A Review on Damage Modelling and Analysis of Composites

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Abstract. This article presents an overview of advances and some results of the authors' research interest in the modeling and analysis of progressive damage of fiber-reinforced composites and joining operations viz., lap joint. Similarly different models were studied and presented in comprehensive to the progressive damage of composites in meso scale level. A complex multi-scale and interactive nature of the damage at mesoscale level were studied and presented with possible sophisticated modelling and analytical techniques considering simplified assumptions to bring model simplification from unduly complexities. Such models with test data were studied for damage recognition patterns.

Key words: Progressive failure, composites, damage study of mechanical joints.

1. Introduction

Composite is a combination of fibre and matrix as constituents forming a new material with better strength and mechanical properties than that of its constituents individually. So in course of time, there had been a continuous development for better composites for light weight, corrosive resistant, better performance and so on. As the demand increases for better quality and sustainability of materials, the look into their properties, characteristics, behavioural attributes, and failure mechanisms increased. In such an attempt, progressive failure and damage modelling methods came into existence. Failure analysis of constituent is one part and failure analysis of a component/assembly of components is another part to consider in view of failure models.

In the present study, a mesoscale to microscale progressive damage modelling procedures that evolved with respect to failure in component/assembly of components level will be discussed. Several failure criteria like Hashin criterion, LaRCO3 criterion, Tsai-Wu criterion, MMF3 criterion etc., are in existing models.

These failure criteria can be grouped into two main groups:
- Failure criteria neglecting interactions between different stress components.
- Failure criteria considering interactions between different stress components.

In our present study, both the cases will be touched to view how the progressive damage will be occurring in composite plates with lap joint or adhesive bonded joint, fastened joint, notched and un-notched composites, cracking of a laminate, pin-loaded analysis of composites, hole and openings of composites.
ASTM D5961 [1] and D7332 [2] are widely used for mechanical joint tests of a composite laminate with different types of joints defined as per the standards. For a single lap joint, the tension load that occurs in the joint is transferred through the fastener in pull direction as well major load is carried over through shear load transfer. Certain parameters like joint area and dimensions, type of a joint, loads on the joint, and type of fastener used need to be considered to study the behaviour and analyse the structure as per design requirements. For features like hole, openings in middle are kind of complications while analysing a composite structure.

The stress concentration factor (SCF) is considered widely for analysing joint strength and its failure modes in macro level [3]. The distributed load condition on a pin loaded hole was investigated by Chang [4]. As well many other researchers have studied this face of composite laminate joints by looking at its characteristic curves [5,6]. For deriving these characteristic curve, we need to define some parameters for which additional tests like compression test, open hole test are required to get the mechanical properties of a laminate.

2. Modeling and Analysis Methods

There are micro, meso and macro levels of modelling exists in the literature for which this paper will try to define few parameters required in modelling and analysis with definitive models. By mainly focussing on three kinds of damage mechanisms, making complex things simple for future studies and investigations. Fibre breaking, debond between fibre – matrix, matrix cracks are considered to be major damage modes which is the central of discussion. Fibre breaking is due to failure at $\sigma_{11}$, represents crack in a fibre. In direction along the fibre, if failure with $\sigma_{12}$ or $\sigma_{13}$ exists due to the growth of debond failure in between fibre and matrix which is assumed to be a strong interface. Debonding is modelled by considering the maximum length of the crack is equal to the cell length in the direction of thickness/ say depth. Matrix cracks are also sometime called as radial cracks which grows along the fibre direction and modelled as a radial crack in fibre direction. These damage modes have been pictorially represented as shown in Figure 1.

3. Progressive Damage Modelling

Based on the earlier SCF research, a later more refined progressive damage failure analysis (PDFA) was correlated and developed using detailed three dimensional FEM and analysis results. PDFA was carried over single and double lap joints of composite laminates [7,8].

GUL APALAK et.al. [9], investigated about the progressive damage modelling of the composite lap-joint where initiation and propagation of damage zones studied for adhesively bonded single-lap joint composite plates under tension at the mesoscale level. In their paper, composite plates were adhesively bonded with a single lap joint kept in tension and studied its mesoscale behaviour based on Hashin failure criterion. It was observed that the lower plate interface initiates the damage to the adhesive layer where the first ply along the adhesive layer propagates at free edge, so distributed and spreads along the surface through the adhesive neighbor plies of the lower plate of single lap joint.
When first ply loads decrease it increases the ply fiber angle, resulting in delamination due to fiber–matrix failure. It was noted that critical region exists at the right free edge of the lower plate–adhesive interface. In a meso-scale level their work presented an accurate prediction with failure modes and damage zones where the propagation initiated in the composite plates as adhesively bonded with a single lap joint under tension.

To predict the damage propagation of composite fastened joints Mattevset. al. [10], made an attempt to study the case using three dimensional approach of finite element modelling (FEM). Strength of mechanically fastened joints at bearing, tension and shear–out modes were studied. Damage was estimated by using internal state variables in conjunction with global failure criterion for numerical predictions of damage propagation, joint stiffness, and ultimate strength of the joints. They made an attempt to utilize explicit modelling concepts within FEM. This attempt made them to predict joint fracture along with failure loads at maximum hole deformation and occurrence of matrix cracking.

In bearing failure modes, damage propagation tend to occur below the washer, but at the first load drop-off strength of bearing specimen was over-predicted. They suggested the load that occurs here is a failure load after reducing the joint stiffness. It was said to be incapable to model delamination. By using interface elements between the layers, adhesive interface the extended result could have given a delamination response for bearing strength. By including the interface elements a number of assessments can be possible viz., to study the effect of stacking sequence, predicting the clamping pressure at the joint.

