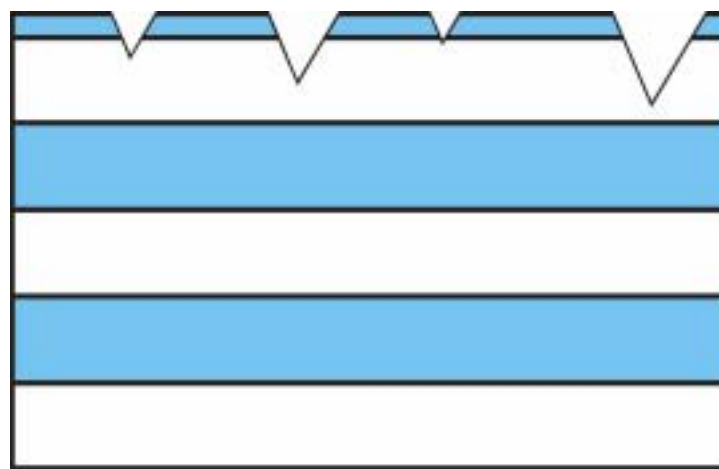


Figure 3-28: Indentations

3.3.2.9 *Missing Layers:* The high susceptibility of structural renewal measures to human error allows for the omission of entire layers within a stacking sequence, particularly in more complex applications, where multiple layers are used. Consequently, the

occurrence of such a defect will result in strength/stiffness properties of the laminate that will most likely be entirely different from the design values.



Figure 3-29: Pullout of Loose Fiber During Infiltration

3.3.3 Prefabricated Material:

The use of prefabricated material involves two distinct interfaces, the concrete/adhesive interface and the adhesive/adherent interface. The strength of each individual interfacial zone is dependent on different factors, including surface preparation as well as preparation of the adherent.

3.3.3.1 Concrete/Adhesive Interface: A highly viscous adhesive putty is commonly deposited on the substrate to form a film of approximately 1mm thickness. Prior to combination of substrate and reinforcing strip, a layer of nearly identical thickness is applied to the adherent. Upon combination, both adhesive films are joined and about 50% of the material is ideally removed in the process, resulting in an overall bondline thickness of 1mm. Since the process of putty application is similar to surface priming, defects at the concrete/composite interface can be considered identical to those discussed previously in section 3.3.1.

3.3.3.2 Adhesive/Adherent Interface: Adequate preparation of the prefabricated composite material is essential in obtaining a strong bond. Similar to concrete, surface preparation of prefabricated material is performed to abrade its surface and, ideally, expose some fibers to the surface. However, care must be taken so the fibers will not be severely damaged, i.e. abraded or cut. Bead blasting [18] and solvent wipe have proven to be suitable methods for enhancing mechanical interlock between adhesive and the adherent surface. On certain systems, strips are pre-sanded as part of the manufacturing process, leaving a smooth outer surface and one with a more pronounced fiber texture (Figure 3-30). Apart from preconditioning of the adherent, the adhesive used must be suitable for the composite material, i.e. it must allow for stress transfer and remain functional at a wide temperature range.

Given the fact that prefabricated strips are applied in a cured state, they are less flexible than wet fabric and do not conform to surface irregularities comparatively well. To obtain high uniformity of the adhesive prior to joining, strips are commonly passed through special resin applicators. If this operation is performed at a highly inconsistent rate, it can lead to resin-poor spots, as depicted in Figure 3-31. These must later be filled in by hand to reduce the risk of air entrapment.

Due to a natural tendency of composite strips to retain their straight orientation, regions of overlapping are usually critical. This includes utilization of grid patterns, which often result in excessive bondline thicknesses, which leads to a higher load being borne on the adhesive causing its premature failure. If strips are excessively rolled in an attempt to reduce bondline thickness, much of the resin becomes removed from underneath the strip, resulting in resin-poor areas once the composite has returned to its natural orientation. A concave, hollow bondline as shown in Figure 3-32 can be observed. In other areas the ends sag downwards/outwards resulting in increased adhesive thickness at ends, which can result in premature peeling or cracking within the adhesive layer itself under load.

