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Inside 40 Years of Advances in Failure Analysis of Polymeric Composite Materials

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Abstract

Use of polymeric composite materials is becoming increasingly widespread. Diverse applications include fixed infrastructure, industrial chemical processing, power generation, and aeronautics. Engineers have codified design principles and manufacturing practices so they are accessible to practitioners with general engineering education. In almost all cases, when polymeric composites enter service, none of the design codes, approaches, or construction standards apply, and they cannot be used to determine Fitness For Service. When failures occur, approaches that are normally followed in investigation yield inconclusive results, which often creates a conclusion that: "There was an undetected manufacturing defect." All polymeric composites are non-crystalline, non-linear viscoelastic materials, and their mechanical properties change continuously while in service. This paper describes how damage occurs in these materials, demonstrates how it can be detected, and provides a methodology for addressing these failures.

Keywords

Fiber reinforced polymer, FRP, failures, creep, relaxation, accumulated damage, laminated structures, engineered rubber, fatigue, failure analysis methods, stiffness of composites, forensic engineering

Introduction

This paper begins with a historical review of how these interesting materials evolved through human intervention, starting with rubber, followed by metals, wood laminates, and thermoset polymers. Rubber, a naturally sourced elastomer, needs to be treated with sulfur and heat (vulcanized) to have useful mechanical properties, as discovered by Charles Goodyear in 1839. The original use of fibers to bolster polymer mechanical properties occurred when R.W. Thompson of Scotland used canvas covered on both sides with India rubber in 1845 for bicycle tires. J. Boyd Dunlop improved upon this by making calendered rubber sheets containing cloth for horseless carriage tires, as described in his 1888 patent[1]. Michelin enhanced the technology and began industrial production of "pneumatiques" for air-cushioned support of bicycle wheels on roads. Assembling such disparate materials with totally different sets of properties required much trial and error, but it was revolutionary and accelerated the transportation industry's progress. The rapid adoption of Dunlop's innovations spread beyond transportation during the Industrial Revolution, often leaving scientific understanding to follow empirical application.

Original analysis of rubber and fiber composites using finite-element models was rudimentary — the concepts of matrix and fiber properties, along with their directional variation, created difficult boundary conditions. The techniques of T.J. Dudek at General Tire[2] were based on the continuum mechanics of composite materials summarized by R.M. Jones in 1975[3]. Rubber is a non-linearly viscoelastic material, and is sensitive to external forces and factors, especially temperature.

Cotton fibers twisted into yarn and woven into cloth had inherent variations. Over time, these yarns were replaced with synthetics, such as Nylon 66 and polyester (polyethylene terephthalate), and the life-cycle performance of

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tires improved. Steel wires for belts on radial tires were often supplemented with polyamide high-strength fibers (Kevlar™ aramids), which augmented the mechanical properties and minimized variations. As the materials changed, the models for engineered rubber composites improved drastically by incorporating the known characteristics of the components into the boundary conditions. Young's modulus (E), Poisson's ratio, elongation to break, and other material properties tie the understanding of the behavior back to fundamentals of polymer physics, and allow real-world feedback to optimize the products for consumers. In the early 1970s, finite-element models of tire behavior[4] emerged from the laboratories connecting field experience with mathematics and mechanics of solids.

In the metal world, the canon of knowledge was developing steadily. In 1679, Robert Hooke observed that certain metals would return to their original length after being loaded (*Ut tensio, sic vis*, or as the extension, so the force), reacting elastically to the addition and then subtraction of forces. Although it was well known since the Middle Ages that metal properties would change with heating, beating, and alloy content[5], the "why" was unclear until the development of the theory of dislocations in 1948. This theory provided a fundamental understanding of how metal grains had interior slip systems that reacted to external forces and stored energy.

The first photograph of an edge dislocation was taken by Sir James Menter and can be seen in Plate 14 of that reference[6]. These geometric crystalline slip systems, when overwhelmed by external forces, allowed the creation of cracks to dissipate energy. With knowledge of what was happening at the microscopic level, the macroscopic level manifestation of the properties could be correctly understood. With the same basic set of knowledge of properties (Young's modulus, shear modulus, and Poisson's ratio), a second rank tensorial representation could be made in mathematics[7]. A second rank tensor is one that takes one vector as input and gives one vector as output, such as the Cauchy stress tensor, such that the expected reaction of a material to stress and strain is modelled successfully. A constitutive equation is typically a phenomenological mathematical model used to describe the relationship between stress and deformation, and can be used to predict behaviors at various applied stress conditions. Equations were developed that could explain the metal's behavior, and, better yet, could be used with explicit criteria (Tresca or von Mises stress limits) to pinpoint when a transition from elastic to yielding would occur.

