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Investigating the fatigue and fracture behaviour of advanced composite materials in aerospace structures

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Abstract: In order to simulate the intricate stress distribution into important locations, Full-scale components, undergo fatigue testing. Parts of a larger structural system, such as sub-assemblies, are sometimes the subjects of these tests. Lastly, they are often performed on little samples with the purpose of collecting fatigue data. This data shows how a material has been affected by factors including stress level, surface preparation, environment, and loading history.

Keywords: fatigue, fuselage, materials, Composites

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INTRODUCTION

As an excellent substitute for metal alloys in situations calling for increased mechanical capabilities at reduced weights, composites are now among the most sought-after materials across a variety of industries. Because of their composition, composites are both lightweight and durable. Composites provide an intriguing alternative to traditional methods of attaining consistent weight reductions in main structures because to the synergistic features that may be tailored to satisfy a broad variety of mechanical performances. The research and prediction of fatigue and fracture mechanical behaviors is made harder by the presence of diverse and complex damage pathways, as well as an overall brittle behavior, which outweighs these favorable qualities.

How designers will adjust to the possibilities presented by composites while taking into consideration the material's unique damage mechanisms and reaction is an essential question that must be answered as the composites industry advances new materials and methods. Design professionals need to be well-versed in damage mechanics, accumulation, and mechanisms as well as the intricate failure behavior of structures in order to anticipate how those structures will react, with the help of structural health monitoring that enables a damage-tolerance strategy. Consequently, improving the evaluation of the material's behavior under stress relies heavily on the application of experimental methods.

If you want to know when and where damage started, you may utilize thermography, acoustic emissions, or digital imaging correlation. In addition, they include various parameters for damage models that attempt to forecast the remaining life of the material under certain loading circumstances. This special issue showcases the latest findings in the field, with the following goals in mind: to demonstrate novel structural functions (such as composite patches for fixing fractured structures); to introduce novel methodologies for processing data collected from various sensors in order to evaluate parameters for studying the material's damage behavior. The purpose of this special issue is to address these difficult elements of evaluating composite materials' behavior by enhancing our understanding of mechanical performance, damage mechanisms, and design principles in order to suggest novel approaches to testing and analysis.

LITERATURE REVIEW

Demelio, P.G. & De Finis, Rosa & Galietti, Umberto & Palumbo, Davide. (2016). For a thorough investigation of materials' fatigue behavior, thermal techniques are a reliable ally. Benefits include a reduction in experimental time and costs and the ability to assess damage processes associated with dissipative heat sources that developed during fatigue. Using a new and fast method for determining endurance limit, this study intends to conduct fatigue characterization of GFRP composite materials. Several damage-related indices may be obtained using the suggested approach, which employs a multi-parameter analysis.

De Finis et al. (2021). The temperature signal and mechanical energy rate of C45 steel are examined in this study after it undergoes frequency domain testing with two distinct fatigue stepwise loading series at stress ratios of 0.1 and -1. The analysis of the energy distribution across the harmonic components of the signals was the first step in detecting changes induced by various stress ratios. In addition, the research considered and assessed the relationship between mechanical energy rates and the second amplitude harmonic (SAH) of heat dissipated. Since it is material-specific, it holds true independent of test type and makes no assumptions about energy input or material hysteresis loop stability. With this method, intrinsic dissipations may be studied using fast, full-field, contactless methods, and neither the loading situation nor the stability of the temperature signal are prerequisites.

De Finis et al. (2022). A subject that still has unanswered questions is the use of thermal indices measured by infrared detectors to reconstitute the S/N curve as dependable damage metrics in monitoring quick fatigue testing. Choosing the right thermal index to indicate damage is an important first step, and there should also be some debate about how the results of the quick stepwise test compare to those of the constant amplitude test. In this paper, we address this kind of problem by studying thermoelastic processes and dissipative effects via the First Amplitude Harmonic (FAH) of the thermal signal. Evidence suggests a connection between FAH and stress-induced effects and stiffness deterioration. In addition, it offers a local, artifact-free examination of the impact particular to material fatigue damage.

Meneghetti, Giovanni & Ricotta, Mauro. (2021). It is assumed that the inherent dissipation is proportional to the second harmonic of the Fourier transform of the temperature signal, an analytical framework was created. All input mechanical energy is assumed to be converted into heat in the theoretical model, without limiting its generalizability. Elastoplastic materials that are either completely plastic or that adhere to the Ramberg-Osgood criterion are covered.