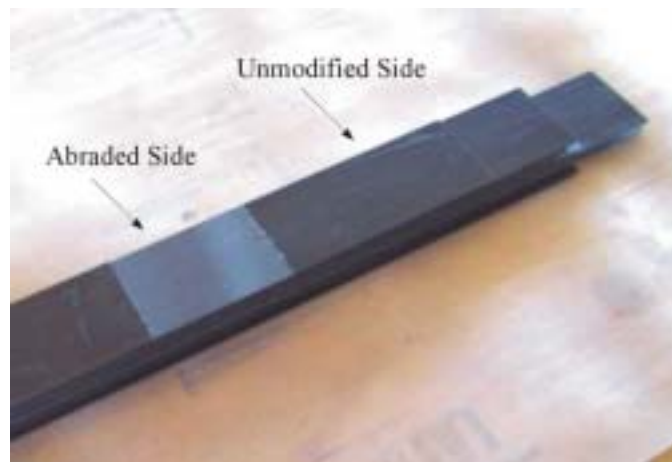


Figure 3-30: Differences in Texture of Various Pultruded Strips



Figure 3-31: Formation of Void During Putty Application

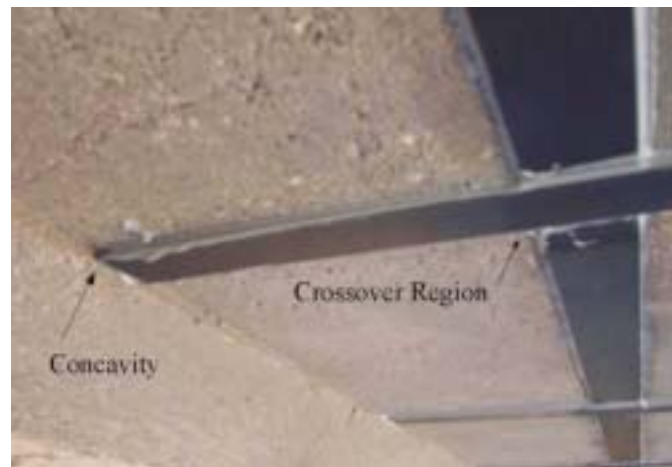


Figure 3-32: Bondline Concavity in Critical Applications

While these problems are unique to application of prefabricated strips, other defects include non-uniform concrete/composite interfacial thickness, porosity and voids, as discussed in sections 3.3.1.2, 3.3.1.3 and 3.3.1.4, respectively.

3.4 Service:

Most in-service defects found in rehabilitated structures may be considered to have long-term effects only, assuming that no significant defects have been induced during the installation process. Service induced damage can be divided into phases:

- Damage initially caused during service
- Growth of existing defects

Latter includes the propagation of existing flaws at the concrete/composite interface or inside the composite. Service loading, fatigue or environmental effects, such as moisture or heat, can cause growth of defects. Damage initially caused during service includes moisture diffusion, both from outside as well as inside the concrete and impact of objects. Although impact will be rarely encountered in civil structures, occurrences such as hail storms or road debris can induce subsurface delaminations that are often barely visible on the surface. Instead, damage increases with depth and can therefore cause substantial damage to the concrete/composite interface.

3.4.1 At the Concrete/Composite Interface:

3.4.1.1 Penetration of Moisture and Chemicals: Penetration of moisture and chemicals over time can degrade the interfacial properties by plasticization or other forms of reversible and irreversible changes of the resin/adhesive. This change in material properties results in reduced stiffness of the resin and increases the likeliness of delamination. In general, bonded joints are especially susceptible to damage from aggressive chemicals and moisture.

3.4.1.2 Heat Damage: The glass transition temperature T_g of each individual resin system, depending on resin type and cure conditions, predetermines maximum service temperatures at which the resin will start to severely degrade. Exposure to high temperatures influences the mechanical properties of most adhesives/resin systems. Under elevated temperatures, polymers may soften and lose their ability to transfer stresses efficiently (Figure 3-33). Under extreme conditions such as exposure to fire, the material completely degrades.

3.4.2 Inside the Composite Material:

3.4.2.1 Penetration of Moisture and Chemicals: Moisture can be absorbed from the air or can diffuse through the concrete to the concrete/composite interface and ultimately even into the composite itself. These phenomena are promoted by either inadequate or damaged surface coatings (Figure 3-34), which are designed to protect the material from any form of diffusion or a high degree of concrete moisture. To allow evaporation of entrapped moisture inside the concrete, placement of composite sheets over large areas without space for evaporation and/or drainage must be prevented. Instead, gaps providing adequate space for “breathing” shall be included at specific intervals. Those regions already containing delaminations, voids or other forms of air entrainment attract

moisture and serve as a depository. Figure 3-35 shows moisture accumulation at interlaminar- and concrete/composite interface regions.