Such information can be related to design stress characteristics for metal structures and components, which ties the real world to the microscopic world in a useful way for engineers. Best of all, one can work backward from a crack origin to solve for the conditions of initiation of the fracture — and, from this, an understanding of causation — for a failure of a component. In practice, the engineering world does not use yielding directly — traditional designs use the 0.2% offset stress on the stress-strain diagram, and then apply factors of safety. When these techniques are properly applied, a layman need not worry about whether a metal structure can safely take the load. The elastic behavior assumption dominates classic calculations for structures.

Wood-based laminates with glass or carbon fiber reinforcement rose to prominence during the World Wars for airplanes. They continued to be constructed in volume with the rise of the wind-turbine industry. The blades of such electricity-generating stations are wing-shaped and travel rapidly around the hub of the nacelle, enduring cyclic loading. Design code requirements for fatigue testing to qualify for service are restrictive, as prescribed by design codes to simulate service loadings[8]. Models of the behavior encounter the same complications as others, with assumptions necessary to complete the description of the response of the laminates to external stimuli.

An important subset of materials was developed when the epoxies and thermosetting polymers were combined with the fiber glass mats to create formable, light, strong structures: fiber-reinforced polymers (FRPs). Entrepreneurs could take a mold, add gel coat, fiber mat, and chopped fiber, and, before curing with heat, create their own boat, canoe, or motorcycle fairing. Since their introduction in the 1930s, applications now range across household products, amusement parks, marine structures, reinforced concrete, armor, heavy industrial equipment, electrical generation and distribution, spacecraft, and others. Polymers that cure irreversibly are termed thermosets. The design and fabrication of thermosets can be tuned precisely to match service conditions of combined mechanical and chemical environments. Thermosets are used for a wide variety of applications to take advantage of some key properties:

- Superior resistance to corrosion compared to many construction materials

- Lower density than many construction materials

That brings us to today, where we have many applications, but the fundamental understanding has stalled since the original rapid advances. Each family of material type provides a different mix of information for the forensic engineer seeking to understand why a structure or component has failed in service, as shown in **Figure 1**.

This paper describes how standard engineering failure analysis methods must be adapted to yield conclusive results. It then describes how a shift from introducing unconventional knowledge can often reveal what happened in the failure and why.

Practical Designs Based on Experience

As applications were explored, engineers developed design methods based essentially on experimental design and the application of safety factors to provide allowable stresses. As usage of load and resistance factor design (LRFD) evolved, such as for building codes, resistance factors have been developed. These developments continue to provide design and fabrication methods that engineers with conventional education can apply. This has resulted in a growing population of standards and codes that can be used for design and construction.

In the case of FRP materials, the empirical observation that failure can occur at stresses less than the measured ultimate strength of the as-built FRP led to the practical application of safety factors to reduce the maximum applied stress to an allowable level. This mirrors allowable stress design as used for much mechanical design. Resistance factors used for LRFD are a form of safety factor.

	Metals	Rubber FRPs	Wood Laminate FRPs	Thermoset FRPs
Property characterization and measurement	Excellent	Good	Rudimentary	Rudimentary
System characteristics	Isotropic or anisotropic	Orthotropic	Orthotropic	Orthotropic
Developed constitutive equations or deformation models	Excellent reproducibility	Equations are limited to the new condition and do not incorporate changes to the materials from service damage.	Constitutive equations or models are not available for damaged materials.	Poor constitutive equations or models are not available for damaged materials.
Fracture theory maturity	Defined and characterized by dislocation theory	Moderate and covered extensively in published material	Poor. There is no coverage in published material.	Poor. There is no coverage in published material.
Energy absorption or dissipation behavior	Overload and fatigue	Temperature degradation	Delamination by fatigue	Non-linear viscoelastic creep that leads to brittle fracture
Established techniques for examination	Visual; microscopy; metallography; scanning electron microscopy	Visual	Visual; microscopy	At the time of this writing, there are no established standards for visual or microscopy. Ultrasonic and acoustic methods.
Certainty of analysis of causation	Excellent possible match to theory	Results are usually inconclusive because no standard is available.	Results are usually inconclusive because no standard is available.	Results are usually inconclusive because no standard is available.

