A MULTISCALE FEM FRAMEWORK FOR PREDICTING PROGRESSIVE FAILURE IN AEROSPACE COMPOSITE MATERIALS

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ABSTRACT

Failure in composite materials is known to initiate at the level of constituents. Further development of the failure process and ultimate failure of the composite structure depend on the fiber architecture and other geometrical details. A composite failure analysis must therefore be at multiple length scales. This paper will outline a multiscale modeling scheme and illustrate the approach with two examples: tensile fiber failure and transverse matrix cracking. For the case of fiber failure, a five-cylinder axisymmetric finite element model containing an initially broken fiber at the center will be used to conduct stress analysis and formation of a failure plane will be simulated by a crack growth procedure. The transverse crack formation will be analyzed as a linking up of fiber-matrix de bond cracks. Formation of these cracks will in turn be analyzed by an energy-based criterion. The local scale modeling will take account of the manufacturing induced irregularities and defects by appropriate representation of these in the failure analysis. Finally, an assessment of the multiscale approach as a rational alternative to the currently used failure theories, which are formulated on homogenized composites, will be presented and the challenges remaining to address in future will be outlined. This manuscript presents a multiscale stochastic failure modeling approach for fiber rein-forced composites. A homogenization based reduced-order multiscale computational model is employed to predict the progressive damage accumulation and failure in the composite.

Keywords: *Composite Failure, Multiscale Modeling, finite element model, Failure Theories*

INTRODUCTION

Consequently, composites are more prone to a wide range of failure modes and damages throughout the course of their lifetimes than metallic ones. The internal damage to the composite construction might also significantly diminish his performance. Of these damages, the low-velocity impact accounts for over 80% of service damages in laminated composite structures, making it one of the most essential types of damage. It is capable of drastically lowering stiffness and strength without leaving any surface damage. In order to comprehend the potential progressive damage that low-velocity impacts may cause to composite laminate constructions, it is crucial to do research into this area. In order to detect and identify any problems, it is crucial to examine this component throughout its life. Ultrasound, active thermography, x-ray radiography, stereography, and sonic emission are just a few examples of the many non-destructive techniques (NDT) that may achieve this goal. They provide a safe way to examine the composite parts without causing any harm. The manufacturing process, as well as operation and maintenance, may benefit from component inspection. However, one of the most effective methods for accurately predicting the impact's effects, damage to buildings, and subsequent residual behavior is numerical prediction of residual resistance after impact. Thus, bulk reduction and the avoidance of costly testing will be facilitated by the numerical forecast after impact. In order to simulate the beginning and the spread of various damage modes in composite materials, a great deal of research has offered a variety of prediction methodologies. Researchers mostly use the finite element model (FEM) to examine composite laminates' impact damage problems. Predicting the complicated internal damage pattern that may emerge in composite laminates in a very short amount of time is an attractive goal. To simulate impact behavior, many commercial finite element algorithms have been employed recently, including, among others. Reviewing numerical damage prediction in composite structures using FEM is the subject of this research. It all starts with researching potential flaws in the composite and what may trigger them. Most of the damage in this building was caused by impacts with very slow velocities. Thus, it will constitute the bulk of this effort. In order to simulate the evolution of damage in composite laminates during design, it is crucial to understand his damage processes. How to represent the microstructural changes in the material and how to link those changes to the material's reaction is the biggest challenge in developing a computationally efficient numerical method to forecast damage. Even with basic unidirectional layup and in-plane stress, the findings of the Word Wide Failure Exercise show that existing failure models and criteria do not adequately describe or predict failure. Actually, we still don't have a complete picture of what causes composite materials to fail. The need of knowing how each failure mode occurs, or having a physical model for each failure mode, becomes apparent when considering the usage of composite materials in structural applications. In addition to describing what happens after a failure, these physical models should pinpoint exactly when the breakdown occurs. For instance, in order for a physical model to account for matrix compression failure, it has to specify when a certain stress state is reached, the direction of the fracture plane, and the amount of energy that should be dissipated during crack formation.

