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# Effect of high through-thickness compressive stress on fibre direction tensile strength of carbon/epoxy composite laminates

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## ABSTRACT

The fibre-direction tensile strength of carbon/epoxy laminates under the influence of through-thickness compressive stresses has been experimentally investigated. In a unidirectional (UD) laminate, the through-thickness compressive stresses will cause premature longitudinal fibre-splitting, masking the effect of transverse stresses on the fibre-direction strength. Here a cross-ply laminate has been used. With the addition of 90° plies preventing the 0° fibres from splitting, it effectively allows the dependence of fibre-direction tensile strength on high through-thickness stresses to be studied. The severity of the through-thickness loads has been varied using cylindrical indenters of different radii, up to the loads near the through-thickness compressive failure stress of the cross-ply laminate. The results show that there is a linear decrease in fibre-direction strength with the mean through-thickness stress. In all the test cases, the specimens failed in a catastrophic brittle manner, with scanning electron micrography showing primarily a fibre tensile fracture mode. The detailed stress state in the specimens has been calculated via finite element analysis. Two failure criteria are proposed, which can be used as conservative design criteria concerning fibre-dominated failures in multiaxial load scenarios.

## 1. Introduction

With the increasing use of composite materials replacing metals in aerospace applications, the need to consider complex load conditions is also increasing. Highly localised through-thickness stresses can often be seen in components where localised contact conditions exist, such as in bolted joints. These stresses may interact with co-existing primary in-plane tensile loading in the fibre-direction, leading to earlier failure.

Multiaxial stress problems in composites have gained attention through efforts such as the Worldwide Failure Exercises (WWFE-I and II) [1,2]. However there is still a paucity of reliable experimental data for biaxial or multiaxial load cases, especially for those involving through-thickness compression and in-plane tension, due to the cost and complexity of multiaxial testing. A number of works have investigated the unidirectional tensile strength of composites under hydrostatic pressure [3–9]. The results of these studies show that the strength and the failure mode of composites depend strongly on the magnitude of the hydrostatic pressure. There is a general trend of decreasing longitudinal tensile strength with increasing pressure.

Works by Collings [10] compared the differences between transverse compressive failures in unconstrained and constrained conditions for unidirectional carbon fibre reinforced composites. The failure modes are totally different, i.e. in the unconstrained case the planes of failure are always parallel to the fibres (inter-fibre failure), whereas the specimens in a transversely constrained condition fail on planes parallel to the direction of constraint in which the failure mode is shear through the fibres caused by the resolved shear stress component of the applied load. Similar observations were also obtained by Henriksson [11] when he studied through-thickness compressive loading on unidirectional and cross-plied carbon/epoxy AS4/8552 laminates.

The through-thickness stresses that interact with the unidirectional composite fibre direction strength found in the literature are mostly in the form of hydrostatic pressure, at most up to moderate values of ~700 MPa. The current study is a detailed expansion of initial results presented in [12]. In this work, a biaxial test method is developed to apply highly localised through-thickness compressive stress (locally as high as −1700 MPa, as calculated by linear elastic finite element analysis) on a simple cross-plied carbon/epoxy tensile test specimen. The high through-thickness compressive strength of a cross-plied laminate allows the interaction between a broad range of through-thickness compression and in-plane tensile strength to be examined. Multiple experimental load cases are presented and finite element models have been used to study the stresses within the specimens so that a simple failure criterion can be proposed for engineering design purposes.

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## 2. Experimental

### 2.1. Specimen preparation and rig setup

The material under consideration is Hexcel's carbon epoxy prepreg system, IM7/8552 with a nominal ply thickness of 0.125 mm. Four identical panels with a cross-ply stacking sequence of $[(0/90)_7/0/(90/0)_7]$ were fabricated, from which specimens were cut for the various load cases. The actual thickness of the laminates is 3.63 mm. The 0° direction refers to the longitudinal tensile loading direction. The 90° plies were present to prevent the specimens from splitting transversely due to the high through-thickness compressive loading. The laminates were cured according to the manufacturer's specification. In order to avoid damage due to mechanical gripping, end tabs 100 mm long, made of cross-plied glass/epoxy, were glued to both ends of the panel, leaving a 100 mm-long untabbed gauge section. Specimens of 10 mm width (Fig. 1d) were cut from it using a water-cooled diamond wheel cutter. For accurate stress calculation, the width and thickness of every specimen was measured.

The tests were performed using a Zwick/Roell 100 kN tension/compression biaxial testing machine, equipped with four independent hydraulic grips mounted horizontally on a flat steel base (Fig. 1a). One pair of actuators was in the longitudinal direction while the other pair was in the perpendicular through-thickness direction. Both the displacement and load could be monitored independently for all four actuators. Since the longitudinal actuators could not be brought very close together due to the presence of the transverse actuators, custom designed fixtures and jaws were manufactured from EN24 high tensile steel to hold the specimens (Fig. 1b). For gripping and applying the tensile load on the specimens, two pairs of clamps were built with knurled surfaces to enhance friction. Four M8 high tensile bolts were used for tightening each clamp at 40 Nm of torque. The clamps were each connected to the hydraulic grips on the longitudinal actuators with a steel extension rod via an M20 bolt.