Figure 1
Matrix of the family of materials.

Nomenclature

In this paper, the following variables are used:

A = Extensional stiffness matrix (3x3).
B = Coupling stiffness matrix (3x3).
D = Bending (flexural) stiffness matrix (3x3).
ε = Strain tensor (3x1).
E_0 = Young's modulus at start.
E_g = Young's modulus of elasticity for glass.
E_p = Young's modulus of elasticity for polymer.
$E\tau$ = Young's modulus at time τ.
Ex = Young's modulus of elasticity in x-direction.
Ey = Young's modulus of elasticity in y-direction.
K = Curvature tensor (3x1).
M = Moment resultant tensor (3x1).
N = Stress resultant tensor (3x1).
Φ_E = Coefficient for general loading condition.
Φ_i = Coefficient for loading condition i.
r = Exponent applied to exposure time for general loading condition.
r_i = Exponent applied to exposure time for condition i.
τ_i = Time of application of condition i.
t_g = thickness of glass.
t_p = thickness of polymer.
t_t = total thickness.
v_{ab} = Poisson's ratio in b-direction from strain in a-direction.
v_g = volume fraction of glass.
v_p = volume fraction of polymer.

Design Basis for Composite Structures

Engineers spend much of their formal education understanding the fundamental principles of the design of any structure. In many cases, structural, load-bearing materials are considered to have constant Young's modulus, Poisson's ratio, and to be linearly elastic so that Hooke's Law can be used to describe their stress-strain response to applied loading.

When these conditions are met, structural analysis of any material can follow systematic approaches from several references and textbooks that deal with linear elastic materials. Virtually all design and construction standards and codes expect and dictate linear elastic behavior. Occasionally, interest arises in analyzing structures composed of different materials joined together, each of which is distinct and identifiable. The engineering properties of these materials are an amalgam of the properties of their individual components. Known as composite materials, examples include tires, car windshields, and fiber-reinforced polymers.

When different materials are combined, such as in the layers of shatterproof glass, the behavior of each component material can be modeled, and engineering properties of the mixture can be calculated (or measured by testing). A model of the layers of glass and polymer in a shatterproof car windshield is shown **Figure 2** and calculations in Equations (1) to (3).

The calculations will be based on unit width and unit depth of the material mixture. Glass sheet and polymer sheet used for each layer is isotropic, with equal mechanical properties in all directions. Equation (1) determines the Young's elastic modulus in the x-z plane[9].

$$E_x = E_z = \frac{\sum t_g E_g + \sum t_p E_p}{t_t} \tag{1}$$

This elastic modulus applies to plane stress in the x-z plane. If bending moments are applied to the plate, the elastic modulus needs to incorporate the distribution of the constituent materials. This will result in a different elastic modulus value, normally referred to as the flexural modulus. Equations (2) and (3) show the calculation of the flexural modulus for the laminated plate in **Figure 2**. Equation

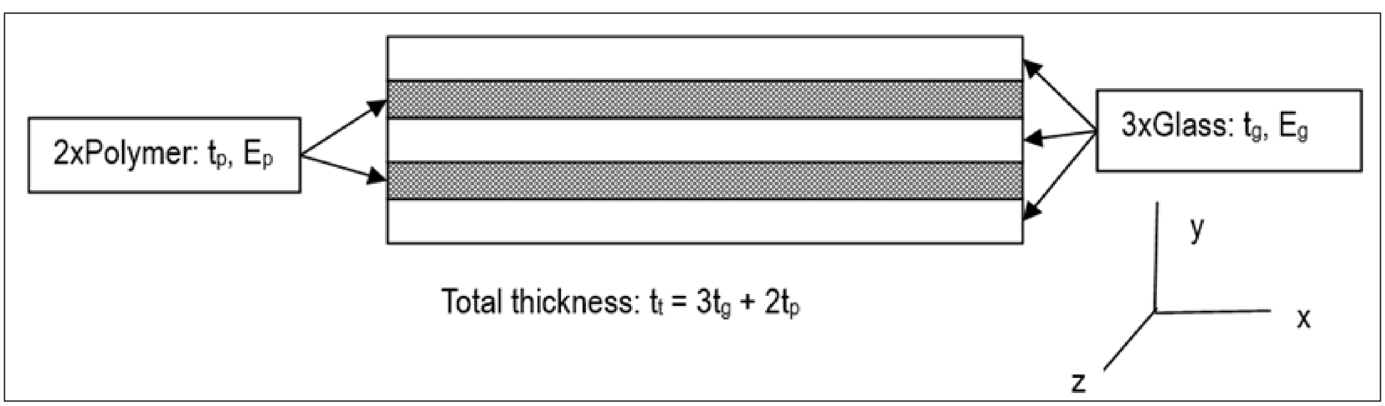

Figure 2
Model of laminated shatterproof glass.