LITERATURE REVIEW

Ashutosh Maurya et al. (2024) devised a novel failure criteria. A multi-scale modeling technique based on a mix of virtual and laboratory testing is used to generate a point cloud failure surface in the stress/strain space, instead of the analytical expression that has typically been used for failure prediction. Microscopically, the composite's individual parts are used to create a representative volume element (RVE) that undergoes a multi-axial stress condition until its first failure is identified. At the structural or meso levels, the relevant parameters at the meso size are derived using a volumetric homogenization approach. Using the k-nearest neighbor (k-NN) classification principle, finite element analysis queries the point cloud data to determine whether the present stress state in the finite element is within or outside the failure surface. An explicit finite element program incorporates the failure criteria within the failure sub-model. The produced method for two structural systems utilizing thin shell finite elements is demonstrated with the help of a representative unidirectional composite. These systems include stacked-ply tests with tensile and compressive loading under quasi-static, room temperature conditions, as well as an impact-loaded flat panel.

Ismail Yaser et al. (2023) Because of their exceptional mechanical qualities, fibre-reinforced polymer (FRP) composites have been the subject of several numerical modeling efforts in the aerospace, automotive, and marine industries in the last few decades. Because of their anisotropic and inhomogeneous properties, various failure modes, and interaction, particularly under multiaxial loading circumstances, it is still problematic to precisely anticipate the failure of the composites. In order to evaluate current failure criteria and comprehend the progressive failure processes of composites, numerical models based on micromechanics, such as representative volume elements (RVEs), were created. In order to achieve this goal, this review article compiles the evolution of RVE models of unidirectional (UD) FRP composites based on micromechanics that have been published in the literature.

Mr. Sharma and colleagues (2022) Aerospace, automotive, marine, civil, and many other technologically demanding sectors have found polymer composites to be the appropriate material due to its exceptional multi-functional qualities. The growing need for these composites necessitates a thorough examination of their mechanical, chemical, and physical properties under various environmental circumstances. The predictive value of machine learning (ML) for data-driven multi-physical modeling has been widely acknowledged, allowing for the discovery of previously unseen system features and insights that would have been impossible with more conventional computational and experimental methods. Our goal here is to condense the results of the mountain of literature on the subject into a manageable format, drawing attention to the many ways in which machine learning (ML) can be applied to polymer composites.

Emine Tekerek (2021) In this article, we provide a new approach to updating failure models for composites. Both the experimental and computational methodologies used contribute to the innovative approach that is presented. When it comes to data-driven failure models, one of the biggest obstacles is figuring out what kinds of data may be utilized to calibrate or update the models. To solve this problem, this paper uses non-destructive evaluation data from laboratory-scale mechanical testing to create a damage metric. This metric is based on a series of processing steps that use raw sensing inputs to generate progressive failure curves. Then, the damage initiation point, which is calculated using full-field three-dimensional finite element models of fiber-reinforced composite materials, is calibrated using these curves. The model accounts for both intra- and interlayer damage. The progressive failure process may be efficiently monitored using curves produced using non-destructive assessment data. These curves might be utilized to construct modeling inputs at various length scales.

Failure multi-scale analysis

In a composite material, like in any heterogeneous solid, failure might start at an interface or in a component. As a result, the microstructure is the site of failure start. However, the criticality requirement for the probable failure mode and the local stress field determine when and where failure begins. Thus, in most cases, recording the event of failure start will not be possible by homogenizing the microstructure. The averaged stress field at the macro level provides a useful expression for the requirement for the occurrence of the exceptional scenario when only one failure mode is operational. When more than one failure mode is feasible, it is not always practicable to define the winning (first) failure event's circumstances using stress fields that reflect averages of the often non-uniform local fields. Local stress fields are often three-dimensional, even when applied uniaxially at the macro level. Unit cells with three distinct fiber-packing configurations were used to depict the microstructure in the cross-section of a UD composite in Asp. On the other hand, the distribution of fibers in actual composites is not uniform.

Criteria for Failure Mechanisms

There are three distinct stages to composite structure failures, as mentioned before. The first is the elastic phase, during which the structure shows no signs of damage. The second stage occurs when the structure begins to exhibit damage at certain stress levels. Finally, the post-failure phase is characterized by the propagation of damage inside the structure. The primary goal is to provide failure criteria that will help designers get a better understanding of the structural behavior of composite components and make more accurate predictions about their durability under various loading circumstances. There isn't yet a standard that all designers agree upon. But the truth is that the most common criteria fall into one of two categories: dependent failure modes and non-dependent failure modes. It should be noted that some of them also enable modeling of the post-failure period, including the deterioration of the stiffener matrix that happens as a result of damage propagation.