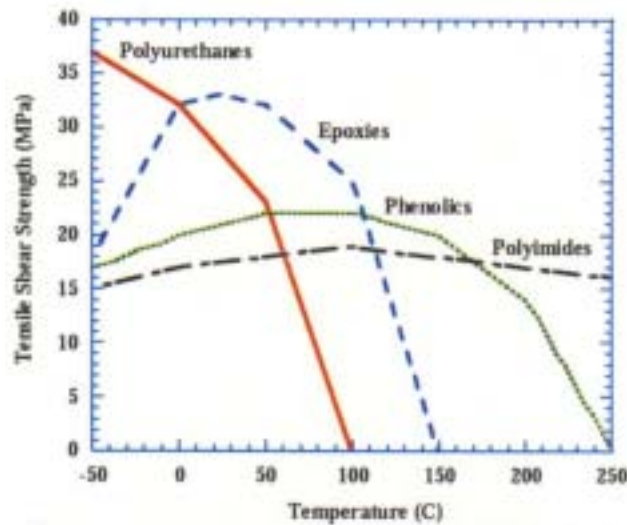


Figure 3-33: Typical Working Temperature Ranges for Structural Adhesives



Figure 3-34: Damaged Surface Coating

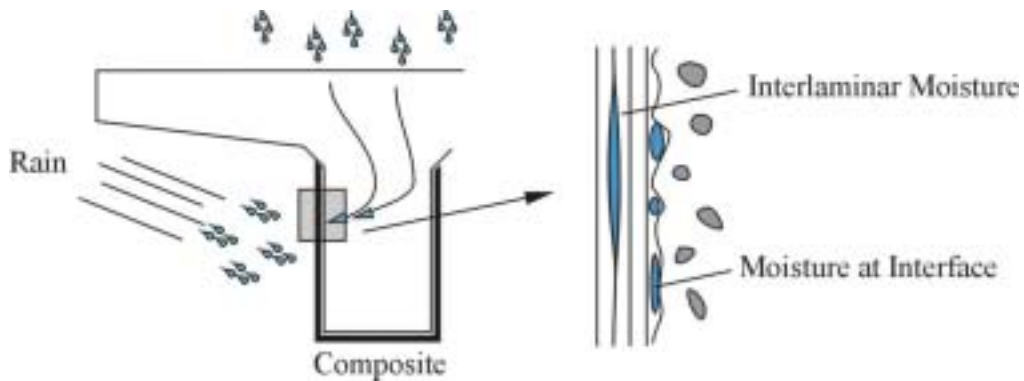


Figure 3-35: Penetration of Moisture

3.4.2.2 Heat Damage: Unlike the adhesive/resin system, fibers are capable of resisting extremely high temperatures. Nevertheless, degradation of the matrix has a significant effect on mechanical properties since it does not allow for stress transfer between fibers.

3.4.2.3 Interlaminar Matrix Cracking: Most matrix cracking occurs in form of interlaminar cracks (delamination), as opposed to translaminar (perpendicular to the layer direction) or transfibrous (perpendicular to the fiber direction) [12]. Initiating factors can be entrapped air and excess resin, causing sudden changes in direction of load transfer and local stress concentration. Since the transverse tensile strength of a typical composite is much lower than its longitudinal (or fiber direction) tensile strength, such cracks may easily propagate under sustained loading. An example of interlaminar cracking is presented in Figure 3-36.

3.4.2.4 Surface Scratches: Unless they propagate deep into the fibers, scratches can be considered a benign flaw that has a negligible influence on strength and stiffness. However, if scratches are caused by impact of an object, internal damage in forms of subsurface delamination can result. Figure 3-37 displays a severe form of surface damage as found on a bridge after rehabilitation through the application of composites in Sweden.



