A review on Progressive failure analysis of composites

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Abstract. This article presents a review of the progressive failure theories for analysing composites by using computational analysis methods like finite element method. Failure severity can be represented by the degree to which the elastic properties of a ply are damaged. Fibre failure is usually assumed to cause the failure of the matrix. So these fibre ply-to-ply failure mechanisms will be studied and analysed for better usage of the models for respective analysis. Sudden degradation models study the ply loading history with increase in loading, elastic properties will be reduced by a discrete factor resulting to successive failure mechanisms. Such models and failure mechanisms were studied and a detailed review was presented with possible simulation models in progressive failure of composites.

Key words: Progressive failure, composites, damage tolerance, RVE model, Multi Scale Model.

1. Introduction

Carbon fibereinforced plastics (CFRPs) are being developed and optimized for better performance and usage over the past 50 years. Composite structures have been evaluated to ensure the integrity of a structure they were incorporated in. Fiber failure is usually assumed to cause the failure of the matrix. So these fibre ply-to-ply failure mechanisms will be studied and analysed for better usage of the models for respective analysis. Sudden degradation models study the ply loading history with increase in loading, elastic properties will be reduced by a discrete factor resulting to successive failure mechanisms.

2. Evolution of Failure models

Composite structures have been evaluated to ensure the integrity of a structure they were incorporated in. Fibre failure is usually assumed to cause the failure of the matrix. So these fibre ply-to-ply failure mechanisms will be studied and analysed for better usage of the models for respective analysis. With the help of several models, testing methodologies and structural analysis theories, mechanical behaviour and characteristics of a composite material with minimal cost were developed in course of time [1]. In such a view point, if we go through the sequence of development in the failure theories Tsai-Wu tensor criterion would be an earlier one [2]. They are usually the concepts which describes the phenomena in conjunction with the models under certain assumptions to predict the
strength of materials like composites. They are usually considered as semi-empirical models. These models have certain assumptions with composite as a material. One of such assumption is that in a single-ply the composite exists with homogeneous properties. At macro level the failure of a material can be defined on the basis of stress-strain data which gives an engineering emphasis due to its wide usage from Hook’s law.

But when we go into deeper levels to master a material for desired outcome, there is a need to study deeper than just what it looks to be at macro scales. So certain theories evolved to state micro and meso scale of attainment with the mechanism of how a material works and fails at last in particular state of scaled position, how it behaves in different scales of constituent level. For explaining the failure of a composite along with its mechanical behaviour at a constituent level many studies have been carried over and focused on failure mechanisms. In such effort, there came an evolution of non-empirical theories like Hashin criterion [3], Puck’s criterion which explains the action planes and strength [4]. A criteria that can predict matrix and fiber failure with better accuracy, without the curve-fitting parameters have been emerged, and named as LaTCO3 criterion [5]. It is capable to suggest a crack initiation in the matrix failure due to fiber compression by a combination of five interactive conditions [6]. All these failure theories mainly used for macro-level analysis of stresses and material behaviour by considering the failure components [8]. When characterization becomes difficult, there will be a necessity of considering one or more additional constitutive or phenomenological interactive parameters. Similarly in failure behaviour study and its characterization such interactive parameters were required. Researchers like Chamis et.al [9], described failure modes based on modified distortion energy (MDE) of stressed laminates which gave rise to more scope in micro-mechanics based models of failure. In this model the macro-effective strength can also be determined by using homogenized constituents of strength in a laminate.

With these studies, a general consecutive statement can be given as, the micro-level events leads to the consequence of macro-level failure mechanisms. To predict the failure aimed at the constituents of the composite material became more intuitive so that fully determined micro-mechanical failure methods can be established. Disadvantage of such model is inefficient in modelling and numerical computation difficulties arises [10, 11].

Another way of characterization is to consider the representative volume elements (RVEs) to determine the properties and so the behaviour of the material in study along with its constituents (fibre and matrix). Using these RVEs, Bouaoune [12] and Beicha [13] studies the effects of periodic and random distributions of fibers in composites. Global effective elastic properties can be captured by using periodic RVEs. With these models there is a defect where the effective properties of composites with high fiber fractions are affected by micro-structures.

So to make a probable situation for better analysis and estimating a proper failure of the composite the model should possess both the advantage of the efficiency of macro models and the accuracy of micro models [14, 15]. For such a case, new models have been evolved taking advantage of combining the macro models with the RVE models forming to generic study of multi-scale approaches.

3. Need of Multi-Scale strategy in failure modelling

There are certain studies carried out by world-wide failure exercise (WWFE), their results concluded that there should be further development in the failure models and testing methodologies as the existing knowledge on failure models lacks certain features like predicting tolerable limit. Predicting an experimental response is also a task to be fulfilled. As the difference between a predicted value and the experimental response were not unusual in practice, the order of magnitude definitely doesn’t match.

So researchers are continuously working to fill this gap. LaRCO3 model might be the first of its trials with predicted failure envelops nicely correlated with the experimental results, in the case of matrix or fibre failure under compression [5].

Studies of Benbouras [7] states that, Tsai-Wu criterion overestimates the succession and first macroscopic failure whereas Hasin, LaRCO3, Tsai-Hill and maximum strain theories were well
established along the lines. Their studies also provided a strong correlation between the different failure criteria tested. They proposed an algorithm in which the deflection causing the damage allows the calculation of the force applied using the nonlinear approach of Venetis [16].

