Experimental and theoretical investigation of the critical load of U-notched laminated composite specimens under in-plane shear loading

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ABSTRACT

Numerous failure models for prediction of the load carrying capacity of cracked and notched laminated composites have been of interest to researchers in the field of fracture mechanics. The cause of importance of this subject was the extensive use of notched composite laminates in aerospace industries in the last decades. In this investigation, it was tried to predict the load carrying capacity (critical failure load) of U notched laminated composite specimens with various layup configurations under pure mode II loading (in-plane shear loading) conditions, by utilizing a simple and novel concept proposed recently by the authors. The new composed criteria have been proposed in the field of orthotropic fracture mechanics for the first time. For this aim, by using a newly proposed concept, namely the Virtual Isotropic Material Concept, and combining it with two well-known brittle fracture criteria in the field of linear elastic fracture mechanics, namely the maximum tangential stress and the mean stress criteria, the experimental results of the failure of the U-notched laminated semi-circular bend composite specimens under pure mode II loading condition, were theoretically predicted by using new last-ply-failure load curves. It was revealed that the experimental results are in good agreement with the theoretical predictions.

KEYWORDS

Laminated composites, U-notch, Critical load, semi-circular bend, Translaminar fracture toughness

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1. Introduction

A careful literature survey on fracture prediction of laminated composites indicates that there are generally three different approaches for this purpose; i) the models based on fracture mechanics [1, 2], ii) the stress-fracture models [3, 4], and iii) the progressive damage models [5, 6].

To the best of authors' knowledge, no paper or technical report is available in the literature dealing with fracture analysis of U-notched composite laminates. Most of the fracture investigations on notched composite laminates or laminas have been performed on O-notched (open hole) and cracked (slit) specimens. In order to simplify the procedure of the last-ply-failure (LPF) prediction in U-notched laminated composites, it is tried in the present study to use directly the linear elastic notch fracture mechanics (LENFM). For this purpose, the composite laminate is equated with a virtual isotropic plate of the same thickness and some brittle fracture criteria in the context of LENFM are utilized for failure prediction [7, 8].

2. Experiments

The experimental work is carried out on the Epon 828 as a thermoset epoxy resin or matrix material reinforced by the E-glass unidirectional fibers. The composite laminate is fabricated by the vacuum bag-autoclave molding technique.

According to the VIMC, which is described in the next section, for predicting the last-ply-failure (LPF) loads of the U-notched laminated composite specimens, two important laminate characteristics, namely the ultimate tensile strength (σ_u) and the trans-laminar fracture toughness (K_{TL}), should be specified. The average values of σ_u and K_{TL} for the three types of lay-up configurations, namely unidirectional, cross-ply, and quasi-isotropic laminates tested are presented in Table 1.

Table 1. Mechanical properties for three types of laminates

Lay-ups	σ_u (MPa)	K_{TL} (MPa $\sqrt{m}$)
Unidirectional	876	41.4
Cross-ply	498	30.7
Quasi-isotropic	442	34.1

As shown in Figure 1, a U-notched semi-circular bend laminated composite specimen is placed on the two bottom supports located at the same horizontal distances from the center of the specimen. The compressive load (P) is monotonically applied to the specimen along the vertical axis.

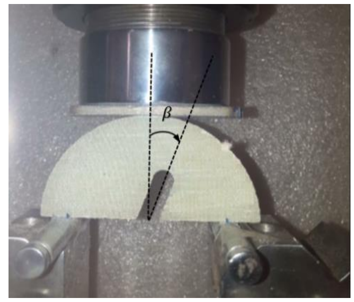

Figure 1. A USCB laminated composite specimen subjected to mixed mode I/II fracture test under TPB loading.

3. Methodology

Considering that the values of σ_u and K_{TL} are available for the composite laminate, a new concept, called the Virtual Isotropic Material Concept (VIMC), is proposed with the aim to take an engineering permit to use LENFM criteria for LPF load prediction of notched composite laminates. According to VIMC, a virtual brittle material, as an equivalent isotropic material, is employed for simulating the bulk behavior of the tested composite laminate. This means that a real laminated composite material is equated with a virtual isotropic brittle material for predicting the LPF loads of the U-notched composite laminates. For more clarity of this new concept, Figure 2 represents the VIMC schematically, by which the orthotropic composite laminate is equal with a linear elastic isotropic brittle plate of the same thickness.