Amraei, Jafar & Katunin, Andrzej. (2022). When polymers and polymer-matrix composites (PMCs) are vibrated or exposed to fatigue stress, a catastrophic event known as the self-heating effect may happen. Such structures exhibit this phenomenon as a rise in temperature because of their poor thermal conductivities. Thermomechanical stress occurs when the surrounding polymer matrix has a lower coefficient of thermal expansion (CTE) than the fibers, which in turn starts or speeds up structural deterioration and eventually causes fatigue failure. For this reason, understanding the self-heating phenomenon's degradation process at nano, micro, and macroscales and finding ways to mitigate it is crucial for a variety of real-world applications. One practical approach is to enhance heat evacuation by convection by cooling the surfaces of the structures under consideration. This may be achieved through a variety of cooling scenarios, including climatic and operational conditions. In addition, structural damage may be avoided or reduced to a minimum by carefully choosing materials based on their thermomechanical qualities, which include heat conductivity.

ENGINEERING CHARACTERIZATIONS OF SAFE-LIFE

When planning for uses with cyclic loading amplitudes that are repeatable and anticipated lifetimes that include millions of cycles at low loading levels, the results of testing with the sort of loading indicated in Figure 1 may be useful. Here we have the stress life strategy. Another subject, referred to as a strain-life method, handles situations with heavy loads and reduced failure times. Figure 1 displays a few instances of cyclic stress. The stress range and the loading parameter are two of the most important ones.

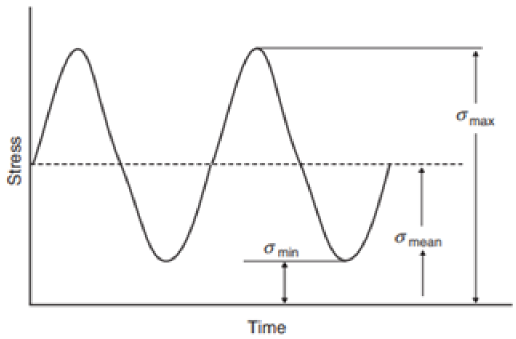

Figure 1. Cyclic variation of stress.

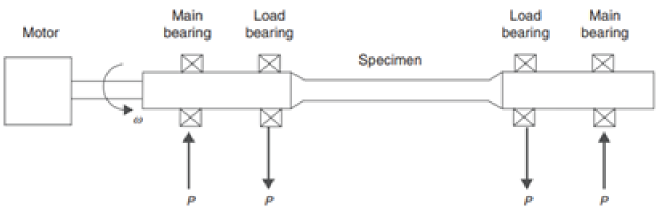

Figure 2. Experimental design for a four-point rotating bend.

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$

coupled with stress ratio

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

Since $\sigma_{\min}$ R could have a negative value if it is decided to be compressive.

A four-point rotating bend test is shown schematically in Figure 2. There is a static load applied, yet the specimen is really rotating. All of the surface materials undergo extreme stress testing as a result of the rotation.

THE THREE FATAL DESIGN APPROACHES: FAILURE-SAFE, DAMAGE-TOLERANCE, AND SAFETY-FIRST

An examination of the Comet's fuselage's structural integrity was initiated in the 1950s in response to the simultaneous loss of many aircraft. The failures seen during the pressurization test on the sample aircraft were most likely caused by fatigue and stress accumulation at the corner of the window. The development of fatigue techniques for aircraft design was prompted by these and other accidents. The oldest and most conventional approach to fatigue management is to test a structure's strength against loads that are many times its expected lifespan of service. In a fatigue test conducted in a controlled environment, for instance, an airplane wing would have to endure loads that are four times more than its expected service life.

The term "safe-life" describes a design philosophy that includes such requirements. A certain number of permissible landings or flying hours is often used to specify when aircraft components need to be replaced using the safe-life method. It doesn't matter whether there are fatigue cracks; once a component's replacement time comes, it is retired since its safe-life has been used up. But there are two major issues with this approach: (i) it doesn't ensure aircraft safety in the event of a manufacture, incident, failure caused by maintenance, or accident, and (ii) the conservative safe-life safety parameters might lead to the premature retirement of several components.

Following this, the failsafe technique is used in aircraft fatigue design. Structures with several load routes are the foundation of this approach, which first surfaced in the 1960s. The basic premise is that the system can withstand the additional strain caused by a failed component until the source of the problem is located and corrected. A complete system failure may occur in some designs due to the interdependence of individual components.

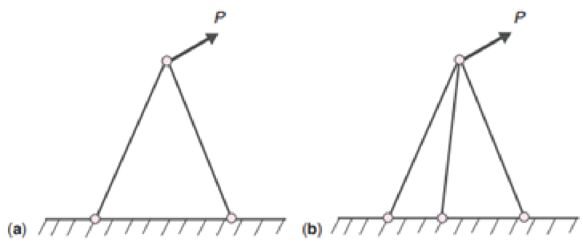

Figure 3. (a) A two-bar truss; and (b) a three-bar truss (fail-safe).

