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Fracture characterization of glass fiber composite laminate under experimental biaxial loading

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ABSTRACT

This study proposes a mixed-mode fracture criterion for glass fiber reinforced composite laminates based on numerical and experimental biaxial loading. An optimal cruciform geometry is introduced first based on finite element (FE) simulation. Characterization testing is performed successively on uniaxial and cruciform specimens to determine equivalent loaded area, notch sensitivity behavior and critical fracture toughness properties of cross-ply GFRP laminates. In experimental biaxial testing, two types of crack orientations (0°, 45°) are studied with varying crack lengths. The experimental failure points show that cross-ply GFRP laminates attain higher load bearing capability under biaxial tensile–tensile loading compared to uniaxial testing. Appropriate non-dimensional geometry factor relevant to cruciform shape is determined based on experimental data points and FE simulation. Eventually, a mixed-mode fracture criterion is proposed for cross-ply composite laminate based on the findings from biaxial experimental loading.

1. Introduction

In the presence of discontinuity, materials usually fail earlier to their neat state. This plays a more complex role in composites due to their catastrophic brittle failure pattern. Presence of imperfection is also a normal occurrence in composites due to their distinct manufacturing process that differs from metal manufacturing routes. Hence, fracture characterization of composites is crucially important. Moreover, composite materials used in different industries are regularly subjected to combination of loads acting in multiple directions. Owing to their anisotropic nature, strengths of these materials obtained using uniaxial testing procedure often do not represent the true scenario of a multi-axially loaded condition. This stands as a significant limitation towards wide scale, efficient usage of composites in engineering structures. Additionally, the ability to successfully model and simulate the multi-axial behavior of composites largely depends on proper choice of multi-axial failure criterion that eventually ensures wide applicability of the respective failure model in describing the corresponding material behavior under variety of complex loading conditions. A relevant comprehensive failure study under the name of world-wide failure exercise (WWFE-I) was performed during 1996–2004 whereby 19 different composite material failure theories were compared with existing experimental data under 2D stress state and it was eventually concluded that the most successful failure theories only can predict the behavior of composites for maximum 75% load cases for tubular specimens [1–3]. Later the same group of researchers initiated another round of failure exercise, as WWFE-II, which focuses on validation and benchmarking of composite failure theories under tri-axial stress state. The results of WWFE-II are similar to those obtained from WWFE-I where only a few failure theories able to predict the composite behavior within ±50% correlation of test data for around 75% of test cases. It was additionally understood from these exercises that there is a lack of reliable experimental data that could be compared with these theories. A prioritized future work direction from these exercises can be viewed as more reliable and rigorous formulation of composite failure theory is necessary based on comprehensive biaxial and multi-axial experimental data for representative specimen geometries (e.g., tubular, cruciform, dog-bone, iosipescu shape) [1,4]. This paper focuses on fracture characterization of cruciform shape, symmetric, cross-ply glass fiber reinforced plastic (GFRP) composite laminate under experimental biaxial loading.

Over the past decades, a few research laboratories have attained experimental biaxial testing capabilities for anisotropic composite materials. These can be divided into two major sub-classes – (i)

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Nomenclature

σ_f	failure strength of notched specimen	E	Young's modulus
σ_x	transverse stress	$G_{1C,I}$	mode I strain energy release rate
σ_y	axial stress	K_I, K_{II}	mode I, mode II stress intensity factor, respectively
σ_{yff}	far-field uniform y-direction stress, away from crack tip	$K_{K_{IC,I}}$	mode I interlaminar stress intensity factor
$2a$	crack length	$K_{K_{IC,T}}$	mode I translaminar stress intensity factor
w	width of the specimen	P_x	transverse force
$A_{equiv.\ x}$	equivalent loaded area under transverse force	P_y	axial force
$A_{equiv.\ y}$	equivalent loaded area under axial force	Y_1, Y_2	non-dimensional area correction factor associated with cruciform geometry
BC	boundary condition		
COV	co-efficient of variance		