A thorough approach to analyzing composite failures

a thorough approach to determining the cause of composite laminate failure. It combines the three solutions to the existing failure theories that were mentioned before. The first stages of failure analysis include finding the stress fields inside the relevant RVEs of the UD composite microstructure and any accompanying faults. This will help determine the mechanisms of failure. There are a few ways to classify these modes: fiber failure, matrix failure, and fiber/matrix interface failure. The UD composite will fail under certain situations caused by instability in the evolution of failure modes. It is anticipated that these conditions will be related to the material constants, such as the critical value of the dilatation energy density for the matrix polymer, and the applied (uniform) tractions on the RVE borders. It is anticipated that the relationships would include statistical characteristics for the distribution of fiber failures for the various forms of failure. Please be aware that the analytical formulations (criteria) used in the existing theories of failure do not correspond to these circumstances.

How flaws affect the failure of composites

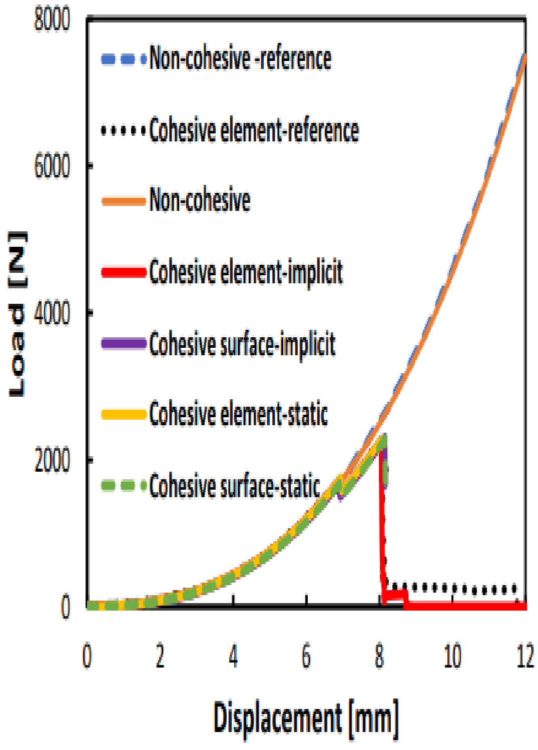
It is impossible to produce practical composites without making some mistakes. It is becoming more and more important to reduce the manufacturing cost of composite structures. The failure analyst has the problem of evaluating the consequences of flaws on failure and conducting a cost/performance trade-off. The failure theories discussed in Section 2 above clearly can't account for faults since they're based on homogenized composites, which don't retain any direct knowledge of the defects. Incorporating flaws and other microstructure characteristics requires a multi-scale study. Such analyses have been conducted for UD composites with voids in order to assess the elastic characteristics and local failure modes, specifically looking at the interactions between the voids and the fibers in a UD composite that was loaded transversely. In mode I cracking and out-of-plane delamination buckling, further research has looked at how voids affect crack propagation in resin-rich regions of composites. Adding artificial, simulated faults to a composite to measure the deterioration in failure-related attributes was a frequent practice in the early days of studying the impact of defects.

