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Failure prediction for a glass/epoxy cruciform specimen under static biaxial loading

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ABSTRACT

Material models were developed to predict the mechanical behavior of glass/epoxy multidirectional laminates under complex stress states. An incremental plane stress analysis was performed, taking into account the anisotropic material non-linearity, separate damage onset conditions and distinct post-failure stiffness degradation rules. Theoretical formulations were implemented in a shell element of the 1st order shear deformation theory. Numerical results were validated via comparison with test data from cruciform specimens subjected to static biaxial tensile loading. Local strain gauge and full-field strain measurements, obtained using the Digital Image Correlation (DIC) technique, corroborated numerical predictions. Improved strength and failure mode results were derived when, in addition to stiffness reduction, compressive strength degradation in the fiber direction was also considered.

1. Introduction

A comprehensive study of failure developing in composite structures under complex stress fields is of vital importance in understanding material performance and establishing damage tolerant design practices. Numerous meso-mechanics damage models have been so far proposed and validated, based on test results from uniaxial coupons, thus contributing in the exploitation of the laminate load bearing capacity.

However, the World Wide Failure Exercise (WWFE) [1–3], a global comparison of the most prominent failure model predictions against common experimental data, highlighted a strong disagreement between theoretical results and test data from specimens under biaxial loading. Although multi-axial test methods have been used in the past to assess material models [4,5], a strong effort is currently directed towards the development of more reliable experimental procedures for strength determination of laminates under biaxial loading. Mainstream experimental research work focused on two discrete specimen geometries, i.e. tubular [6–11] and cruciform [12–14].

In the framework of a European research project [15], several material constitutive models simulating composite laminate mechanical response and failure under monotonic static loading were established and compared [10,11,16]. Alternative concepts were based on well-known failure theories implementing distinct degradation strategies regarding stiffness and strength values i.e. progressive or sudden (ply discount). These were incorporated in a thick-shell element of a commercial FEM code, provided with user defined material constitutive equations and performing layer-by-layer incremental plane stress analysis.

Material model predictions regarding stress–strain curves, laminate strength and ply failure patterns were successively validated against experimental results from prismatic coupon tests [16] and tubular specimens under combined axial loading and torsion [11]. The effectiveness of these models was further investigated in this study through comparison of theoretical predictions with experimental data from local (strain gauge) and full-field (DIC) deformation results from a laminated glass/epoxy cruciform specimen [17] under static biaxial tension. Predicted damage patterns and strains at failure were also compared to the experimental data.

2. Test and specimen configuration

The concept of the specimen design was explicitly presented in [17], where geometry '*C*' was selected as the most suitable for biaxial strength characterization. Its geometric details are illustrated in Fig. 1, where the *x*-axis coincides with the direction of the unidirectional (UD) fibers. Cruciform specimens, fabricated from E-glass/epoxy, were of $[(\pm 45/0)_4/\pm 45]_T$ stacking sequence. A smooth thickness decrease showing a tapering angle of 15° was achieved by milling the three outermost layers from both specimen sides, resulting in a $[(\pm 45/0)_2/(\pm 45)]_T$ asymmetric lay-up in the middle of the specimen.

Material properties used in the simulation examples were the same as those presented in Section 2.1 of [11], non-linear in most

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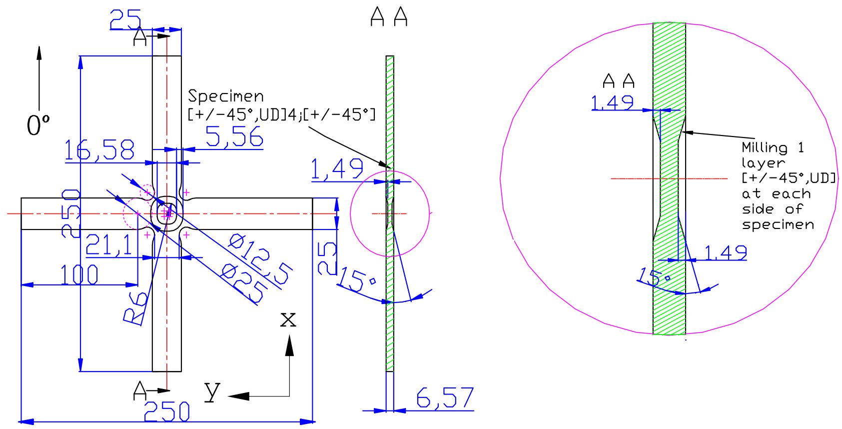

Fig. 1. Cruciform specimen geometry '*C*'.

aspects e.g. shear performance. In addition, individual ply thicknesses were assumed equal to those encountered in the multidirectional (MD) prismatic coupons studied in [16], i.e. 0.95 mm for the UD layer and 0.292 mm for each ply of the stitched [±45] fabric, since the ply material, lay-up and manufacturing method were exactly the same, thus resulting in the same fiber volume fraction [15].