single loading system and (ii) double or even more loading system. Single loading system fixes the biaxial stress ratio on the basis of loading fixture configuration or specimen geometry [5]. Test methods including hydraulic bulge test, cantilever beam bending, anticlastic bending of flat plates and rhomboidal shape fall into this category. In multiple loading systems, the magnitude of loading in individual axis determines the biaxial load and corresponding stress ratio. Axial loading together with internal/external pressure (tubular specimen), axial loading together with simple torsion (tubular specimen), flat cruciform specimen, round bar under combined torsion and bending fall into this category. Out of this, testing with tubular specimen is quite popular as it is capable of maintaining a constant load ratio during testing. But it also carries few shortcomings; e.g., composite structures are mostly flat or gently curved rather than of tubular shape – hence, tubular structure cannot represent most of the products; additionally, the free edge effect is not available in case of tubular shapes. Elastic instability issues and difficulty in fabrication are other major concerns that cannot be neglected while considering the tubular specimen [5]. Accordingly, to match with the composite products of flat or gently curved structural shapes, multi-axial characterization with cruciform shape specimen stands as a better choice. Cruciform shape specimens are usually tested under in-plane tension/compression loading along two perpendicular arms where the load is applied by hydraulic or pneumatically controlled cylinders driven by actuator mechanism.

Smits et al. [5] have recently developed such cruciform specimen based biaxial testing facility with four servo-hydraulic actuators. This system offers test arrangement in tensile–tensile direction; thus limiting the experimental capability in the first quadrant of the biaxial stress space. Corresponding research group has proposed an optimal cruciform specimen out of experimental and numerical results, based on loading and fixture constraints. A few parameters are considered in this connection to find the optimal geometry; viz., (i) the radius of the corner fillet at the intersection of the arms, (ii) the thickness of the biaxially loaded test zone in relation to the thickness of the uniaxially loaded arms and (iii) the geometry of the biaxially loaded test zone. The numerical results were compared consequently with experimental ones using the digital image correlation technique for full field strain measurements. Based on the final optimal geometry, they tested non-symmetric GFRP cruciform specimen with [(±45/0)4/±45] layup under tension–tension loading for five different biaxial load ratios. Corresponding failure points lie outside the failure boundary rings of Tsai, Puck and maximum stress failure criteria; accordingly, it can be inferred that existing failure theories are still significantly conservative in their predictions; and, hence, more light weight composite designs still can be achieved with composites [6]. Gower and Shaw [7] also evaluated optimal carbon fiber reinforced epoxy specimen out of different geometries based on $[+45°/0°/-45°/90°]_{2s}$ laminate sequence. In one such geometry, the central gauge section thickness was reduced from 4.7 mm overall thickness to 2.3 mm via a tapered 5 mm long zone to promote failure in biaxially loaded gauge section. In another geometry, a smaller gauge section was considered with lower arm length and gauge-section diameter. Finally, strain distribution of the loaded specimens was numerically analyzed on the basis of biaxial strain field uniformity and occurrence of true gauge section failure; an optimal specimen was thus proposed for biaxial experimental tension–tension testing [7]. Welsh and Adams [8], in another study, conducted experimentation on thickness-tapered cruciform specimen made out of symmetric cross-ply $[0/90]_{10s}$ IM6/3501-6 carbon/epoxy laminate. This study achieved desirable biaxial failure in gage section of neat specimen; and eventually presented ultimate failure boundary ring for all four quadrants of biaxial failures. Relevant biaxial failure study for discontinuity based cruciform shape geometries is, however, rare in prominent journal databases. Closest ones focused on hole based study. In one such through-thickness central hole-based study, the influence of hole was examined in quasi-isotropic $[0/\pm45/90]_s$ SP-286T300 graphite/epoxy plates under equi-biaxial tensile loading where strength reduction ratio for biaxial loading exceeds that for uniaxial loading by approximately 30% [9]. In another follow-up study, same research group performed similar experimentation using graphite/epoxy specimens of different orientation $[02/\pm45]_s$; these results also followed the previous trend [10]. These studies, however, did not characterize the composite specimen for their fracture performance in terms of hole diameter or layout sequence. In comparison to these studies, fracture characterization in the presence of crack is significantly more crucial due to its rapid progression and associated stress discontinuity that greatly influences the ultimate brittle failure of composites. The present article, accordingly, characterizes $[0/90]_s$ cross-ply GFRP composite lay-up based on varying length and angular orientation of through-thickness central cracks. Novelty of the study stands on the premise that there is no published article for biaxial fracture characterization of composite material with cruciform geometry. In product industries, many composite designs are plane or gently curved and a cruciform geometry better resembles these shapes in comparison to tubular or other frequently studied specimen shapes.

2. Materials and methods

Key steps of the study sequentially include finding an optimal cruciform geometry based on finite element (FE) simulation, determination of equivalent loaded area for cruciform geometry, evaluation of notch-sensitivity behavior for chosen composite laminate, determination of inter-laminar and trans-laminar mode I fracture toughness of the laminate, FE simulation on cruciform specimen