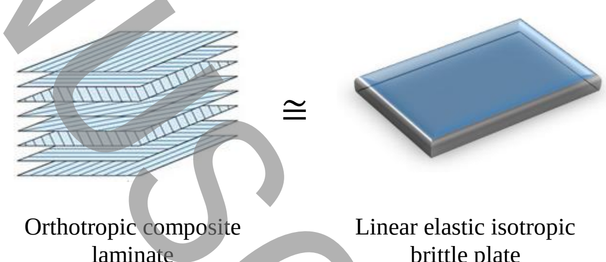

Figure 2. The virtual isotropic material concept (VIMC) schematically.

4. Stress-based brittle fracture criteria

according to VIMC described in Section 3, the critical stress σ_c and the plane-strain fracture toughness K_{Ic} values for the isotropic brittle material can be replaced with the ultimate tensile strength σ_u and the trans-laminar fracture toughness K_{TL} values for the orthotropic composite laminate, respectively in order to use the MS and MTS criteria for LPF load prediction of the U-notched laminated composite specimens.

Finally, two important expressions can be proposed to calculate the critical distances for to the VIMC-MTS and VIMC-MS combined criteria as follows

$$r_c = \frac{1}{2\pi}\left(\frac{K_{TL}}{\sigma_u}\right)^2 \qquad (1)$$

$$d_c = \frac{2}{\pi}\left(\frac{K_{TL}}{\sigma_u}\right)^2 \qquad (2)$$

Hence, because of the linearity of the FE analyses, the LPF load predicted by the VIMC-MTS criterion can be easily computed for an arbitrary load (e.g. 1000 N) as

$$P_{VIMC-MTS} = \frac{\sigma_u}{\sigma_{\theta\theta}} \cdot (1000N) \qquad (3)$$

$$P_{VIMC-MS} = \frac{\sigma_u}{\overline{\overline{\sigma_{\theta\theta}}}} \cdot (1000N) \qquad (4)$$

5. Results and discussion

As previously mentioned, the theoretical results of the LPF load for the VIMC-MTS and VIMC-MS criteria are obtained from Eqs. 3 and 4. To compare the results, the variations of the theoretical and experimental LPF load versus the notch root radius are depicted in Figure 3, for three types of lay-ups, namely unidirectional, cross-ply, and quasi-isotropic laminates, under pure mode II loadings.

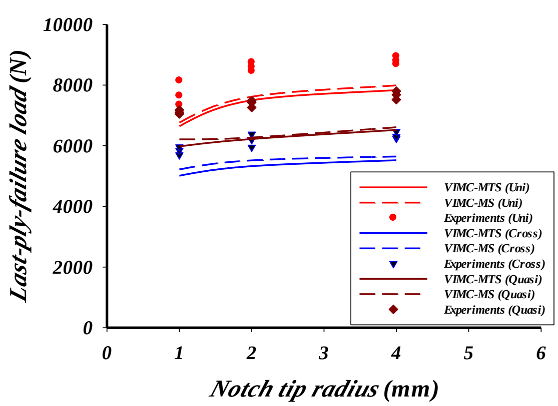

Figure 3. Prediction curves of load bearing capacity of semi-disk bend composite specimen versus the notch tip radius for unidirectional, cross-ply, and quasi-isotropic laminates.

The average discrepancies for VIMC-MS and VIMC-MTS criteria are 9.3 % and 10.8 %, respectively, demonstrating that both criteria can provide good predictions to the LPF loads of the USCB laminated composite specimens under pure mode II loading conditions.

6. Conclusions

The concluding remarks regarding this investigation can be presented by the following bullet points:

. To avoid layer-by-layer failure analysis, employing the progressive damage models, and writing subroutines, which are time-consuming and rather complex, the orthotropic composite laminates with three different lay-up configurations and two numbers of ply were equated with virtual isotropic brittle plates of the same dimensions by means of the novel Virtual Isotropic Material Concept (VIMC).

. It was found that both combined failure models, i.e. VIMC-MTS and VIMC-MS models, are well capable of estimating the LPF loads of the U-notched composite plates under pure in-plane shear loading conditions.

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