Think of a two-bar truss subjected to an outside force as an easy illustration (Figure 3a). There will be a complete breakdown of the structure's intended function if even a single bar fails. In contrast, a three-bar truss may continue temporarily perform its intended function even if one of the bars fails (Figure 3b), since the stresses between the remaining bars are simply redistributed. We may say that the second case is fail-safe after that. This is a typical design solution in airplanes, and it's clearly desired. An airplane that follows the rules of fail-safe design should be able to take a hit and keep flying until the problem is found and fixed.

In order to ensure the load-bearing parts are in good shape, this concept calls for regular inspections. Because this method's inspections were not grounded in fracture mechanics the study of how cracks grow it is possible that fractures may form simultaneously in various portions of the load path. Therefore, it was crucial to identify weaknesses and repair them before to failure, as shown by the mid-1970s loss of many "fail-safe" aircraft. Even with a crack in it, a load-sensitive component could continue to operate correctly. In the fissure, a time-dependent extension sometimes called "stable" growth may take place. There may be a critical length beyond which the crack's growth becomes unstable and catastrophic.

During a steady growth phase, the system's structural integrity is maintained and the forecast of when the system will reach a critical length is the primary emphasis. To do this, one must be familiar with the loading history of the broken component. To prevent a crack from reaching its critical length during the inspection period, fracture mechanics is used in conjunction with prescribed inspection intervals. This means that fractures may start appearing at any moment and will be detected during the subsequent inspection period, preventing them from becoming serious. Associated repairs would inevitably follow. Evaluating component tolerance to crack existence is the reasoning behind the stated work, which is complicated despite the reduced presentation.

This is when the complex process known as damage tolerance began to take shape. The United States Air Force pioneered the use of damage tolerance fatigue design in the early 1970s. Thanks to the safety and cost advantages it provided over past techniques, In the end, commercial aviation adopted the damage tolerance mentality. The damage tolerance method seeks to identify PSE fractures before to their critical length, as previously stated. A probable structural element (PSE) is any part of an airplane that may collapse if it couldn't withstand the plane's flight, ground, or pressurization loads.

Time spent at each gross weight, speed, and altitude are included in this profile, along with flying circumstances such as taxi, climb, cruise, descent, and landing impact. Then, close to the aircraft's center of gravity, a load factor spectrum is generated using the consumption profile. Finding the PSEs is the next stage, after which each site's load factor specification will be converted to a stress specification. Finally, the effects of the service environment will be taken into consideration. The number of cycles needed for a fracture to reach the critical length may be calculated by integrating the stress spectrum with data on material properties and the solutions to the crack growth (da/dN) equations, such as the Paris or Forman equations, using the detectable length as a starting point. Dividing this number by 2 usually yields the inspection interval. That way, if a PSE develops a fracture, it may be examined before it fails completely.

The damage tolerance strategy differs from the safe-life approach in that it only replaces components when a fracture is discovered during an inspection, rather than retiring them regardless of damage. Keep in mind that if an inspector finds a fracture of any size, the component in question must be replaced—no matter how little, even if it means the component may make it until the next inspection. Unlike the S-N technique, which is characterized by a great amount of dispersion, the damage tolerance approach has fracture formation that is very predictable. Therefore, it permits a decrease in design safety factors.

ANALYSIS OF FRACTURE BASED ON ENERGY

Using the idea of energy release rate G, another approach to fracture issues may be taken that avoids the seeming contradiction of having a single solution close to the crack tip. Originally proposed by Griffith (1921) in his seminal work on brittle material fractures, this idea measures the drop in total potential energy caused by a microscopic crack propagation, that is

$$G = -\frac{\partial \Pi}{\partial A}$$

location of the crack is denoted by A. The formula dA = b da applies to plates having a width of b, where an is the fracture length. Crack propagation energy is therefore represented by the energy release rate, which is measured in J/m^2. So, the energy-based crack initiation criteria look like this: G_c is the material's fracture toughness, or the amount of energy needed to generate fracture surfaces. We find that in the linear elastic case, When the change in strain energy associated with an infinitesimal advance of the crack tip is calculated, stress- and energy-based fracture techniques are equivalent. Accordingly, the following is the connection between stress intensity factors and the energy release rate G. K_k (k = I, II, and III):

$$G = \frac{K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2}{\bar{E}} + \frac{1+\nu}{E} K_{\mathrm{III}}^2$$

where $\bar{E} = E$ about the strain on the aircraft and $\bar{E} = E/(1-\nu^2)$ is used for planar strain and stands for Poisson's ratio. In the energy approach to fracture, the J-integral plays a significant role; it was first postulated by Rice (1968) and described by.