For studying the physical sense of micro-strength properties of a composite Zhidong Guan [8], recorded an experimental data of sensitivity analysis with description as shown in the table 1. It describes about the micro strength in modified – micromechanical failure (MMF3) criterion and their influence over macro strength with sensitivity analysis considerations. This reference study can make an adjunct point for the further development of new models towards multi-scale approach.

Table 1. The matrix-dominant micro strength for the sensitivity analysis [8].

| Number | $T_m$(MPa) | $C_m$(MPa) | $S_m$(MPa) | Description               |
|--------|------------|------------|------------|--------------------------|
| 1      | 138.7      | 353.3      | 145.1      | Reference value          |
| 2      | 208.1      | 353.3      | 145.1      | $T_m$ is increased by 50% |
| 3      | 92.5       | 353.3      | 145.1      | $T_m$ is decreased by 50% |
| 4      | 138.7      | 530.0      | 145.1      | $C_m$ is increased by 50% |
| 5      | 138.7      | 235.5      | 145.1      | $C_m$ is decreased by 50% |
| 6      | 138.7      | 353.3      | 217.7      | $S_m$ is increased by 50% |
| 7      | 138.7      | 353.3      | 96.7       | $S_m$ is decreased by 50% |

The influence of matrix-dominant micro strength of the composite over the macro level off-axis strength is in accordance with their physical definitions. Here we can notice that the micro tensile properties are affected with relatively to the off-axis angles. Also the compressive strength of the matrix gets involved with the strength affecting the off-axis strength at the small off-axis angle. Authors also noted that, the micro compressive and shear strength of the matrix in a composite does actually have a little influential over the macro level relative strengths (compressive and tensile) at the off-axis angles. The influence is more over the shear strength at macro-level.

4. Multi-Scale Failure models

Gosse et al. [17] proposed a new theory based upon micro-strains and named it as the strain invariant failure theory (SIFT) which was based on the micro-strains. Upon later development to this theory Tay et.al. [18] Combined the element-failure method (EFM) with the SIFT. Tay’s method studied the damage propagation of the composites. Based upon SIFT micro-level failures were studied on open-hole compression strength of laminates by Cai et.al. [19]. Stacking sequence plays a crucial role in SIFT for finding the critical values that need to be determined by testing the laminates. Here the laminates were arranged in a specially designed stacking sequences that can determine the micro-properties.

In further developments, notched and un-notched laminates based on a multi-axial mixed model continuum damage model (MMCDM) which is considered as a 3-D extension of Hasin criterion was proposed by Stier et.al. [20]. This method based upon the average strains within the RVE determines damage initiation in a laminate. Another set of researchers collaborated to draw a set of conditions for predicting failure of composites by utilizing average stresses within the matrix and fibre constituents raising to give Multi-Continuum Theory (MCT). Mayes et.al. [21, 22] proposed MCT, where micro-level property changes were considered.

For countering the demerit of these models where localized peak stresses in a laminate can be difficult to distinguish the damage initiation and degradation; Ha et.al., [23] proposed a new theory, micromechanics of failure criterion to predict the ultimate strength of a laminate [24]. Efforts of Muthusamy [25], Huang et. Al [26] made a new path towards multi-scale approaches with MMF
criterion. Here several researchers studied about failure and life of composites utilizing the benefactor of MMF multi-scale models [28, 29].

The drawback of this model is that it has two significant demerits: 1) under any longitudinal tension there exists a premature failure of a matrix. 2) Shear strength will be predicted much lower than it used to be.

In this setting, the present study focussed the development and advantages of multiscale models. The thermal residual stress adding upto multilevel strategy inclusion to MMF3 criterion where the damage initiation was defined and degradation of the properties of constituent elements. The fundamental stand with the modification of the micromechanics-based criterion focuses directly on defining the matrix damage.

The off-axis loading using multiscale model were analysed and studied for knowing the matrix-dominant mechanical behaviours [8]. The RVE model really played a major role in the development of composite failure analysis. If square and hexagon are considered for the representative of different fibre distributions, then a quantitative relationship between the micro and macro level stresses were determined.

![Figure 1. A sample RVE model with Square and Hexagon elements [8].](image)

There is a continuous development in the field, further studies can be contributed towards different RVE models evaluated upon modified multi-scale damage method applied to progression of damage in the composites with long and short fibres is recommended.

5. Conclusion

A comprehensive review on the development of multi-scale strategy has been presented. Macro-scale models and micro-scale models were discussed towards how and why multi-scale models have been evolved. The RVE model really played a major role in the development of composite failure analysis. If square and hexagon are considered for the representation of different fiber distributions, then a quantitative relationship between the micro and macro level stresses were determined. In the multi scale strategy first stress were calculated and later the micro strength was reverse calculated from the macro strength of laminates. When the properties of damaged elements are observed to be degraded at fiber or matrix constituent level then, the more full-fledged multiscale models which were established are applied for studying the failure analysis of the composite. In the literature the studies with multi-scale strategies are effective with the constituent failure analysis of a laminate.

Also with the thermal residual studies, the effect cannot be negligible before damage initiation. This is because matrix failure under shear loading will lag which attains an overestimated strength not feasible to fit the fitment criteria. But as the load increases thermal residual stress value tends to descend.

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