Biaxial tensile experiments were conducted in a custom-made test rig with four hydraulic cylinders. Detailed description of the setup, process and test results can be found in [17,18]. Strain measurements took place in three directions (0°, 45° and 90° with respect to the UD fiber orientation) in the middle of the specimen via three-element bonded rosettes in both laminate surfaces. A single rosette was placed in one specimen surface when the other was used for full-field strain measurements using the DIC technique.

Thirty (30) specimens were tested in total at eight biaxiality ratios $k = F_x/F_y$, namely 0/1, 0.9625/1, 1.925/1, 2.567/1, 3.85/1, 5.775/1, 7.7/1 and 1/0. Specimen failure was acknowledged when the maximum force value was reached in at least one direction [17].

3. Material models

The meso-mechanics plane stress material models developed for E-glass/epoxy systems were discussed in detail in [11,16] and are summarized in Table 1. Non-linear constitutive equations were implemented in the principal material system using the formulation of Richard and Blacklock [19]. The mechanical properties of the ply were extensively characterized through a comprehensive experimental program [15]. Failure theories, i.e. failure mode dependent damage onset conditions, were incorporated to evaluate damage initiation along with associated stiffness degradation assumptions.

Model B integrated Lessard and Shokrieh [20] failure criterion implementing a ply discount post-failure analysis, i.e. specific stiffness values, depending on the emerged failure mode, were zeroed after incipient matrix failure. Three different matrix failure modes were predicted. The fiber–matrix shearing, developed under combined tensile and shear stresses in the fiber direction, was assumed to affect only shear modulus. The other two failure modes, matrix cracking in tension and compression, were expected to affect transverse Young and shear moduli. The material stiffness matrix was totally diminished after fiber fracture prediction, multiplying axial, transverse, shear moduli and major Poisson's ratio by a factor of 10^{-10}.

As an alternative, material model C, incorporating Puck and Schürmann limit theory [21] for matrix failure initiation, implemented a progressive stiffness degradation strategy instead of ply discount. Damage onset prediction was followed by gradual decrease of pertinent engineering constants, depending on the calculated mode. The three predicted matrix failure modes were accompanied with discrete degradation strategies. Tensile matrix cracks (IFF_A) were assumed to influence transverse Young and shear modulus. Compressive matrix cracks (IFF_B), occurring from high shear and low transverse normal compressive stress combination, were assumed to degrade shear modulus, while compressive matrix cracks (IFF_C) emerging from lower shear and higher transverse stresses were supposed to reduce transverse Young and shear modulus. Fiber rupture conditions, either in tension or in compression, were modified so as to account for the shear deformation contribution in strength evaluation, formulating a new limit condition. The degradation strategy introduced in model B was implemented for fiber breakage.

Nevertheless, interlaminar stresses in tested specimens were present in the tapered and the free-edge boundaries, causing delaminations, Fig. 2. Since shell theory constitutive equations were incompatible with the specific failure mode, a simulation technique suitable for plane stress analysis was proposed so as to take into account the out-of-plane damage. This technique was previously applied with success to tubular specimens under biaxial loading [11]. Static compressive strength degradation along the fibers was assumed to be a function of shear modulus reduction due to both material non-linear behavior and damage accumulation. Degradation of in-plane shear modulus (G_{12}) was considered to provoke local fiber kinking and, as a consequence, potentially contribute to the initiation and propagation of delaminations.

Table 1
Material models.

	Pre-PF non-linear const. eq.	Fail. crit.		Fiber kinking	Post-PF elastic degradation
		IFF	FF		
Model A	Not used, from Ref. [11]	–	–	–	–
Model B	Richard–Blacklock	Lessard	Lessard	Rosen	Ply discount
Model C	Richard–Blacklock	Puck	Modified Lessard	Rosen	Gradual