(2)[9] determines the location of the neutral axis from the bottom surface of the laminate in **Figure 2**.

$$h_n = \frac{\left(\frac{9t_g}{2}+3t_p\right)E_g+(3t_g+2t_p)E_p}{t_t E_x} \quad (2)$$

And Equation (3) determines the elastic modulus for out-of-plane loading, which typically produces bending moments. This is commonly known as the flexural modulus.

$$E_f = \frac{\left(3t_g^3+2t_g\left(\frac{3}{2}t_g+t_p-h_n\right)^2\right)E_g+(2t_p^3+2t_g\left(\frac{t_g+t_p}{2}\right)^2)E_p}{t_t^3} \quad (3)$$

The differences between Equations (1) and (3) show clearly that the tensile properties can be substantially different from the bending properties of laminated composites, with bending properties highly dependent on the distribution through the thickness of the constituent materials.

In general, design of equipment using composite materials is dominated by in-plane tensile or compressive loads. When elastic instability or buckling occurs, empirical testing has shown that both tensile and flexural modulus contribute. Design for in-plane stress commonly uses allowable stress design where the tensile strength of a particular composite is determined by destructive testing, and a factor of safety is applied to provide the allowable stress for design. When designing to ensure elastic stability, the factor of safety is usually applied to the expected collapse load of the member, such as from compression or applied external pressure. Note that the factor of safety used for the two situations is not usually the same value.

Now consider the situation where the composite material shown in **Figure 2** is comprised of glass and polymer mixed more intimately together, such as small-diameter glass fibers surrounded by polymer that is bonded to the glass. In these cases, the properties of a layer become a function of the combined component properties. This forms the basis for micromechanics lamination theory, meaning a layer comprised of this mixture is treated as an orthotropic, homogeneous material with a unique elastic modulus in each direction and a single Poisson's ratio for each direction. The volume fraction of the component materials is used for this calculation. For the example shown in **Figure 2**, the volume fractions are given by Equations (4) and (5).

$$v_g = \frac{\sum t_g}{t_t} \quad (4)$$

$$v_p = \frac{\sum t_p}{t_t} \quad (5)$$

NASA played a key role in developing methodologies for modeling laminated composite material. This started with a lamination theory that determines the mechanical properties of layers and laminates[10] using the rule of mixtures. These models take advantage of approximately linear elastic material mixture response at a given state of reinforcement and polymer condition. The initial model does not include provision for changes to material properties as a result of damage. The models also include some important boundary conditions: no slippage at the interfaces of laminae; and no slippage at the coupling of reinforcement and polymer. It can also be general enough to incorporate bending and in-plane stresses. This modeling works well for allowable stress design of components and is used by codes such as RTP-1[11]. Equation (6) shows examples along the orthogonal material directions of the component in plane stress.

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon \\ K \end{bmatrix} \quad (6)$$

where A_{ij}, B_{ij}, and D_{ij} incorporate elastic modulus and Poisson's ratio of the constituent materials and the fraction occupied by each. Note that the methods described to this point do not provide any values for the strength of the material — only stresses and stiffness result.

These models look very similar to the generalized equations that may be used for any linear, elastic material, such as metal alloys. They have been in regular use for polymeric composite design since the 1970s.

Experience with applications of components made using composites found that lifetime reliability of components was increased by applying simple factors of safety[11,12]. For Allowable Stress Design methods, the factor of safety is applied to the measured strength of the composite to determine allowable stress for design. For membrane stresses, it is common for this factor of safety to be 10. When the design must include elastic instability, stress is no longer a key element; therefore, the factor of safety is applied to increase the collapse load (often the buckling point). The factor of safety commonly used for elastic instability is 5. For load and resistance factor design (LRFD), a typical resistance factor applied to the 5th percentile tensile strength is 0.55, and elastic instability conditions are generally avoided.