Figure 3-36: Microscopic View of Interlaminar Cracking

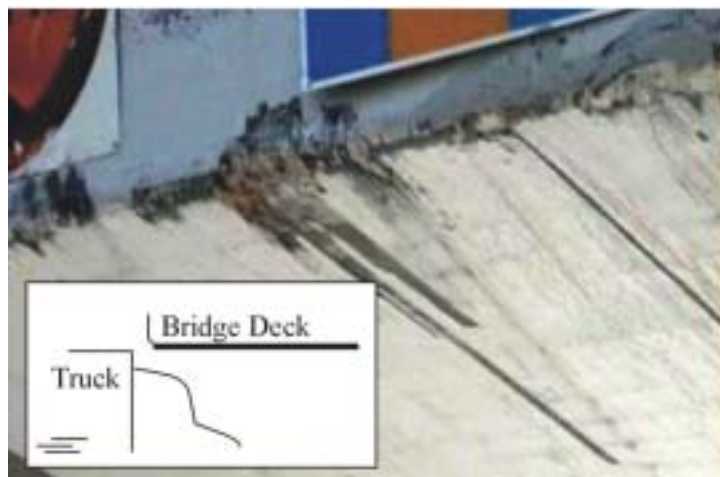


Figure 3-37: Severe Form of Surface Scratching Caused by Trucks

3.4.2.5 *Impact Damage:* Barely visible impact damage (BVID) is considered one of the most critical material flaws that may occur during service of a composite member [14]. If a hard, slow moving object impacts the surface of a composite laminate it may cause only slight damage to the surface, while severe subsurface matrix cracking is likely to occur (Figure 3-38). Road debris or environmental effects (hail, etc.) are some of the factors that can cause impact damage. It has been shown that little loss of strength is evident if the composite is stressed in tension, whereas extensive local buckling and rapid failure can occur under compressive loading [13].

3.4.3 *Other Service Defects:*

Other service defects include matrix brittleness due to ultraviolet radiation, exposure to freeze/thaw cycles as well as growth of any existing defect due to service loading or environmental effects. Detailed information on various types of in-service defects in composite materials is presented in the CERF/MDA document [19]. Unprotected composite surfaces lacking adequate protective covers (paint, epoxy coating) are especially susceptible to ultraviolet radiation that causes a steady increase in polymer chain linking. This results in a more brittle matrix behavior and unfavorable mechanical properties. Growth of existing defects is one of the critical aspects in servicing of rehabilitated structures, since it demands continuous monitoring of composite and concrete/composite interface quality. While many defects may remain constant in size and to some respect, criticality, others may grow quite rapidly under service loading or environmental influences to form flaws that call for immediate repair measures.

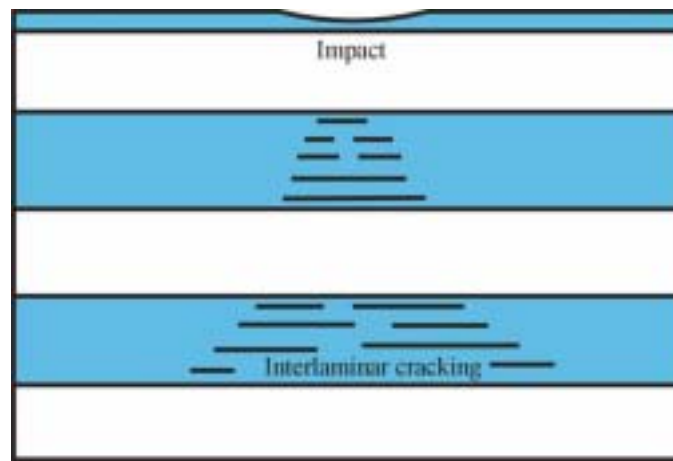


Figure 3-38: *Subsurface Damage Due to Impact*

4. CONCLUSIONS AND FURTHER RESEARCH

For concrete rehabilitation, application of fiber reinforced polymer composites continues to grow in popularity. However, performance and expected lifetime of such rehabilitation measures are greatly depending on quality of workmanship and are jeopardized by a wide range of material defects. Prior to installation, potential defects must be known and evaluated upon their likeliness of occurrence during the individual project. Special attention should be paid to storage, handling and preparation of incoming materials as well as site preparation. Apart from a well-coordinated installation process, a suitable environment for work with composite materials must be provided. Although a successfully performed installation procedure with low defect occurrence would yield a fairly long service life, harsh environmental conditions can cause rapid deterioration of most composite strengthening systems. Hence, quality monitoring must be performed beyond the installation stage and continued throughout the lifetime of a rehabilitated structure. Tables 4-1 through 4-4 summarize all previously discussed defects by their initiating phase. Furthermore, possible potential effects are listed.

