COMPOSITE FATIGUE DAMAGE EVOLUTION USING DISCRETE DAMAGE MODELING

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Abstract
Damage initiation and propagation in laminated composites under static and fatigue loading is addressed by using the Discrete Damage Modeling (DDM) method. The essence of this technique is the insertion of true displacement discontinuities independent of mesh orientation to simulate matrix cracking. Multiple cracking in each ply is allowed. All plies are tied together by using cohesive interfaces, which are allowed to delaminate. Matrix cracks in two adjacent plies interact through the interface cohesive model and their presence is a major delamination initiator. The computation begins without any matrix cracks present. A matrix crack is inserted when the material history variable value reaches unity. Delamination and matrix cracking extent under fatigue loading in open hole graphite epoxy laminates was predicted and showed good correlation with experiment. IM7/977-3 $[30/60/90/\text{-}60/\text{-}30]_{2s}$ laminate was modeled under cyclic loading with load amplitude of 40% static strength including residual strength prediction in tension and compression after 200,000 fatigue cycles. The experimental data showed a 4% increase in tension and 7% decrease in compression residual strength. The predicted data showed the same trend in tension and no change in compression. The predicted values for tensile strength were within the confidence bounds for the experimental data and 14% higher in compression.

1. Introduction

Fatigue properties of CFRP were studied intensively in the past and satisfactorily described most isolated damage modes. The transverse strength properties have been shown to satisfy exponential S-N behavior, and the fracture related damage modes, such as delamination, have been shown to follow the Paris law. The delamination onset and propagation investigation in composite laminates has been a critical research topic for several decades and is the subject of many reviews, e.g. [1-3]. Significant achievements in practical application of the virtual crack closure technique VCCT [4] to delamination propagation in laminated composite panels, both in static and fatigue regimes, were recently reported by Deobald and co-authors [5]. Although the delamination failure mode is of great practical importance, it cannot be considered in isolation from other less critical damage modes, e.g. matrix cracking [6]. Depending upon the layup and loading profile, the delamination propagation can be

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precipitated by matrix crack formation, which can drastically affect its propagation. Several scenarios directly influencing the damage tolerance assessment are possible: matrix cracking can temporarily arrest the delamination; it can divert the delamination to a different interface; it may cause an avalanche of multiple delaminations through the thickness of the part.

Availability and rapid increase of computer power has enabled recent successes in the development of the discrete damage modeling (DDM) technique, which is based on the direct simulation of displacement discontinuities associated with individual instances of matrix cracking occurring inside the composite plies, and delaminations at the interfaces between the plies. These methods employ variants of eXtended Finite Element Methodology (X-FEM) [7] and its regularized implementation (Rx-FEM) [8-10] in particular.

The Rx-FEM allows modeling the displacement discontinuity associated with individual matrix cracks in individual plies of a composite, without regard to mesh orientation, by inserting additional degrees of freedom in the process of the simulation. The propagation of the mesh independent crack is then performed by using the cohesive zone method. The kinematic aspect of the technique does not require any modification for fatigue loading, however the constitutive component does. There are two components of DDM framework which require modification: the failure criterion for crack insertion, and the cohesive law for damage initiation and propagation. It is these developments which will be discusses in the present paper whereas the detail of Rx-FEM can be found in [8-10]. We will begin by describing the static and fatigue solution algorithms and fatigue extension of the cohesive zone model (CZM) formulation.