$$J = \int_{\Gamma} \left(W n_1 - \boldsymbol{T} \cdot \frac{\partial \boldsymbol{u}}{\partial x_1} \right) \mathrm{d}\Gamma$$

Connecting stresses and strains, W is the strain energy density via, and designates any shape that surrounds the fracture point. $\sigma_{ij} = \partial W / \partial \varepsilon_{ij}$, This formula describes a unit outward normal to the contour, a traction vector T, and a displacement vector u. The J-integral is unaffected by the contour that defines it, regardless of whether the material is linearly or nonlinearly elastic. Thanks to this crucial feature, we may connect the dots between far-field loading amounts and near-tip characteristics (such stress intensity factors). Also, Rice demonstrated that the energy entering the fracture tip region—the rate of change in potential energy relative to the crack's advancement—is directly related to J for a (non)linearly elastic material. This means that for a material with linear elastic properties, it boils down to G, the strain energy release rate. The maximal energy release rate criterion and other energy-based criteria have been suggested as potential means of fracture path prediction. When it comes to stress-based criteria, these suggestions are quite comparable, to complete this part on the energy approach to fracture.

THE PARIS LAW ON FATIGUE CRACK GROWTH

When it comes to fatigue, the load levels are usually rather small, and An explanation for the stress field outside of the small nonlinear zone might be provided by the asymptotic solution. The assumptions about small-scale yields depend on this. The geometry of the problem determines the range K of the (mode I) stress intensity factor that may be linked to the cyclic load applied to the specimen. Figure 4 shows a schematic representation of the relationship between crack progress per cycle, da/dN, and K, as shown in the seminal work of Paris (1960) when plotted on a log-log graph. The Paris curve, as this curve is often known, displays three separate regimes of fracture propagation. The power law relationship between da/dN and K exists in the steady-state regime (region II):

$$\frac{da}{dN} = C(\Delta K)^m$$

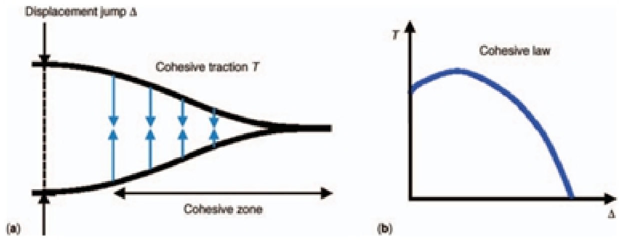

Figure 4. Cohesive zone modeling of a crack: (a) schematic of crack tip region; and (b) cohesive failure law.

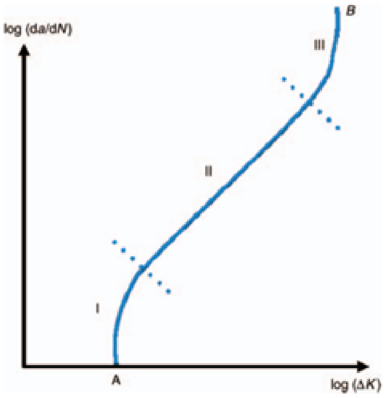

Figure 5. Three separate regimes of crack propagation are shown by the typical Paris curve.

where m is the exponent, which is about 3 for many metals and around 10 for polymers, which is much higher. No fracture propagation is detected below a certain threshold value A in the fatigue response at lower loading amplitudes (region I). As the load level gets close to the point where the crack propagation rate is linked with monotonic loading, it develops rapidly over the maximum range of loading amplitudes. The anticipated fatigue life of a cyclically loaded structure may be predicted using experimentally derived parameters defining the material's fatigue response (19) and precise information on the location and extent of any fractures in the structure, as previously mentioned.

CONCLUSION

Last but not least, "small fatigue cracks" and "below threshold" fatigue crack propagation is a significant area of present study. Fatigue crack development under the so-called "Paris regime" has been researched extensively and used extensively in damage tolerance in aerospace. If the "threshold" value of K is less than K, fractures will not form under this regime. But it is well-established that fractures do form below the threshold, and one might spend a significant portion of their lives in the "below threshold" regime. The alloy microstructure (grain size) influences the growth below threshold, which is marked by increasing dispersion. To guarantee appropriate damage tolerance measures for aircraft components and to provide a seamless shift from the "Paris regime" to the "below threshold regime," physically based processes are required.

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