While the types of defects to be encountered are mostly known, information on defect criticality and their effect on short/long-term structural performance remain widely unknown. Nevertheless, previous research has shown that defects like localized porosity, surface scratches or single broken fibers do not have a significant effect on material performance. Instead, they should be considered a material property that must be accounted for, especially if processing of composites is performed manually. Assessment of criticality of such “normal” defects will therefore be done on the basis of previous research results, whereas different techniques must be employed to characterize and quantify the effect of defects such as severe debonding, delamination, large voids, tow breakage or moisture accumulation, to name only a few. Thus, the need for further investigation in this field arises. Part 2 of this report will address defect criticality of defects discussed in the previous chapters, categorizing them by criticality with respect to structural performance (strength and stiffness) and short/long-term durability. A comprehensive understanding of defect type, typical appearance and, most importantly, criticality and repair schemes is essential to the installer/inspector and will aid in maintaining rehabilitated structures at their full potential throughout the design-lifetime.

Table 4-1: Defects in Raw and Constituent Materials

	Defect Type	Cause/Description	Potential Effect
Resin	Overaged resin	Expired shelf-life	Low strength and modulus. Potential for incomplete cure & nonuniform impregnation
	Resin inclusions	Dirt and/or chemicals	Change in chemical consistency, voids. Potential effect on cure
	Resin moisture	Inadequate storage/environmental exposure	Change in chemical consistency, voids due to evaporation, resin degradation
Fabric	Incorrect fiber/fabric type	Fiber/resin mismatch, human error	Change in strength and modulus, low fiber/matrix bond (sizing)
	Kinked or wavy fibers	Handling/manufacturing flaw	Fiber breakage, loss in composite properties
	Broken fiber tows	Handling/manufacturing flaw	Stress concentrations
	Fabric contaminations	Environmental exposure/storage	Initiator for debonding and crack propagation
	Fabric wrinkles	Handling/manufacturing flaw	Lower modulus, higher strain at failure, resin-rich encapsulated areas
	Sheared fabric	Handling/manufacturing flaw	Off-axis alignment, lower strength and modulus, resin-rich regions
	Damage to free edges	Handling/manufacturing flaw	Loss of integrity, stress concentrations
	Pull-out of fiber tows	Handling/manufacturing flaw	Resin richness, localized low strength & stiffness
	Fiber gaps	Handling/manufacturing flaw	Resin richness, low crack arresting capability
	Fabric moisture	Inadequate storage/environmental exposure	Reduced fiber/matrix bond, effect on composite performance and durability

Table 4-2: Defects from Site and Material Preparation

	Defect Type	Cause/Description	Potential Effect
Resin System	Moisture absorption	Inadequate storage/environmental exposure	Change in chemical consistency, voids due to evaporation. Potential for incomplete cure & decreased performance levels
	Incorrect stoichiometry	Type or proportions of resin and hardener/catalyst	Inadequate matrix strength/modulus, incomplete and/or nonuniform cure
	Incorrect mixing	Low degree mixing, drawing of air	Partial cure, porosity, nonuniform rheology
Substrate	Inadequate primer coating	Over-, undersaturation of substrate	Low stress transfer capability, potential for poor bond
	Lamination on top of 'marked-out' regions	Placement on duct tape, crayon layer, etc.	Weak or no bond to substrate
	Degraded substrate	Microcracks, spalled concrete	Lower or no composite action
	Inclusions at imperfections	Dirt, moisture or chemicals in concrete cavities	Low bond of primer/putty to substrate
	Galvanic corrosion	Intimate contact of carbon fibers with steel reinforcement	Deterioration of matrix/steel

Table 4-3: Installation Defects

		Defect Type	Cause/Description	Potential Effect
Wet Layup	Composite-Concrete Interphase	Concrete cavities	In current practice, concrete cavities are not filled with putty	Stress concentrations
		Sagging of infiltrated fabric	Critical in overhead regions	No composite action, potential moisture entrapment at concrete/composite interface
		Resin-rich/poor concrete/composite interface	Non-uniform primer coating and over-, undersaturation during lay-up	Low stress transfer efficiency
		Porosity and Voids	Porous primer, entrapment of air pockets during lay-up	Low stress transfer, stress concentrations, debond & crack initiation sites
		Highly uneven concrete surface	High degree of sandblasting	Voids or air pockets
	Inside Composite	Porosity and Voids	Air entrainment in resin, entrapment of air pockets during lay-up	Low stress transfer, stress concentrations, decreased performance attributes
		Delamination	Moisture, Inclusions	Low or no stress transfer
		Debonding	Fiber contamination, tubular voids	Low stress transfer (localized), sites for wicking of moisture
		Incorrect stacking sequence	Misplaced fabric, human error	Alteration of strength and stiffness
		Resin-richness/poorness	Non-uniform infiltration	Low crack arresting capability, decreased stress transfer capabilities, locally weak zones
		Indentations	Handling damage	Damaged fibers, stress concentrations
		Missing layers	Human error	Entirely different (and decreased) laminate properties
		Damaged edges	Fiber pull-out during infiltration	Stress concentrations, site for crack initiation
	Prefabricated Material	Voids at concrete/adhesive interface	Adhesive applied to highly porous concrete substrate	Stress concentrations, moisture accumulation, local zones of weakness
Disbonding at adhesive/composite interface		Smooth surface of prefabricated strip	Low stress transfer/inadequate bond strength	