2. Computational Methodology

2.1. Static Fracture Simulation

The DDM approach consists of Mesh-independent Crack (MIC) modeling of transverse cracks in each ply of the laminate, and modeling the delamination between the plies by using a cohesive formulation at the ply interface. The matrix cracks are modeled by using the regularized formulation [8-10], termed Rx-FEM. The regularized formulation deals with continuous enrichment functions, and replaces the Heaviside step function with continuous function changing from 0 to 1 over a narrow volume of the so called gradient zone. The formalism tying the volume integrals in the gradient zone to surface integrals in the limit of mesh refinement was discussed in [10]. The simulation begins without any initial matrix cracks, which then are inserted based on a failure criterion during the simulation. The LaRC04 [11] failure criterion is chosen in the present work. What is inserted is a CZM associated with a matrix crack, which then begins to open. We will imply the same by saying that we insert a MIC. The propagation of each MIC, i.e. opening of the CZM, is performed by using formulation [12]. Note that the delamination between the plies is also simulated by CZM, however, the cohesive elements between the interfaces are inserted during initial model preparation. The schematic of the process is shown on Figure 1. After the failure criterion is met at a certain location a MIC is added by using Rx-FEM. Next the load is increased and the program enters a nonlinear Newton-Raphson iteration step at which the inserted crack(s) and/or delaminations are being opened. After convergence is achieved the failure criterion is checked again for new crack insertion. This process is coupled with progressive simulation of fiber failure and/or fiber criterion if applicable. In the present paper both methods will be used. We will perform static failure analysis following fatigue cycling by using Critical Failure Volume Method [13] for residual tensile strength prediction and progressive fiber failure (PFF) for compressive residual strength prediction. More detailed description of the PFF can be found in references [14].

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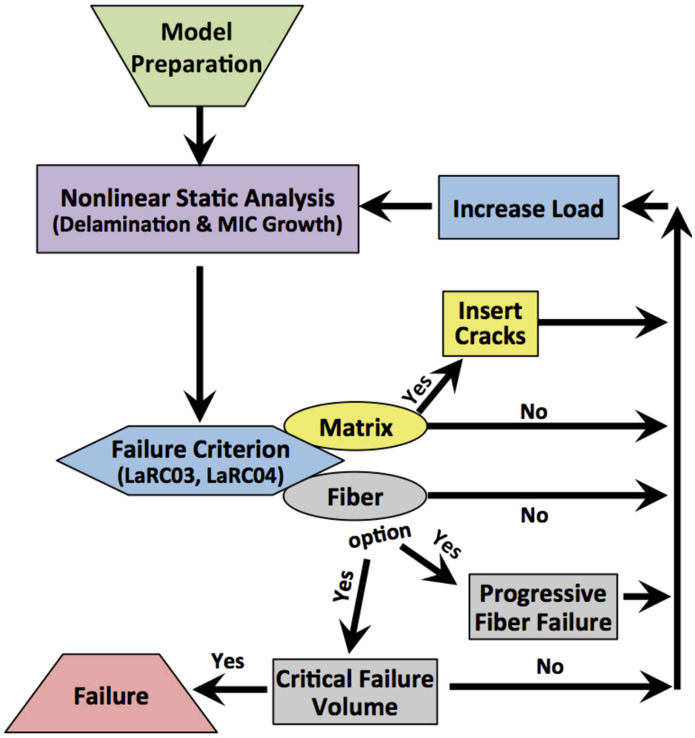

Figure 1. Static Solution Algorithm

2.2. Fatigue Solution Algorithm

Conceptually, the extension of the DDM framework shown on Figure 1 to fatigue loading is relatively straight forward. Indeed, the kinematic aspects of the DDM framework in terms of MIC insertion and delamination modeling remain unchanged, what requires development is the constitutive modeling of MIC and delamination opening, as well as crack insertion. In the present paper, we are developing ply level phenomenological framework for modeling fatigue response. Namely, we will use the S-N curves for ply level strength properties for modeling the damage initiation phase, and Paris law for modeling the growth of damage. A key element of our static framework is the cohesive zone model, which is used both for MIC and delamination modeling. Extension of the cohesive zone model to fatigue regime is a topic of ongoing research and will be addressed in the subsequent section. We will formulate a cohesive zone model addressing damage initiation and its transition to propagation in fatigue regime without any explicit or implicit assumptions of initial damage size.

Two types of algorithms can be envisioned for modeling progressive failure in fatigue:

(i) *Cycle based algorithm (CBA)*. In this algorithm one predefines a number of fatigue cycles on each solution step and simulates the damage which occurs during this cycles
(ii) *Event based algorithm (EBA)*. In this algorithm one defines an increment of damage or damage event, such as new crack insertion or delamination extension for one element, and computes the number of cycles required to advance to this event.

