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Spatial vulnerability analysis for the first ply failure strength of composite laminates including effect of delamination

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ABSTRACT

The present investigation deals with the first ply failure strength of laminated composite plates for spatial variation of loading position, which can render a clear idea about the locational sensitivity of the loading positions in a two dimensional space. In this context, the effect of delamination is investigated on the failure strengths considering angle ply and cross ply laminates. A finite element model is developed based on different failure criteria of composites, such as maximum stain, maximum stress, Tsai-Hill, Tsai-Wu-Hahn and Tsai-Hill-Hoffman. An eight noded isoparametric quadratic element is considered in the present finite element formulation incorporating transverse shear and rotary inertia. Results are presented in deterministic as well as stochastic regime. For obtaining the probabilistic descriptions of failure strengths following different failure criteria, Monte Carlo simulation is carried out in conjunction with the finite element model following a non-intrusive approach. The variation of failure strength is portrayed considering the effect of stacking sequence, ply orientation, number of layers, degree of orthotropy and ply thickness. In this article, consideration of stochastic material and structural attributes along with critical service-life characteristics such as delamination for spatially varying loading positions provides a comprehensive understanding about the failure strength of composite laminates for practical applications.

1. Introduction

Modern competitive industries exhaustively use the laminated composite materials. From under water to ground even space vehicles, applications of composites are found as cost-effective and efficient, while being more sound and application specific in terms of structural attributes. The extended applications range from medical prosthetic devices, sports equipment, automotive parts to high-performance defence structures. The use of composite materials in structural applications is dictated by the outstanding strength and stiffness, low specific gravity, low maintenance costs, and the flexibility in tailoring the stiffness and strength in the preliminary design stage of complex structures. The use of composite structures in advanced underwater, ground and space vehicles can result in significant increase in payload, weight reduction, range and speed, maneuverability, fuel efficiency and safety. The functional requirements and economic considerations of design require designers to use reliable and accurate but economical methods of determining stresses and identifying failure mechanisms. The mechanism of failure of laminated composites is complex in nature predominantly governed by dissimilar phases of independent and interactive effects of elastic-brittle rupture of fibers and yielding of the matrix. The assessment of the failure process can be predicted by the maximum amount of load withstood prior to first-ply failure analysis based on some failure criteria. In spite of the practical importance of the aspect of failure in composite structures, the number of technical papers and reports dealing with this crucial subject is limited due to the complexity involved. A concise review on this aspect is provided in the next paragraph.

A review of all the failure theories of composite materials was presented by Talreja [1]. Dvorak, Laws, Reddy and Pandey [2–5] were the first pioneers to analyze the first ply failure of the composite laminates including cracks induced failure. Bruno and Zinno [6] extended their work on the composite plate using the Reissner-Mindlin plate theory that accounts for moderate rotation. Almost half a decade later [7–9], various works on first ply failure using the non-linear and progressive analysis methods were adopted. Different theories were applied as to analyze the crack development which could lead to the failure of the laminate. Reliability analysis using the finite element method was performed during the mid-90s by Kam and Chao [10] and Kam and Chang [11] in this context. Later the above methods were

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applied to the composite shells [12] and other physical characteristics and responses of composite laminates such as buckling and bending [13–18], wherein the composite structures were studied along with the progressive failure. Of late, Kumar and Srivastava [21] analyzed the failure of stiffened plate, while Chang [19] studied the experimental and theoretical analysis of the first ply failure on composite laminate. Pal and Ray [20] investigated the progressive failure analysis of laminated composites using the finite element method. Rattanawangcharoen [22] studied on the first ply failure analysis on the laminated composite cylindrical panels employing the 3D layerwise mixed stress-displacement finite element model. The other subsequent works in this area focused on the failure of composite laminates with various physical characteristics and responses including the presence of different external influences such as static and impulsive water pressure, static and fatigue loads etc. [23–28]. A Statistical model of the transverse ply cracking in cross-ply laminates by strength and fracture toughness based failure criteria was developed by Andersons and Spārniņš [29], who studied the elucidation of the relative importance of the crack initiation and propagation phenomena in the fragmentation process at different transverse and longitudinal ply thickness ratios. Meiche et. al. [30] studied the analysis of hybrid cross-ply composite laminates using the modified shear-lag analysis to evaluate the effect of transverse cracks on the stiffness reductions. Adali and Cagdas [31] studied the failure analysis of curved composite panels based on first-ply and buckling failures. Gadade et al. [32] worked on the stochastic buckling and first ply failure analysis of laminated composite plates using the higher order shear deformation theory in conjunction with Tsai-Wu failure theory. Gohariet al. [33] and Ghosh and Chakravorty [34] modelled the progressive failure behavior for unsymmetrical composite laminates using the prediction theory. Moreno et al. [35] determined the difference in behavior of laminated composite under tensile and compressive loading in context to the failure analysis of composites. Patel and Guedes Soares [36] investigated on system probability of failure and sensitivity under low velocity impact while Romanowicz [37] used computational micromechanics to find the effect of first ply failure when subjected to uniaxial tensile load. Rehan *et al.* [38] investigated the effect of ply orientation angle considering carbon/epoxy composite and found that toughness decrease with both sub-adjacent and adjacent ply angle at the crack initiation. Dimitri et al. [39] and Abdullah et al. [40] presented the effect of crack and delamination in composites using XFEM and SFEM. Kumar et al. [41,42] investigated on the failure of sandwich panels considering deterministic as well as probabilistic input parameters. Of late, Naskar et al. [43] have studied the effect of matrix cracking on the dynamic response of composite circular beams in a probabilistic framework, while Li et al. [44] have carried out analytical and numerical investigation on the stiffness matrix for edge-cracked circular shafts. Yao et al. [45] used Paris relation and Hartman-Schijve equation for determining the fatigue delamination of composite delaminates. Jang and Kim [46] utilized high speed Fiber Bragg Grating (FBG) sensing system for the analysis of delamination of composite when subjected to impact loading, while Yelve et al. [47] used Lamb wave based nonlinear method to determine the delamination of composite and later on, a generalized probabilistic approach (GPA) is employed on failure assessment by Carpinteri et al. [48]. Progressive failures of composite with different loading conditions are analyzed [49–53]. The floating node method is employed to modelling tensile failure of composite by Chen et al. [54] while a hybrid failure criterion is applied to determine the matrix failure of composite by Chowdhury et al. [55].