Table 4-4: In-Service Defects

	Defect Type	Cause/Description	Potential Effect
Concrete/ Composite Interface	Penetration of moisture and chemicals	Exposure to aggressive environments	Degradation of adherent layer, plasticization, reduced stiffness, potential for premature failure through peel and/or delamination
	Heat damage	Exposure to sun or fire damage	Softening/degradation of matrix, peel and/or separation from substrate
Composite	Penetration of moisture and chemicals	Exposure to aggressive environments	Plasticization, reduced stiffness, degradation of composite
	Heat damage	Exposure to sun or fire damage	Softening/degradation of matrix
	Matrix Cracking	Interlaminar crack formation	Initiator for delamination and/or splitting
	Surface Scratches	Traffic, hail, etc.	Fiber breakage and initiator for premature local failure
	Impact damage	Traffic, hail, etc.	Delamination

5. GLOSSARY¹

Adherent	A body that is held to another body usually by an adhesive.
Adhesive	Substance capable of holding two materials together by surface attachment. Can be a film, paste or liquid.
Bond Strength	The amount of adhesion between two surfaces.
Catalyst	A substance that changes the rate of chemical reaction without itself undergoing permanent change in composition.
Debond [†]	An initially unbonded or nonadhered region between two adherents. Also used to describe a separation at the fiber-matrix interface. In the construction industry, debond and delamination are sometimes used interchangeably when referring to separations at the concrete-composite interface.
Degradation	Deleterious change in physical properties or appearance.
Delamination	Separation of the layers of material in a laminate, either local or covering a wide area.
Disbond	An area within an initially bonded interface between two adherents in which adhesion failure or separation has occurred.
DMTA	Dynamic mechanical thermal analysis. Provides information on presence of solvents, changes in structure and chemical reactions.
DSC	Differential scanning calorimetry. Detects loss of solvents and other volatiles.
Galvanic Corrosion [†]	Galvanic reaction between metals and conductive carbon fibers, resulting in degradation of matrix and metal.
Hydrolysis [†]	Process of degradation that generically includes the splitting of chemical bonds and the addition of water.
Inclusion	Mechanical discontinuity occurring within a material, consisting of a solid, encapsulated material.
Interface	Boundary between two different, physically distinguishable media.
Laminate [†]	A product made by stacking of multiple layers of unidirectional fibers or oriented fiber configurations embedded in a resin matrix.
Porosity [†]	Trapped pockets of air, gas or vacuum within a solid material, typically less than 10 μ m in diameter.

¹ Based on terminology of ASM Handbook of Composites, Part 1 [20]

[†] Terminology of authors

Pot Life	Time a thermosetting resin retains a viscosity low enough to be used in processing.
Prefabricated Material [†]	Composite material manufactured and cured under controlled factory conditions with a generally high material uniformity and used in cured state in the field.
Prepreg	Ready-to-mold material in sheet form impregnated with resin and stored for use. The resin is partially cured to a B-stage.
Rheology	The study of flow of materials, particularly plastic flow of solids.
Saponification [†]	Specific form of hydrolysis involving alkalis.
Shelf Life	Length of time a material can be stored under specific environmental conditions and continue to meet all applicable specification requirements.
Stoichiometry [†]	Quantitative relationship between constituents in a chemical system.
T _g	Temperature at which increased molecular mobility results in significant changes in the properties of a cured resin system.
Undercure	A condition resulting from the allowance of too little time and/or temperature for adequate hardening.
Vitrification [†]	Process of conversion into a glassy phase.
Voids	Air or gas that has been cured into a laminate or an interface between two adherents. Porosity is an aggregation of microvoids.
Volatiles	Materials, such as water or alcohol, in a resin formulation that are capable of being driven off as vapor at room temperature or at a slightly elevated temperature.