Some design methods use allowable strain as the basis of the design. This approach places a limit on maximum strain values that may be used for design. In this method, a factor of safety — sometimes the same as that used for allowable stress design — is applied to the minimum elongation at failure of the constituent materials. Some codes, such as RTP-1, use arbitrary values that amount to about 5% of the minimum constituent elongation at failure.

More advanced calculations may be used to model the behavior of individual layers with their own unique anisotropic properties. Typically, each layer is modeled as a 2D material with five independent uniaxial strengths. These are aligned and orthogonal to the principal direction of reinforcement — tensile and compressive in each principal direction and shear with respect to pure shear in the principal directions. This is described by Daniel et. al[14]. The basic principle is to determine the actual material strains that will cause failure of either the polymer or the reinforcement. Versions of this process include the "Tsai-Wu Interaction Criterion"[9] or "Quadratic Interaction Criterion"[11]. It is particularly important to note that these processes do not include or recognize yielding, nor do they include provision for changes to failure strain of composite constituents as a result of damage.

Damage Accumulation in Practical Terms

As FRP composites were included as an option for sophisticated uses like aircraft and space vehicles, the need arose for both explicit engineering analysis and for definitions of failure incorporating an understanding of damage accumulation. This analysis provided the foundation for calculating the time until failure. This was especially important to allow planning for replacement or obsolescence, particularly for complex or inaccessible structures.

It is normal for designers and engineers to use some method to predict future properties and the expected lifetime of structures. For metal alloys, this often includes consideration of corrosion rates and the effect of service conditions on the structure. For reinforced polymers, the mechanical properties, such as elastic modulus and strength of the individual structural constituents, usually change because of most service conditions: stress, applied strain, chemical attack, corrosion, etc. These changes accompany irreversible damage accumulation within the structure. For components that will be inaccessible or where tolerance of failures is low, it is desirable to have a model that will predict damage development, as addressed by Dillard, et al[13].

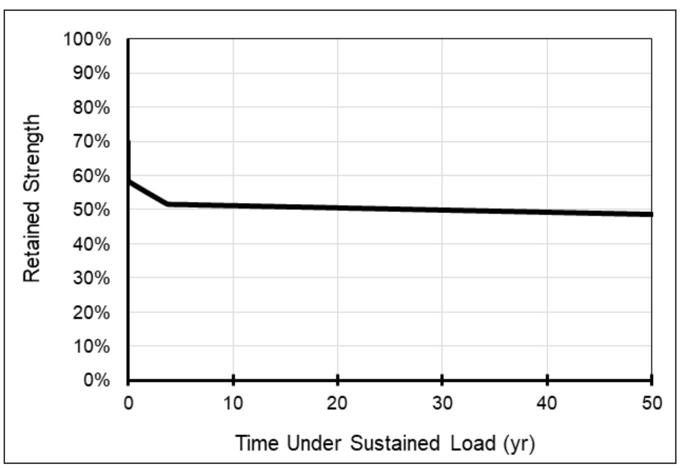

Figure 3
Change in strength of glass reinforcement. (Source: Owens Corning)

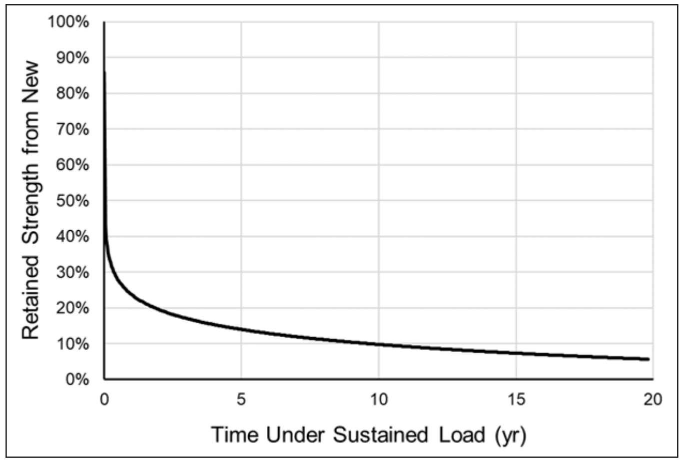

Figure 4
Change in strength of thermosetting polymer
(Source: Ashland literature)

Figures 3 and **4** show typical strength vs. time in service for glass reinforcement and thermosetting polymer subjected to mechanical stress only. The reader can see from both curves that the change in strength is non-linear and shows continuous reduction from its maximum of 100% for load application time of about 1 microsecond. These are non-linear viscoelastic materials.