Highly localised through-thickness compressive loading was applied via a pair of heat-treated steel (BS4659 B01) indenters with different radii of curvature. Four different radii ($R = 10$ mm, 20 mm, 40 mm and 80 mm) were used to give different severity of the localised through-thickness compression. A spirit level was used to ensure good horizontal alignment of all the extension rods and the indenters. A high speed camera was set up from the top (Fig. 1a) to capture the instant of failure at 216,000–300,000 fps.

### 2.2. Test procedures

After the specimen was clamped in position, one of the transverse indenters was brought in until it just touched the specimen and was locked in position (i.e. in a displacement control mode). The other was then set in load control and the through-thickness compressive load applied at a rate of 1 kN/s. Note that in load control mode, load is the prescribed quantity and the resulting displacement is a function of specimen compliance. There was no noticeable bending due to this slightly asymmetric loading arrangement as there were two M20 bolts (Fig. 1b) that allowed transverse movement and the specimens were sufficiently long. This was confirmed upon checking the negligible difference in load readings between the two opposite hydraulic actuators. After the compressive load stabilised, both the longitudinal actuators loaded the specimen under displacement control, each at a nominal rate of 0.5 mm/min simultaneously to preserve the symmetry of the loading condition and also to minimise the influence of friction between the indenters and the specimen. The specimen was loaded until catastrophic failure.

The through-thickness compression in load control mode would tend to crush and obliterate any features of the fracture surface as soon as the specimen failed in tension. Therefore 8 additional specimens were loaded in displacement control with indenters of $R = 20$ mm so that the fracture surfaces could be preserved and inspected. Two additional specimens were also loaded purely in through-thickness compression with indenters of $R = 10$ mm but without a longitudinal mechanical grip (Fig. 1c), to check if the end restraints had any effect. The failure surfaces were then examined in a scanning electron microscopy (SEM).

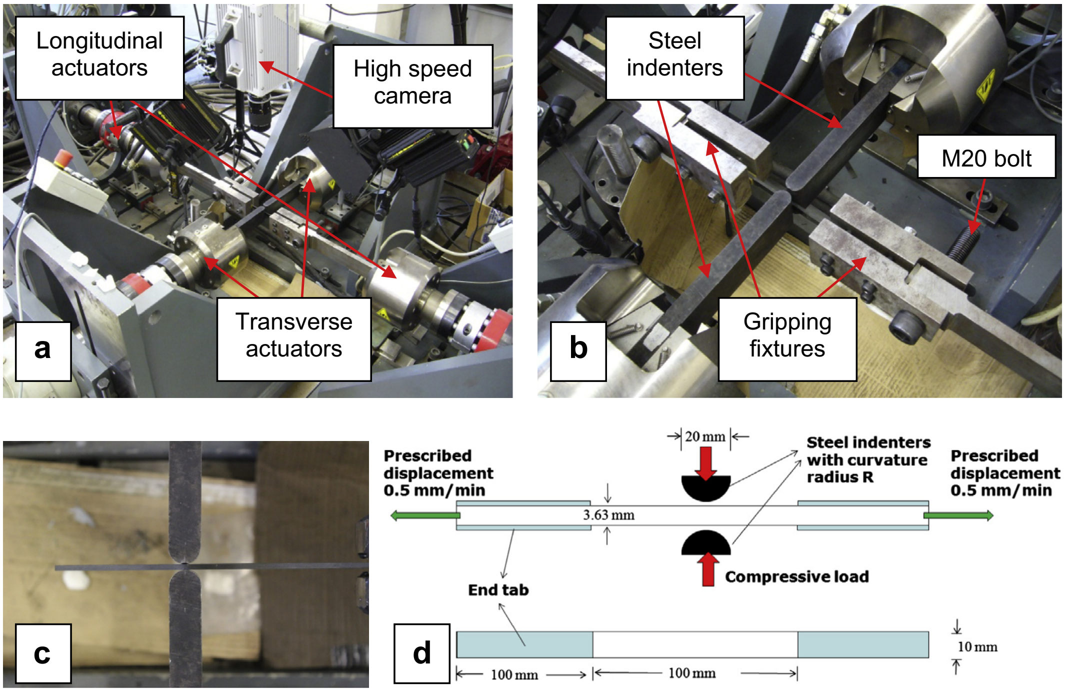

**Fig. 1.** (a) Overview of biaxial actuator positioning and the high speed camera. (b) Details of test configuration. (c) Pure through-thickness compression loading with indenters of radius of curvature $R = 10$ mm. (d) Specimen with its dimensions used in the biaxial testing.