6. REFERENCES

1. Astrom, B. T., *Manufacturing of Polymer Composites*, Chapman & Hall, London, 1997.
2. Gutowski, Timothy G., "A Brief Introduction to Composite Materials and Manufacturing Techniques," In *Advanced Composites Manufacturing*, ed. Timothy G. Gutowski, New York: Wiley, 1997: 5-41.
3. Ali, M. S. M., Oehlers, D. J. and M. A. Bradford, "Shear Peeling of Steel Plates Adhesively Bonded to the Sides of Reinforced Concrete Beams," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, V140 (3), 2000: 249-259.
4. Zhang, S., Raoof, M. and L. A. Wood, "Prediction of Peeling Failure of Reinforced Concrete Beams with Externally Bonded Steel Plates," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, V110 (3), 1995: 257-268.
5. Triantafillou, Thanasis C., and Costas P. Antonopoulos, "Design of Concrete Flexural Members Strengthened in Shear with FRP," *Journal of Composites for Construction*, V4 (4), 2000: 198-205.
6. Geng, Z. J., Chajes, M. J., Chou, T. W. and D. Y. C. Pan, "The Retrofitting of Reinforced Concrete Column-to-Beam Connections," *Composites Science and Technology*, V58 (8), 1998: 1297-1305.
7. Kaliakin, V. N., Chajes, M. J. and T. F. Januszka, "Analysis of Concrete Beams Reinforced with Externally Bonded Woven Composite Fabrics," *Composites Part B - Engineering*, V27 (3-4), 1996: 235-244.
8. Hawkins, G. F., Johnson, E. and James Nokes, "Typical Manufacturing Flaws in FRP Retrofit Applications," *Concrete Repair Bulletin*, July/August 1998: 14-17.
9. Bishop, Sarah M., "The Significance of Defects on the Failure of Fibre Composites," *Neuilly-sur-Seine, France: North Atlantic Treaty Organization*, Advisory Group for Aerospace Research and Development, 1981, iv, 18p.: ill. 30cm.
10. Davies, P. and O. Brunelliere, "Effect of Defects on Interlaminar Fracture of Glass Fibre-Reinforced Polyester Composites," *Journal of Material Science Letters*, V12 (6), 1993: 427-429.
11. Parslow, Nigel, "An Empirical Appraisal of Defects in Composites," in *Characterization, Analysis and Significance of Defects in Composite Materials*, AGARD Conference Proceedings, no. 355, 1993.
12. Purslow, D., "Fractographic Analysis of Failures in CFRP," in *Characterization, Analysis and Significance of Defects in Composite Materials*, AGARD Conference Proceedings, no 355, 1983.
13. Cawley, P. and R. D Adams, "Defect Types and Non-Destructive Testing Techniques for Composites and Bonded Joints," *Materials Science and Technology*, V5, May 1989: 413-425.
14. Potter, R. T., "The Significance of Defects and Damage in Composite Structures," in *Characterization, Analysis and Significance of Defects in Composite Materials*, AGARD conference Proceedings, no 355, 1983.
15. Farioli, M., Porro, F., Samanni, G. and V. Wagner, "Advanced Techniques for Composite Primary Structures," in *Characterization, Analysis and Significance of Defects in Composite Materials*, AGARD conference Proceedings, no 355, 1983.

16. Ghiorse, S. R., "Effect of Void Content on the Mechanical Properties of Carbon/Epoxy Laminates," *SAMPE Quarterly*, January 1993: 54-59.
17. Woo, E. M., Chen, J. S. and C.S. Carter, "Mechanism of Degradation of Polymer Composites by Galvanic Reactions Between Metals and Carbon Fiber," *Polymer Composites*, V14 (5), 1993: 395-401.
18. Chajes, M.J., Finch, W.W., Januszka, T.F., Thomson, T.A., "Bond and Force Transfer of Composite Material Plates Bonded to Concrete," *ACI Structural Journal*, V93 (2), 1996: 208-217.
19. Karbhari, V.M., Chin J.W. and D. Reynaud, "Gap Analysis for Durability of Composites for use in Civil Infrastructure". CERF Report, 2001.
20. ASM Society of Materials, *ASM Handbook of Composites, Part 1*, Materials Park, OH, ASM International, 2000.

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