The curve shows a logarithmic path where the full, original strength of 100% occurs for about 1 microsecond of sustained load at full strength. When the sustained loads are reduced, the glass fibers will support the load for longer times. In general, this change in strength for the glass is based primarily on a reduction in the strain at failure of the glass, while the elastic Young's modulus remains somewhat constant. The curve shown is for glass in air. When exposed to other substances via cracks that form in the polymer, or diffusion, the retained strength of the glass after five years can range from 84% of the air values for tap water to less than 12% of the air values for weak acid. One could consider the "air" values to represent the expected behavior of glass reinforcement that is embedded in an undamaged polymer or elastomer.

Findley et. al[14] provides a model to describe changes that occur in properties, such as elastic modulus, as a function of time, generally of the form given in Equation (7).

$$E_\tau = E_0 + \Phi_E \tau^r \qquad (7)$$

Where:
E_τ = Property at time, τ.
E_0 = Property at starting time.
Φ_E = Coefficient corresponding to applied conditions.
r = Exponent corresponding to the applied conditions.

It should be expected that, if the conditions applied are not static — and thus have some variation with time — the more general form of the model will incorporate the product of changes from each applied condition, similar to Equation (8).

$$E_\tau = E_0 + \prod \Phi_i \tau_i^{r_i} \qquad (8)$$

Findley et. al. discuss that determining the coefficients Φ_E and r for a non-linear viscoelastic material requires experimentation, probably consisting of at least 30 trials for each combination of condition and material. There are currently no standardized methods for these tests, nor any published record of this experimentation or any of the relevant coefficients. Dillard et. al. chose to adopt the Findley approach for characterization of damage, but the limited availability of coefficients and the amount of variation encountered in test specimens still limit this to an academic exercise, with virtually no published data to allow informed use of damage accumulation models.

Other models are discussed by Greaves[8] for damage accumulations, including the Palmgren-Miner rule, which is linear, and other non-linear models. All of these require specific destructive test data on the FRP being considered to develop the damage model. Furthermore, most models are focused on the strength of layers as a mixture. All models described here to date essentially incorporate time (or its Laplace inverse of frequency) as a key part of the equations.

Polymer manufacturers use changes in flexural modulus[15] of FRP coupons that are exposed to operating environments as the primary means to assess the suitability of a polymer for use in that environment. Generally, a chemical attack is more aggressive than simple stress exposure in damaging polymers. Consider Equation (3), when the physical dimensions are unchanged and the Young's modulus of the glass (E_g) remains constant, a change in flexural modulus is directly related to change in the Young's modulus of the polymer. This same effect is also documented for cases of purely mechanical loading in Appendix D[12] and by Clarkson[16].

Clarkson[17] also decoupled the changes in polymer elastic modulus with reductions in strain at failure from time. This shows that the accumulated damage in FRP from service exposure can be determined using the retained elastic modulus of the FRP, irrespective of exposure time. Non-destructive methods to determine the retained flexural modulus, and thus, the total damage accumulation, are described by Clarkson[16].

Figure 5 shows the retained elongation at failure and retained polymer strength for the source data[18]. The reduced tensile strength from damage also requires less energy input for fracture. It is important to note at this stage that the reduced Young's modulus of the polymer also corresponds to a reduction in shear modulus and shear strength. The reductions will have a direct impact on the interfacial bonding of reinforcement to the polymer and thereby alter the distribution of loads through the polymer and protection of reinforcement from any chemical species.

For most materials, when fractures form, it is common to look at the crack formation and track the crack tip through the material as it "pries" deeper. Nuismer summarizes this, at least within an individual layer[19].

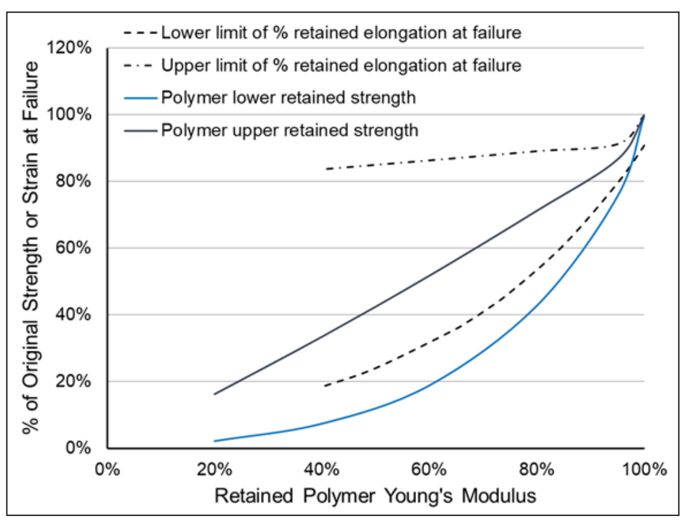

Figure 5
Polymer damage decoupled from time.