The literature review presented above shows that some of the crucial aspects in context to failure of composites have not yet received proper attention, such as the locational sensitivity of applied load and the effect of service-life characteristics like delamination. The point of application of load on the composite panel has considerable effect in the failure strength and it is also significantly affected by delamination, which is one of the most common modes of damage in composites. Moreover, stochasticity in structural and material attributes of composites may lead to significant variability in the predicted failure strengths. Even though recent studies have focused on different aspects of probabilistic [56–67] and non-probabilistic [68] variabilities in material and structural properties of composite structures to quantify their effect on dynamics and stability characteristics, the aspect of failure is yet to be addressed in this context. Aim of this article is to comprehensively analyze the effect of spatially varying loading position on the failure strength of composites considering service-life characteristics like delamination and the effect of stochasticity in material and structural attributes to closely simulate the practical field situation. This paper, hereafter, is organized as follows: Section 2 describes the mathematical formulation for the failure of composite laminates along with the effect of delamination and stochasticity; Section 3 presents deterministic as well as stochastic results concerning the failure strength of composite laminates considering different failure criteria; finally Section 4 renders a perspective of this article along with conclusion and the prospective path of future research.

2. Theoretical formulation

The governing equation of a laminated composite plate (refer to Fig.1) is derived based on the principle of minimum total potential energy. The total potential energy 'Π' is expressed as sum of strain energy 'U' and work done due to external load 'V' as,

$$\Pi = U + V \tag{1}$$

Strain energy can be expressed as a volume integral,

$$U = \frac{1}{2}\int_{\phi} \{\varepsilon\}^T\{\sigma\}d\phi \tag{2}$$

Work done by external load is the area integral,

$$V = \int\int_A \{u\}^T\{q\}dA \tag{3}$$

External load on plate can be expressed as $\{q\} = \{0\ \ 0\ \ q_z\ \ 0\ \ 0\}^T$, where $\{q_z\}$ represents transverse load intensity on the plate. The constitutive equation of the plate is given by,

$$\{F\} = [D]\{\varepsilon\} \tag{4}$$

where the stress resultant vector is $\{F\}$, the strain vector is $\{\varepsilon\}$ and the laminate elasticity matrix is $[D]$. Assuming linearly elasticity and neglecting the normal stress perpendicular to the plate of the lamina, the constitutive relations, in the principal material direction 1, 2 and 3 are given by

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \\ \tau_{23} \\ \tau_{13} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0 \\ Q_{12} & Q_{22} & 0 & 0 & 0 \\ 0 & 0 & Q_{66} & 0 & 0 \\ 0 & 0 & 0 & Q_{44} & 0 \\ 0 & 0 & 0 & 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_{12} \\ \varepsilon_{23} \\ \varepsilon_{13} \end{Bmatrix} \tag{5}$$

where,

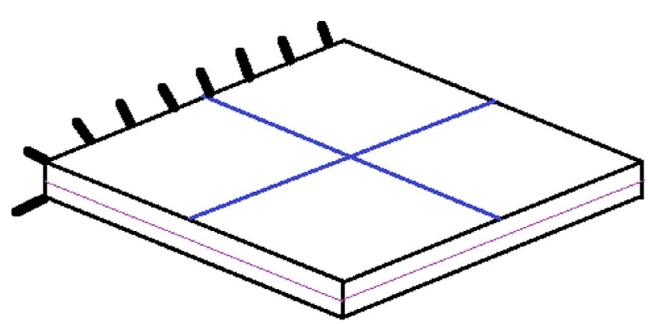

Fig. 1. Laminated cantilever composite plate.