METHODOLOGY

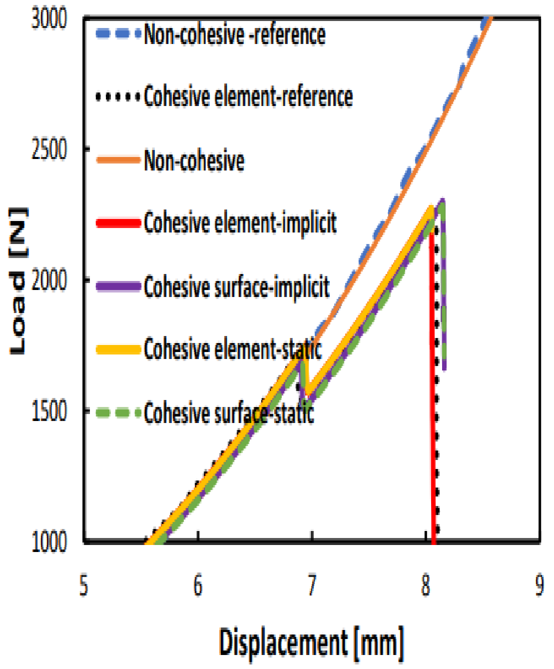
Numerical delamination forecasts have mostly relied on strength-based approaches for the last few decades. Experimental results in the majority of recent studies have validated fracture mechanics-based approaches such as the Virtual Crack Closure Technique the Cohesive Zone Method, and the Extended Finite Element Method.) Intra laminar failures are modeled using XFEM and inter laminar failures using CZM in this thesis. While CZM is limited to initiating and propagating inter laminar damage, XFEM may start and propagate intra laminar failures when coupled with one of the composite failure initiation and propagation criteria. For fracture propagation to occur, the XFEM enrichment zones must be used as regions of interest. While this thesis only utilizes CZM for T-joints, it employs two methods to simulate the progressive failure of composite L-beams. When the traction value reaches the criterion specified by the kind of delamination, damage may be initiated For propagation to be successful, the critical energy release rate the amount of energy required to create a new fracture surface must be reached. Two of them, however traction separation behaviors and continuum behaviors are relevant to delamination models. For surfaces with a finite thickness, like paste adhesives, a continuum-based response is ideal. On the other hand, when the thickness of the interface material is negligible, cohesive components' constitutive reaction is better suited to the traction-separation response.

RESULTS AND DISCUSSIONS

The non-cohesive models in Graph.1 show loads corresponding to a 12 mm displacement, and When the finite element model is generated in accordance with the reference, they achieve an accuracy of within 0.8%. For cohesive and non-cohesive models to have compatible load-displacement curves prior to failure, model stiffness must be appropriate, which indicates that cohesive layers are successfully adapted to the model. Furthermore, cohesive surface-based models and cohesive element-based models are correlated and behave similarly.



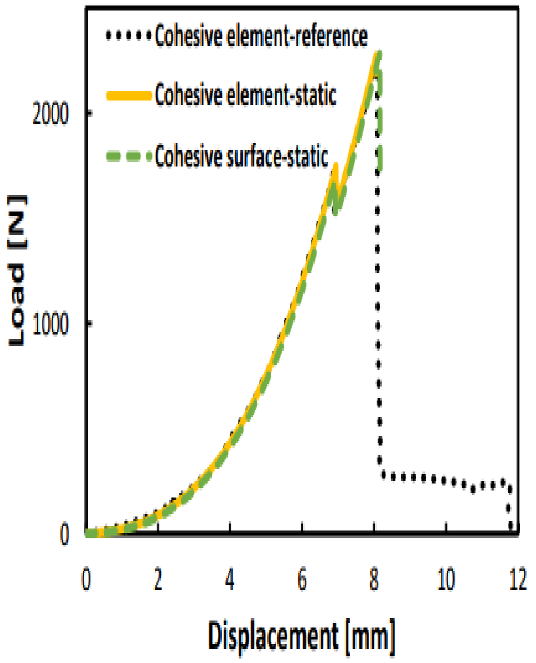
Graph 1 Load-displacement curve comparison of the models



Graph 2 Enhanced version of the load-displacement curve comparison

The graphic below provides a debonding procedure for a broad comprehension of the failure behavior. The combination manner of opening and shear pressures causes the failure to begin toward the top end of the filler. It spreads over the web and becomes stable during the second capture.

When 12 mm of applied displacement is considered, neither model offers converged solutions, according to Graph 3, but an interface based on cohesive parts performs better than cohesive contact.. A cohesive surface-based interface outperforms cohesive parts. Failure propagation at a site where severe nonlinearity and considerable displacements (e.g., dynamic behavior) occur due to integrity loss may still be achieved even with a static solution. In terms of initiation load, the cohesive element-based model is within 4% of the reference cohesive solution, while the surface-based interface is almost similar. The reference cohesive model's value of 6.91 mm is in agreement with the cohesive element failure start forecast, which is 0.03 mm beyond the cohesive surface.