In a complex DDM simulation a combination of CBA and EBA is employed. The first event occurring in the present problem context is likely to be cohesive zone insertion for matrix cracking propagation after ΔN_c load cycles, where ΔN_c will be given by the fatigue crack initiation criterion. Another type of event will be delamination and/or matrix cracking propagation for 1 interval of the finite element

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mesh, which we will denote ΔN_p. The propagation cycle count will be given by the CZM formulation as described in the next section. As the simulation progresses the CZM propagation cycle count ΔN_p becomes smaller and smaller. After it reaches certain predefined minimum value ΔN_{min} the propagation events determine the number of cycles per increment i.e.

$$\Delta N_= \Delta N_P$$

even if ΔN_c is smaller. In this case the cracks are inserted not exactly when their number of cycles is reached but at the end of the step determined by delamination propagation. This may delay a crack insertion somewhat but allows the computation to proceed. The CZM propagation is selected as a dominant driver for fatigue simulation with understanding that it is this event which has immediate impact on the deformed state and requires re-equilibration.

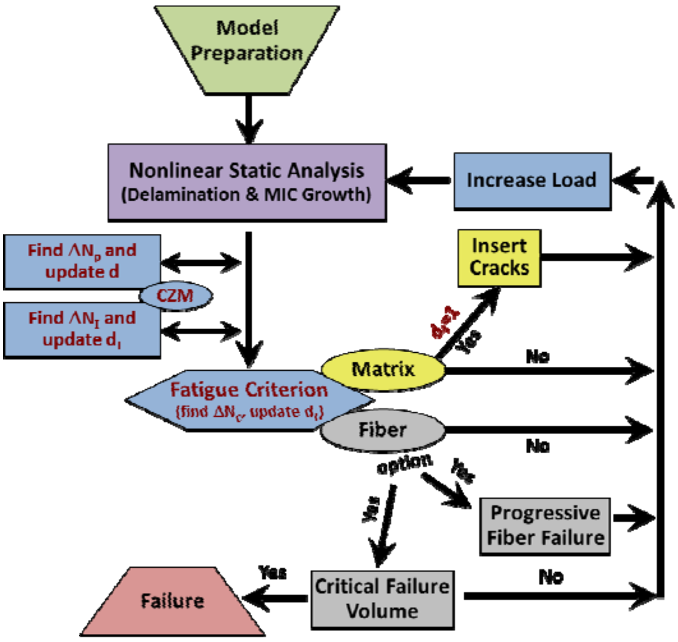

Figure 2. Fatigue DDM Algorithm

The fatigue DDM algorithm is shown on Figure 2 and is based on the static algorithm shown on Figure 1. The modifications and additions are shown in red. Consider a fixed amplitude cyclic loading. The maximum cycle load has a special meaning in progressive fatigue simulation because complex multisite damage evolution evolves both static equilibrium and cycle driven fatigue damage evolution based on Paris law and S/N curves. The static equilibrium is evaluated at maximum cycle loads for obvious reasons. Thus the simulation starts with ramping up to the cycle maximum load in static regime. It is possible that in this process the MIC insertion and opening will already begin and therefore the ramp up should be performed in more than one step. Note that the fatigue failure criterion becomes identical to static if the number of cycles is N=0. Without restricting generality assume that we ramped up the load and neither MIC insertion nor delamination damage took place. At this initial step the EBA will be controlled by number of cycles until the first crack insertion ΔN_c. We record the first step cycle count as $\Delta N^1 = \Delta N_c$ and proceed to equilibrate the solution. This time the equilibration will result in no changes to the stress-strain state because we have inserted a CZM at stress level below static initiation load. On the next step we modify the CZM in all points where the stress based history has led to failure initiation according to S-N relationship and allow the matrix crack, i.e. the displacement discontinuity associated with the matrix crack to start developing. A competing

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mechanism, which takes over after the initial discontinuity has developed is the Paris law based propagation by one interval. We proceed by discussing the fatigue CZM formulation, which consistently combines damage initiation and propagation phases under cycling loading at amplitudes below ultimate static values.

