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FATIGUE OF CFRP COMPOSITE LAMINATES – WAYS FORWARD

Mohd Nasir Tamin
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia,
81310 UTM Johor Bahru, Johor, Malaysia.
Email: nasirtamin@utm.my

ABSTRACT

A paradigm shift from the conventional Test-to-Compliance approach to Certification-by-Analysis for increasingly complex composite structures has been introduced. The latter relies on a credible modeling and simulation approach employing the *Verification, Validation,* and *Uncertainty Quantification* (VVUQ) framework. In this regard, a damage-based fatigue model of CFRP composite laminates is being developed. The model describes the progression of fatigue damage up to crack nucleation, driven by cyclic degradation of the lamina and interfacial properties. The residual properties of the anisotropic unidirectional lamina and thin interfaces are established experimentally. The *Certification-by-Analysis* approach is enabled by the convergence of several technologies, including high-performance computing, AI and surrogate models, and digital twins.

KEYWORD

CFRP composite laminates, credible modeling and simulation, fatigue damage models, residual properties

BACKGROUND

Carbon fiber-reinforced polymer (CFRP) composite laminates are designed to offer a high strength-to-weight ratio and high stiffness compared to their alloy counterparts. The ability to combine different unidirectional tapes or laminas provides flexibility in tailoring layups to optimize the material's directional properties during the fabrication of structural components. CFRP composite laminates are increasingly used in aircraft structural components such as the fuselage, wings, and spoilers, as well as in wind turbine blades and pressure vessel shells. These primary structures experience both static and dynamic loads, including impact and fatigue, throughout their design lives. Additionally, the structure may operate in a moist environment and/or at high or cryogenic temperatures.

CFRP composite laminate structures exhibit abrupt fracture under quasi-static overloading. This suggests that damage initiates near the time of fracture. Catastrophic fracture is often accompanied by multiple failure mechanisms, including matrix cracking and fiber fracture in tension, matrix crushing and fiber kinking in compression, and interfacial delamination. Moderate-energy impact loads often cause barely visible impact damage (BVID), which severely reduces laminate strength without any surface indication. This can lead to early damage initiation and fracture of the structure.

The damage mechanisms of CFRP composite laminates under fatigue loading are similar to those observed under quasi-static loading. CFRP composite laminates are also sensitive to notches. While a sharp crack grows cycle-by-cycle, leaving striations in metals, damage in CFRP composite laminates, including matrix cracks, delaminations, and fiber fractures, interacts and coalesces to form a zone of "diffuse" cracks. The propagation of such a cracking zone in composite laminates does not follow the Paris crack growth law observed in metals.

Consequently, designing CFRP composite laminate structures using a damage-tolerance philosophy assumes the presence of BVIDs from manufacturing or service, and the structure must remain safe until these defects are detected. The structure is designed to arrest or prevent the growth of these defects. It must not fail at ultimate load due to large, detectable damage that could occur before the next inspection interval. This no-growth or fail-safe approach follows from the brittle nature, anisotropy, and lack of plastic yielding of the composite laminates.

NEW PARADIGM FOR CREDIBLE MODELING AND SIMULATION APPROACH

The growing complexity of composite structures makes exhaustive physical testing impractical. In this context, a fundamental shift from the conventional *Test-to-Compliance* approach to a new paradigm for *Certification-by-Analysis* of composite structures has been introduced. Rather than relying primarily on extensive and often expensive physical testing, *Certification-by-Analysis* uses high-fidelity computational models as the primary evidence of airworthiness, supported by a strategic layer of testing designed to build confidence in those models. The credible modeling and simulation approach still uses the classical building-block pyramid, as illustrated in Figure 1, but with rigorous requirements for the *Verification, Validation,* and *Uncertainty Quantification* (VVUQ) framework (ASME.org). Material coupon and element tests at lower levels are used to calibrate and validate the predictive model. The number of physical tests decreases significantly as the role of analysis increases when climbing the pyramid. The final full-scale test shifts from proof to ultimate validation of the entire modeling framework.