> *The initial energy release rate for a branch crack propagating at an arbitrary angle from an existing crack tip is obtained in a simple fashion and in closed form by using a continuity assumption. It is then postulated that the branch crack propagates in the direction which causes the energy release rate to be a maximum and that initiation occurs when the release rate reaches a critical value. It is shown that these postulates yield results identical to the maximum stress theory, since the direction in which the maximum circumferential stress occurs is also the direction causing the maximum energy release rate.*

When the stress to cause cracks is low, as implied in **Figure 5**, cracking can progress easily. In the case of most FRP structures, when a crack tip that formed in damaged polymer encounters polymer that is less damaged, it is arrested and diverted until damage accumulates in the "blocking" polymer. This is illustrated in **Figure 6**, where cracking is shown to change directions within the FRP. The photo is taken from a cutout from equipment that had been in service for several years. For the situation shown in **Figure 6**, the FRP is under hoop stress only, with some chemical exposure on the blackened material on the cracked side. The cracks in the damaged polymer can accelerate damage to the undamaged polymer and reinforcement by providing easy pathways for exposure to chemicals from the service environment.

In fact, the strain at failure of polymers has been shown by Clarkson[18] to correlate to the retained Young's modulus of the polymer. To date, no data are published that addresses the changes that occur to Poisson's ratio with damage, but there is clear evidence that this occurs, also supported by some studies since polymers can degrade to a powder with Poisson's ratio of 0.

Figure 6
Crack progression in composite laminate.

Composites using thermoplastic polymers that include a very low population of cross-links connecting the long-chain molecules might yield and will often undergo measurable creep changes as damage accumulates. When the polymer is cross-linked, such as in thermosets and most rubbers, when applied strain exceeds the failure strain of the material in its current condition, brittle fracture occurs.

Failure Analysis Approach for FRPs

The spectrum of FRP failures can range from visible blemishes to the collapse of a component. In general, we should expect that a failure corresponds to a condition where the component can no longer function. In some cases, failure analysis is intended to determine if it is possible to continue in service for some time. In others, a carcass must be analyzed to determine the cause. Investigation and analysis of failures have been found to work well universally when following a basic, systematic approach that requires detailed information. Many FRP components, such as holding tanks and wind turbine blades, are large compared to humans. When they fail, there is a considerable set of tasks to complete to understand what has happened.

Figure 7 provides a sequential list of the important elements for a large-scale reconstruction of a service failure. Besides the elements that are familiar to most forensic engineers, there are notes for items also recommended for consideration when the material of construction is FRP and other reinforced polymers. These additional items may also be applied to other visco-elastic materials.

The principal task is to locate the most probable origin. Defects involved in a failure are likely to be obliterated by the failure. The best approach to determine if a defect was implicated is to evaluate all of the data available to see if the presence of a defect is required to explain the failure initiation.

The considerations listed in **Figure 7** serve to address this.

The answers to these questions provide data that can be evaluated to reveal the cause of the failure. Many times, another question that arises is whether the new component complied with the design specification or criteria. The discussion above shows that damage accumulation is inevitable for any FRP component that is exposed to service conditions, so failure may be independent of the original design and manufacture.

Figures 8 and **9** provide an example of a large-scale component examination, which attempted to locate the origin of the wind-turbine blade fracture. There had been an allegation that a blemish was seen on the pressure side of the blade near its root a few months prior to an unexpected disassembly event that brought down the steel tower.