Harris et.al. [11], studied the growth of matrix cracks and fiber fracture with notched and un-notched specimens. They believed that penetration notches help to predict the residual strength of the laminate with an appropriate progressive damage methodology. Their discussion is based on the non-linear damage dependent constitutive model where center notched tension panel was designed for testing their model. They named this panel as trans-laminate and the fracture investigation over trans-laminate fracture with a capability of residual strength prediction. They observed a damage growth resistance in their study which define ply bridging. Ply bridging mean a fracture fibre of one ply will be over intact with the fibres of adjacent ply. They employed Allen-Harris constitutive model for their FE model to analyse the notched end stresses exists in the center notched tension panel to predict the matrix cracking and fiber fracture.

The damage progression in the composites has been studied and the progression of the damage can be simulated by using computer finite element formulations. One of such formulation have been developed by NASA into a computer code in the name of Computational Mechanics Testbed (COMET). The scheme of the progressive failure analysis has been shown in Figure 2, which is presented by Timothy et.al [11]. In this flow chart, the first block depicts the inputs required for the model analysis. In every finite element code there exists a mathematical set of arguments for calculating, processing and assembling the elemental stiffness and global stiffness matrices. This computational work at background represented in block 2 and 3. In block 4 damage dependency has been implemented through damage resultant force (DRF) into the finite element analysis code. Using damage growth incremental (DGI) parameters, the damage growth can be predicted and thus laminate failure can be estimated and simulated through the integrated finite elemental code with in the computational mechanics testbed.

There are researchers who later studied the cracks and defined cracks as to be assumed for which it initiates from a nucleus created due to divertive loading by localized fiber debonding and matrix cracking [12]. By modelling a crack as defined above the transverse cracking was studied with an elastic fibrous composite ply. Its low crack density was explored. The interaction of cracks with different plies properties was studied.

Tay et.al. [13] investigated PFA of composites using micromechanics models infused with a novel element failure method (EFM), with a pin loaded in a notched composite laminate analysis. They validated their results with various methods like Tsai-Wu criterion to MMF criterion. Their results were on par excellent experimental results. The more hybrid EFM-cohesive element approach can be
utilized for individually fiber damage analysis of micro scale to component level macro scale. They have illustrated the potential of their model with an analysis of double-notched composite laminate.

Tan et al. [14], investigated the features of micro damage with matrix cracking and fibre breakage under shear crippling or micro buckling. Their results were well correlated with X-ray radiographic experimental results. They extended their work from tensile loading to the compressive loading to study micro damage and characterizing the properties at micro and meso level. This model was not studied for delamination with openings and holes on a composite plate, which can be considered as a demerit of such accomplished and simplified model.

Seng C. Tan [15], investigated PFA model on composite laminates containing openings. He stated that, load increment have a little effect on ultimate strength. He had done an extensive parametric study with experimental investigation to provide a more scientific approach. In this work stress concentrations under in-plane loading were studied for PFA of composite laminates. They used ply-by-ply and element by element approach for analysing the matrix cracking and fiber breakage. They outlined that, damage of lamina signifies the stiffness degradation. So damaged lamina properties can
be found by the respective constitutive relations. To reduce the complexity, they used stiffness degradation factors, introduced stable finite elements for meshing, defined load step increment relation with the ultimate strength. There is a continuous research in the field, the further studies would be on sudden degradation and gradual degradation methods and investigating on a practical problem with evaluations relative to sun [25] and lee [24] models. Table 1 summarizes the matrix failure models with respect to 3D finite element method.

| Model          | E_{11} | E_{11} | G_{23} | G_{13} | G_{12} | v_{12} | v_{23} | v_{13} | v_{21} | v_{31} | v_{32} |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Nagesh [26]    | -0.1   | 0.1    | 0.1    | -      | -      | 0      | -      | 0      | na     | na     | na     |
| Tsai&Wu [18]   | -0.45  | na     | na     | na     | 0.35   | na     | na     | na     | na     | na     | na     |
| McCarthy [27]  | -0.1   | 0.1    | 0.1    | -      | -      | -      | 0.1    | -      | na     | na     | na     |
| Camanho [28]   | -0.2   | -      | 0.2    | -      | 0.2    | -      | na     | -      | -      | -      | -      |
| Camanho        | -0.4   | na     | 0.4    | na     | 0.4    | na     | na     | na     | na     | na     | na     |
| Apalak [29]    | -0     | 0      | 0      | 0      | -      | 0      | -      | -      | na     | na     | na     |
| Tsepes-I [30]  | -0     | -      | -      | -      | -      | 0      | -      | -      | na     | na     | na     |
| Tsepes-II [31] | -0.2   | -      | 0.2    | -      | 0.2    | -      | -      | -      | na     | na     | na     |
| Tsepes-III [32]| -0.4   | -      | 0.4    | -      | 0.4    | -      | -      | -      | na     | na     | na     |

4. Conclusions

Comprehensive procedures for testing and analysing a composite laminate mechanical joints using progressive damage failure analysis was discussed and reviewed critical papers under the scope and thread of PFA of laminated composites with mechanical joints. Different analysis and methods proposed by the researchers were discussed. Micro, meso, and macro scale of looking the failure and failure modes have been noted for further study and future investigations on failure of mechanical joints and their prediction through progressive damage modelling and failure analysis.

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