Graph 3: Evaluation of cohesive and non-cohesive models using static-implicit comparison of load-displacement curves Dynamic Quick Implicit

The cohesive contact model, like the static solver, produces a solution that does not converge. However, the cohesive element model, which employs the dynamic implicit solver, concludes the investigation up to a depth of 12 mm.

CONCLUSION

By integrating these failure models into the FEM environment as constitutive laws or user-defined subroutines, materials may be accurately simulated under realistic loads and environmental circumstances. This allows for thorough simulations. When it comes to modeling the geometric complexity and material anisotropy that are intrinsic to aerospace composites, the Finite Element Method provides unmatched versatility. The use of finite element modeling (FEM) allows for the correct description of orthotropic or transversely isotropic behaviors by discretizing composite laminates into layers with different mechanical characteristics and orientations. Engineers can model the beginning and development of damage processes such delamination, fiber breaking, matrix cracking, and interfacial de bonding using this method. Aerospace structures subjected to dynamic impact conditions, cyclic loads, and high temperature gradients are especially important considerations, and FEM enables coupling of these and other environmental, mechanical, and thermal impacts. Validation and calibration of finite element models using experimental data is an essential part of modeling composite failure in aerospace applications. No matter how advanced numerical tools become, simulations will always only ever be approximations of the actual thing. Hence, it is necessary to conduct laboratory testing in order to ascertain precise input parameters, including elastic moduli, strength limits, Poisson's ratios, and inter laminar fracture toughness.

REFERENCES

1. *Ashutosh Maurya (2024), "Incorporating point cloud failure criterion in an orthotropic visco-elastic-plastic material model", Journal of Composite Materials,ISSN: 1530-793X,Volume.58,Issue.19, https://doi.org/10.1177/00 21 9983241260882*
2. *Yaser Ismail (2023), "A review on micromechanical modelling of progressive failure in unidirectional fibre-reinforced composites", Composites Part C: Open Access, ISSN: 2666-6820, Volume.10, https://doi.org/ 10.1016/j. jcomc.2023. 100348*
3. *A. Sharma (2022), "Advances in Computational Intelligence of Polymer Composite Materials: Machine Learning Assisted Modeling, Analysis and Design", Archives of Computational Methods in Engineering,ISSN : 1754-2340,Volume.29, pages.3341–3385*
4. *Emine Tekerek (2021), "Composite Material Failure Model Updating Approach Leveraging Non-destructive Evaluation Data", Journal of Non-destructive Evaluation, Diagnostics and Prognostics of Engineering Systems, ISSN 2572-3898, Vol. 4*
5. *F. Kahwash (2015), "Modelling of cutting fibrous composite materials: current practice", Procedia CIRP,ISSN: 2212-8271,vol.28,pages.52 – 57*
6. *Gherissi A (2016), "A Comparative Study of Three Different Microscale Approaches for Modeling Woven Composite Material", Journal of Material Sciences & Engineering,ISSN: 2169-0022 Volume.6,Issue.1*
7. *Giuliano Allegri (2020), "Simulation of progressive failure in laminated composites under variable environmental conditions", Materials & Design, ISSN: 1873-4197, Volume.196, https://doi.org/10.1016/j. matdes. 2020.1090 82*
8. *Isa Ahmadi (2017), "Micromechanical failure analysis of composite materials subjected to biaxial and off-axis loading", Structural Engineering and Mechanics, ISSN: 1598-6217, Volume.62, issue.1, pages 43-54 DOI: https://doi.org/10.12989/sem.2017.62.1.043*
9. *J. LLorca (2011), "Multiscale Modeling of Composite Materials: a Roadmap Towards Virtual Testing", Advanced Materials, ISSN: 1521-4095, Volume. 23, Issue.44, https://doi.org/10.1002/adma.20110168*
10. *Katarzyna Gojny (2021), "Investigation Of Finite Element (Fe) Modelling Of Composite Materials: Shell, Solid And Solid Layered Composite Modelling – Comparison Of Impact On Simulation Results", Composites Theory And Practice, ISSN: 2299-128X,vol.21,pages.29-39*