Element	Element of Reconstruction	Specific Considerations for FRP
1	Collect components from the site, and conduct a total station survey or LIDAR scan of the area to preserve spatial information, taking into consideration ASTM E1188 *Standard Practice for Collection and Preservation of Information and Physical Items* by a technical investigator.	
2	Index, catalog, and identify component remnants.	
3	Review original structural drawings and/or obtain an exemplar component.	Drawings are often not complete. Materials of construction may not be documented to provide exemplar component. Determine retained flexural modulus as close to the fractures as possible. Remove specimens of relatively intact materials and deconstruct to allow modeling of the as-built structure.
4	Categorize each piece to determine its original spatial orientation and its fracture mode.	FRP fractures are normally brittle. Spatial orientation of pieces is critically important combined with an effective stress distribution model combined with Young's modulus of damaged composites to identify strains. Recalculate the Young's modulus to incorporate retained flexural modulus distribution.
5	Use fracture mechanics principles to work backward to the origin of the sequence.	Determine the likely elastic strain distribution in the structure and determine the most probable origin.
6	Consider the potential primary mechanism of failure.	
7	Eliminate secondary and tertiary fractures from consideration.	
8	Concentrate on the primary mechanism and the area of origin, to confirm the fracture mode.	Determine if the data available on accumulated material damage supports the conditions at the origin to result in failure or if a defect or increase in assumed loads must be incorporated to meet the conditions for failure.
9	Use a model to better understand the pre-fracture force patterns.	
10	Validate the hypothesis of causation by comparing the evidence and the model, with a designed experiment on similar structures.	Ability to do this may depend on ability to duplicate the structure.

Figure 7
Large scale service failure reconstruction elements.

Figure 8
Parts of a wind-turbine blade set down for inspection and cataloging.

Figure 9
Wind-turbine blade fracture surface.

As described above, compliance with the design specification or criteria can be approximated by determining the details of the FRP construction from the carcass. However, its current properties, as determined by standardized tests, are unlikely to accurately reflect the new properties. Sometimes, additional testing is required from intact materials to determine things like porosity.

From Element 3 of **Figure 7**, the retained flexural modulus of the carcass material can often be determined using non-destructive acoustic and ultrasonic methods[18]. To ensure that the actual construction of the FRP is used in the analysis, specimens of the material from the failed component should be deconstructed, and lamination analysis methods, as described in Equations (1), (2), (3), and (4) and as described in [9] or [10], can be used with the Tsai-Wu or Quadratic Interaction methods to determine the approximate new strength.

Even when details of the original design are unavailable, it is still possible to compare the as-built information with the conditions that existed at failure. This requires additional testing of the failed FRP to determine the actual sequence of reinforcements with the volume fractions of all constituents. This information is then generally used with the "as-new" properties of the constituent materials to construct the stiffness, coupling, and bending matrices for use in the original tensor equation using the applied conditions at the time of failure, thus allowing some assessment of the "original" composite material.

As described previously for damage accumulation, there is little information about properties of "as damaged" materials used here, and properties of new materials are readily available. In addition, damage to the reinforcement from the operating environment also depends heavily on changes in its protection from the polymer as it is damaged.

This approach may help identify whether failures are driven by components that do not comply with relevant construction standards or specifications, but it seldom shows that failures could occur for anything beyond extreme loads that exceed the design safety factors of 5 to 10 applied to new material values. In almost every case where this is requested, the component was often found to still comply with all tests that measure against the original design and thus offers no conclusion on the cause of the failure.

Incorporating the Accumulated Damage Concept

The discussion to this point describes how damage accumulation occurs and how it should be incorporated into failure analysis.

Attenuation-based ultrasonics described by Clarkson[17] has been shown to distinguish between damage accumulation adjacent to fractures from areas that have not fractured. Detailed data from a large structure would allow a sufficiently detailed material model to explain a failure.

Some additional testing may provide supporting qualitative data. This additional testing includes: microscopic examination of the fractured zone using a microscope, where with enough magnification, evidence of reinforcement damage such as notches in the fibers from leaching may be observed; energy dispersive X-ray (EDX) to detect elements or chemicals that may be part of the chemical environment that existed in the composite; and visible features that may support hypotheses. This information may be used to supplement the accurate model of the composite.

Summary of Insights

Although not all the techniques available in the metal world are readily available for the analysis of FRP failures, the general approach to a failure investigation still applies with some additional considerations to be included. Gathering information about the context is important and will set the stage for a coherent analysis of causation. The complexity of FRP failures (especially large-scale ones) means that the origin of a fracture may not be explicitly identified. However, techniques that evaluate the damage accumulation and level of change of the properties of the FRP may provide insight into how and when the structure loses its integrity. Forensic engineers are advised to approach each case by considering these factors, so that the investigation will successfully identify the cause of failure. Employment of non-destructive methods may keep the structure owner ahead of the situation and mitigate costly incidents in industrial equipment.

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