2.3 Fatigue Cohesive Zone Model

Two problem areas in extending the static CZM model to fatigue loading can be identified. One area is simulation of the propagation of existing delamination according to Paris law. The difficulty here is that Paris law is defined within the classical fracture mechanics framework and uses the energy release rate (ERR) or stress intensity factor magnitude associated with ideal crack tip singularity. On the other hand, the CZM introduces a process zone concept instead of the ideal crack tip. Two different approaches have been proposed to address this issue. One is based on explicitly bringing in the process zone length into the propagation mechanism as described in [15]. The other approach proposed in Ref.[16,17] extracts the ERR value of the classical crack tip from the process zone information and uses it to propagate a fatigue crack similar to the virtual crack closure technique (VCCT). The first methodology allows for continuous evolution of the damage variable and maintains the traditional implementation of the CZM method; however, it requires estimation of the length of the process zone in order to conduct the analysis. This presents a problem for variable mode mixity and therefore we will use the second approach for the delamination propagation phase. Thus the ΔN_P will be calculated directly by using the Paris law based on the crack tip energy release rate value and the length of the propagation interval. The second problem area of the cohesive zone model extension to fatigue analysis is the damage initiation phase and its transition into the propagation phase. It is this feature of the cohesive zone method, which has earned its popularity in static analysis. In the present approach we follow similar logic and propose to modify the initiation strength in the original static CZM when a material point has failed under cyclic loading at a stress below static strength as predicted by S-N relationship. The threshold initiation stress is then modified to the reduced value whereas the fracture toughness remains the same. This modification allows the CZM to begin opening at the load level below static strength and after initial crack growth its further extension will be governed by the Paris law.

3. Results and Discussion

The results presented below were obtained as part of two phase exercise involving static and fatigue performance prediction of laminated IM7/977-3 composite laminates. The results reported below are a subset of the second phase, which was devoted to fatigue loading. Each phase consisted of a blind and corrective stage. A $[30/60/90/-60/-30]_{2S}$ IM7/977-3 composite laminate with a 6.35mm central open hole was subjected to fatigue loading at 40% static failure load amplitude under tension-tension fatigue at R = 0.1 and subject to X-Ray CT inspection after 200,000 cycles. These X-Ray CT images of delamination and matrix cracking patterns after fatigue loading are shown on Figure 3 for each interface. A significant overprediction of the delamination extent at the blind prediction stage can be seen in the top row of images above the experimental data. This overprediction was due to an algorithmic error, which was the only modification made after receiving the experimental data. The corrected predictions are shown on Figure 3 on the bottom row of images below the experimental data. We conclude that the delamination and matric cracking patterns predicted at the correction stage of the exercise are similar to those observed by using X-ray CT. The overprediction of the delamination extent in the blind prediction phase led to prediction of short fatigue life of $5 \cdot 10^5$ cycles (Figure 4.a). As previously mentioned the correction of the algorithmic error greatly reduced the predicted amount of damage and showed results, which are much closer to experiment. As one can see on Figure 4a and 4b the experimentally measured residual strength in tension was 4% higher than in pristine laminate and in compression is 7% lower. The results of