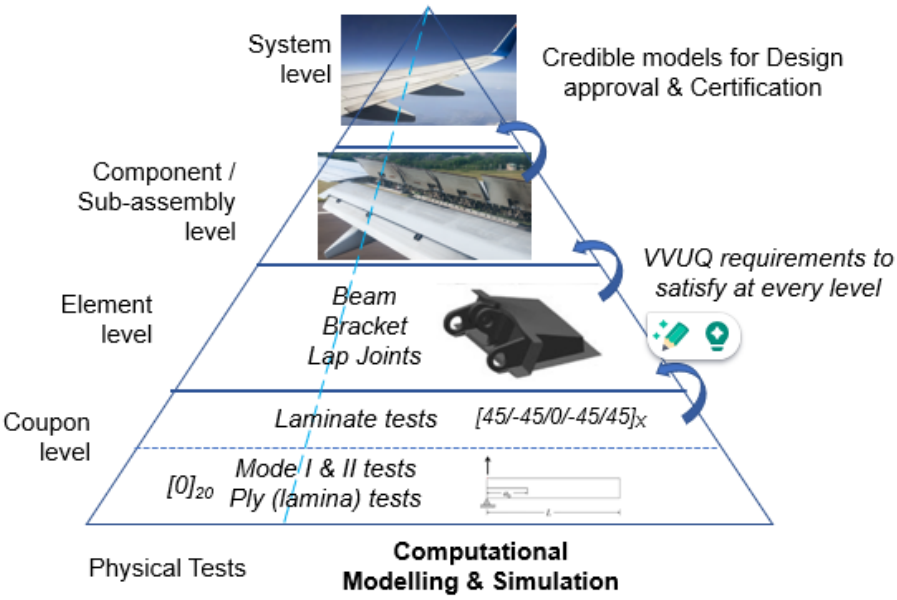

Figure 1: Building block approach pyramid with VVUQ framework.

The *Verification, Validation,* and *Uncertainty Quantification* (VVUQ) becomes the primary method for developing credible computational models at every level of the building-block pyramid. The method establishes the trustworthiness of simulation results enabling risk-informed design approval and regulatory certification of the composite structures.

- The *Verification* aspect ensures that the mathematical model and its numerical implementation are free of coding errors and that the solution converges correctly.
- The *Validation* exercise compares simulation results with physical (measured) data to assess how accurately the model represents reality for its intended use.
- The *Uncertainty Quantification* systematically accounts for all sources of uncertainty – from material variability, such as fiber density and volume fraction, to manufacturing defects, to modeling approximations and scatter in test data. The goal is to quantify the confidence bounds on the predictive outcomes.

FATIGUE DAMAGE MODELS FOR CFRP COMPOSITE LAMINATES

The development of mechanism-based fatigue models is central to building credible computational models of CFRP composite laminates. These damage mechanics models track the residual strength and stiffness of the unidirectional (UD) lamina and interfaces and predict the evolution of fatigue damage over load cycles, making them superior to conventional Strength-Life *(S-N)* or linear Palmgren-Miner approaches for fatigue life prediction. In this respect, a continuum fatigue damage model (CFDM) for the UD lamina and a cyclic cohesive zone model (CCZM) for thin interfaces are being developed (Koloor et al., 2020; Khan et al., 2023).

The conceptual fatigue damage model is illustrated in Figure 2 in terms of equivalent stress and strain. The model applies to both the UD lamina and the interfaces. Fatigue damage manifests as cyclic degradation of strength and stiffness properties (path *a-b-c-d*). The strength and stiffness properties can degrade only up to the maximum stress level σ_{max}, of the fatigue cycles. The onset of the fatigue cracking process (Point *d*) in the lamina is described using modified Hashin-based damage criteria for various damage mechanisms in the lamina and the quadratic mixed-mode cohesive zone equation for interface damage.