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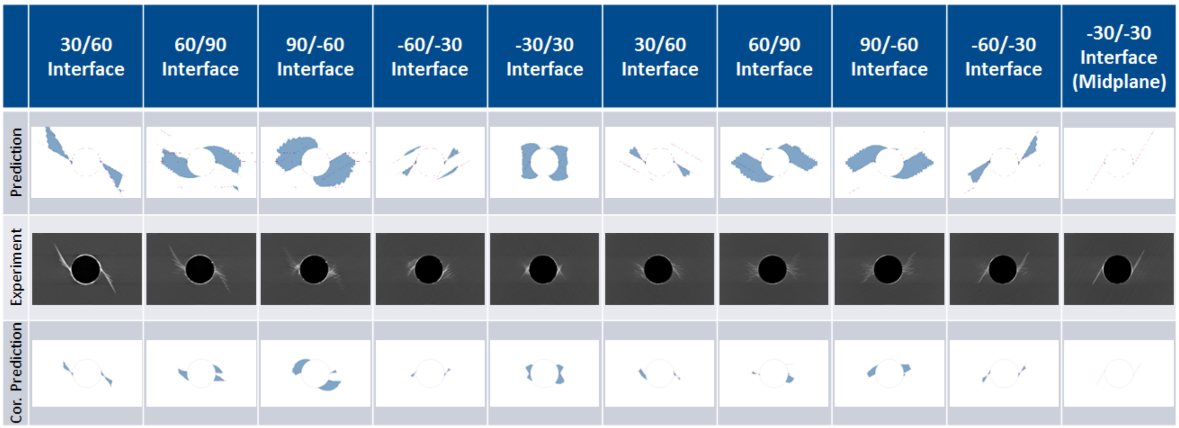

Figure 3. Delamination extent in [30/60/90/-60/-30]$_{2s}$ laminate after 200,000 cycles.

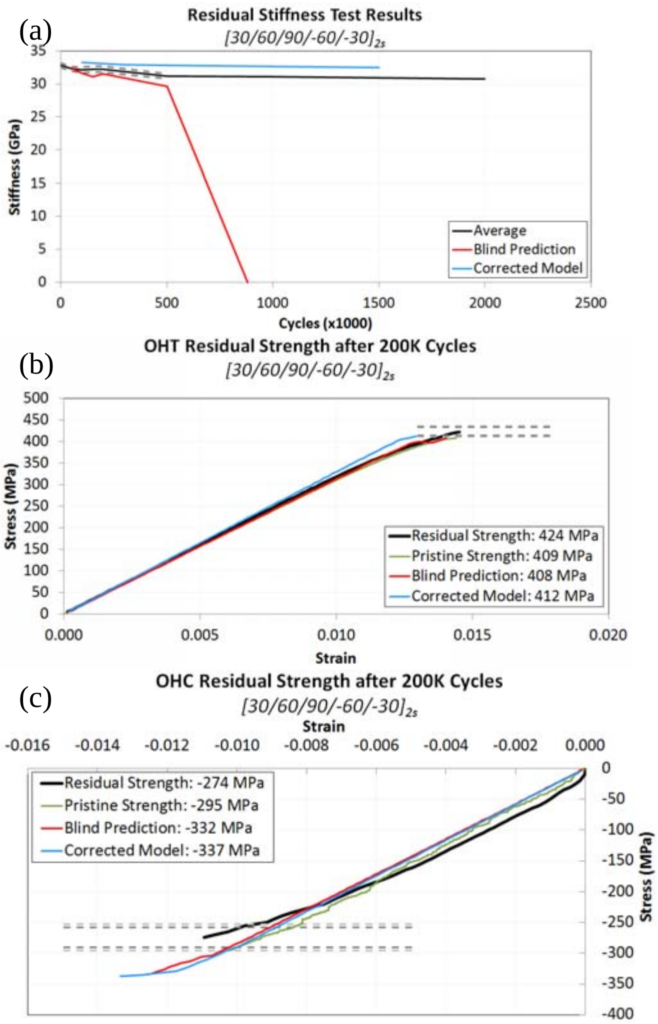

Figure 4. (a) Residual stiffness, (b) OHT residual strength, and (c) OHC residual strength predictions and experiments for the [30/60/90/-60/-30]$_{2s}$ laminate at 200k cycles.

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The prediction displays the same trend in tension; however, in compression we predict a 0.002% increase (no change). Overall the predicted compression strength was approximately 14% higher than experiment and the tensile strength fell with the confidence intervals.

Conclusions

Discrete Damage Modelling (DDM) methodology has been extended to fatigue loading. A combination of cycle and event based progressive damage modelling algorithms has been implemented. The cohesive zone model with consistent transition from failure initiation to failure propagation regimes under fatigue loading, which eliminates any ambiguity or need for initial damage size or presence of any initial cracks or delaminations in the structure, has been proposed.

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