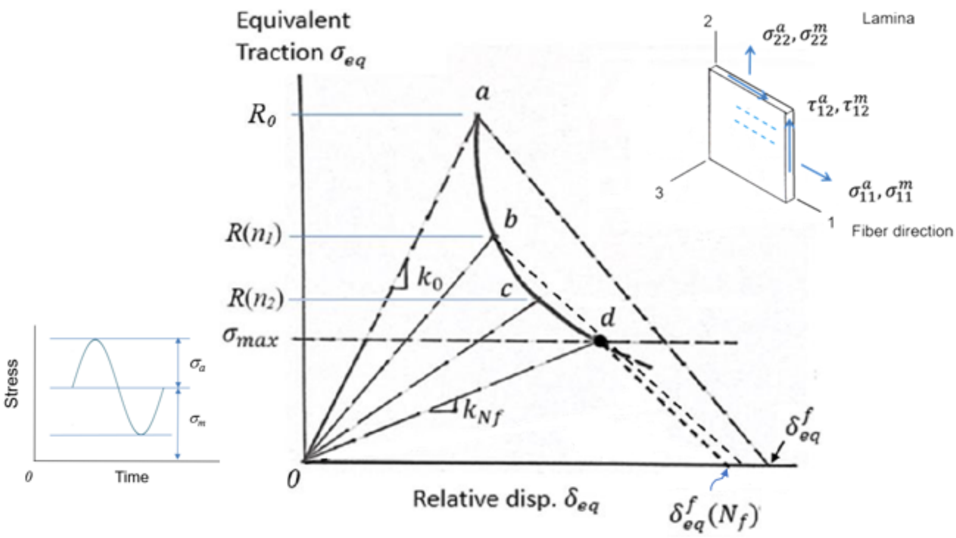

Figure 2: Conceptual damage-based fatigue model, illustrated for the lamina.

An example of the fatigue criterion for the onset of the tensile matrix cracking process in the UD lamina with the transverse stress $\sigma_{22} > 0$, is written as:

$$\left(1 - \frac{Y^T(n)}{Y_o^T}\right)^2 + \left(1 - \frac{S^L(n)}{S_o^L}\right)^2 = D_{mt}^2 \qquad (1)$$

where $Y^T(n)$ and $S^L(n)$ are the residual transverse tensile and longitudinal shear strengths, respectively, while Y_o^T and S_o^L are the corresponding static strengths. The critical damage parameter value D_{mt}, must be determined experimentally. Similar quadratic forms of the criteria are developed for the fatigue damage mechanisms of matrix compression, fiber tensile fracture, and fiber kinking. The subsequent fatigue crack nucleation (material point separation) and the growth of the cracking zone are governed by an energy-based criterion.

Fatigue damage evolution - an example is shown by eqn. (1) for the matrix tensile cracking mechanism, is governed by the relevant cyclic property degradation $\left(Y^T(n), S^L(n)\right)$. A series of interrupted fatigue tests under prescribed cyclic loading conditions is performed to determine the residual properties of the anisotropic UD lamina and the thin interfaces. The effect of mean stress on the fatigue life of the phases is established through a predefined life parameter for each normal and shear loading mode. Similar property degradation characteristics are expected under different stress ratios.

CONCLUDING REMARKS

The no-growth certification of most composite laminate structures considers *Compression-after-Impact (CAI)* strength and the ultimate load check (ASTM D7137). However, the mechanism-based fatigue damage model is applicable to the damage-tolerance design and certification of composite structures with known slow-growth damage. The model can account for load interaction effects under variable-amplitude loading. Additionally, an appropriate fatigue failure criterion can be used to predict the failure of composite laminates under multi-axial loading.

The paradigm shift from the conventional *Test-to-Compliance* approach to the new *Certification-by-Analysis* methodology for composite structures is enabled by the convergence of several technologies, including:

- Availability of high-performance computing (HPC) for running computationally demanding, high-fidelity, multi-scale simulations.
- Use of an artificial intelligence *(AI)*-driven model to generate synthetic, high-fidelity data for uncertainty quantification and the creation of surrogate models.
- Leveraging model-based digital twins to manage the composite laminate structure throughout its lifecycle.

The mechanism-based fatigue damage model is central to the development of a credible modeling and simulation framework for CFRP composite laminate structures.

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