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Test Equipment

Development of a biaxial tensile test fixture for reinforced thermoplastic composites

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Abstract

A new mechanism for biaxial tension tests was developed for loading an in-plane reinforced composite laminate or any injection-molded polymeric specimen simultaneously in two principal directions. This mechanism can be adapted to any uniaxial tension test machine and, thereby, it can reduce the cost of conducting tests on expensive dedicated machines. The fixture provides a uniform state of equibiaxial tension, necessary for characterizing the biaxial state of loading on any polymeric material system and it can also be reconfigured to test non-equibiaxial tension over a short range. The mechanism is presently utilized for understanding the failure behavior of injection molded short fiber polyamide and nanoparticle-reinforced PP thermoplastic composites.

Keywords: Biaxial tensile test; Fiber-reinforced polyamide; Nanoclay reinforced PP; Finite element

1. Introduction

Unlike the situation with metals, the failure of composites under multiaxial loading has until quite recently been poorly understood. Due to the inherently anisotropic structure of the material, its strength under biaxial conditions critically depends on how well the loads match the fiber directions in the material under test. If they are well matched the biaxial strength may exceed the value that might be expected from simple uniaxial tensile and compressive tests. Conversely, if they are poorly matched the strength can be quite low. Although there are numerous approaches currently to predict ultimate failure of fiber-reinforced plastics (FRP) or composite materials, few have been rigorously scrutinized by the presence of accurate multiaxial experimental data. As a result, considerable confusion exists in the composites community as to which approach should be used for the design process. Several advances are taking place as a result of improved numerical capability and theoretical development, resulting in a revitalization of the interest in damage initiation and ultimate failure prediction. However, this renewed attention has only further exposed the paucity of experimental data to which these recent theories based on homogenization techniques can be compared and re-evaluated, thereby hindering their development. Several researchers believe the only way to overcome many of these issues is through a long-term concentrated effort that can

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corroborate numerical predictions with reliable experimental data. Among these, biaxial tests, which results in σ_1–σ_2 stress space, an essential design parameter for composites failure prediction, is the most challenging and expensive to perform.

Different experimental techniques and specimen shapes have been used to produce biaxial stress states. These techniques may be classified into two categories:

(i) tests using a single loading system and
(ii) tests using two or more independent loading systems.

In the first category, the biaxial stress ratio depends on the specimen geometry or the loading fixture configuration, whereas in the second category it is specified by the applied load magnitude. Examples of the first category are bending tests on cantilever beams and tests using special fixtures. Especially for composites, uniaxial testing of specimens having the fibers oriented off-axis produces a complex state of stress in the principal material system, consisting of either two or three in-plane stress tensor components. The respective stress ratios, however, depend on the fiber orientation angle and cannot be selected at will. Examples of the second category are a round bar under torsion combined with bending, thin-wall tubes subjected to a combination of tension/compression and torsion or internal/external pressure, and cruciform specimens under in-plane biaxial loading. The technique with the thin-wall tube is the most popular one and seems to be very versatile, as it allows tests with any constant load ratio to be performed. However, it presents some inconveniences; radial stress gradients may not be negligible depending on the thickness of the tube and the applied load:

- the anisotropic properties of tubes and plate materials are not comparable;
- real construction components in fiber-reinforced composite materials are often flat or gently curved and differ a lot from tubular specimens;
- obtaining perfect alignment and load introduction is not straightforward;
- tubular specimens of thin construction can experience various forms of elastic instability when they are subjected to circumferential or axial compression or torsion loads;
- tubes may exhibit changes in geometry during loading, but these effects are usually ignored when processing experimental results.

The most realistic technique, therefore, is to create a biaxial stress state by applying in-plane loads along two perpendicular arms of a cruciform-type specimen. Presently, work is going on to establish biaxial testing procedures and the development of accurate failure theories after rigorous testing at various research institutions. Some of the work on biaxial fixtures, specimens or testing is described below in reverse chronological order.

The plane biaxial test device by Smits et al. in 2006 [1], as shown in Fig. 1, is a biaxial testing machine using four independent servo-hydraulic actuators with an appropriate independent control unit and load cells, which makes it a very costly equipment. Samir et al. in 2006 [2] studied the behavior of fiber-reinforced composite laminates under static and cyclic in-plane complex stress state; they also developed a biaxial loading fixture using four independent load cells. Potter et al. in 2005 [3] investigated the failure mechanism and stress–strain relations for graphite/epoxy laminates under in-plane biaxial compression. They varied the load ratio from 0.24 to 1.0 and measured the sensitivity of sample failure. Diani et al. in 2004 [4] presented a directional model for isotropic and anisotropic hyper elastic rubber-like materials; they compared uniaxial and biaxial data. El-Hajjar and Haj-Ali in 2004 [5] modified Arcan's fixture for different biaxial stress states. They varied the angle of applied load and measured the axial shear response under different loadings. Welsh and Adams in 1998 [6] investigated the strength of carbon/epoxy cross ply laminates using cruciform specimens. They generated experimental data for all specimen geometries and compared the biaxial failure envelope in σ_1–σ_2 stress space for different laminate configurations. They also demonstrated the ability of thickness tapered cruciform specimens to determine the biaxial strength of composite materials at any stress ratio. Thom in 1998 [7] presented a review of biaxial

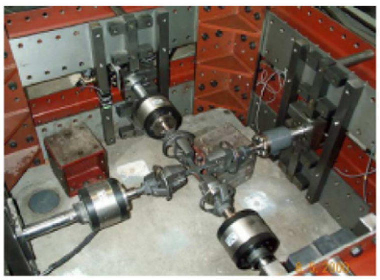

Fig. 1. Biaxial test fixture [1].

strength of fiber-reinforced plastics; he put forward all developments in the field of failure criteria development for composites from 1902 to 1996 and the need for proper biaxial testing. Arnold et al. in 1995 [8] conducted several tests on chopped strand mat laminates and produced the complete failure envelope in σ_1–σ_2 stress space during a biaxial test. Albertini in 1991 and 1980 [9,10] conducted dynamic uniaxial and biaxial tests on austenitic stainless steel at various strain rates using a specially developed cruciform specimen and loading equipment, and demonstrated viscoelastic material properties.

In the classical text on mechanics of composite materials by Jones [11] the importance of the interaction term F_{12} of the two principal stresses as proposed in the Tsai–Wu failure theory brings out the need for biaxial experiments. The determination is very complicated though, since F_{12} has very little sensitivity to biaxial stresses. Consistency of experimental results also depends on the material behavior which therefore needs a sensitivity analysis. Moreover, all the developed failure criteria gave due importance to the interaction term, although in many of the earlier works the interaction term was either assumed as a constant value or simply ignored. However, considering the sensitivity of F_{12}, control experimentation is required for any new material characterization, which brings out the utility of the present experimental research endeavor.

2. Design and development of biaxial tensile testing fixture

This biaxial test facility was designed specifically to evaluate the biaxial (in-plane) response of not only composite materials but also any polymer system. It is capable of generating any combination of tensile–tensile stresses in σ_1–σ_2 stress space.

The geometry of the fixture is so designed that various stress ratios can be applied using a single set-up mounted on any usually available uniaxial material testing system, in any laboratory, and requiring just one load cell. The force required in the transverse direction (σ_2) is achieved through the mechanical configuration of the fixture, as shown in Fig. 2. The load ratios can be changed by fixing the inclined rod (8) at different locations on a fixed plate (6), marked with different holes housed on the horizontal support, in order to provide various angles.

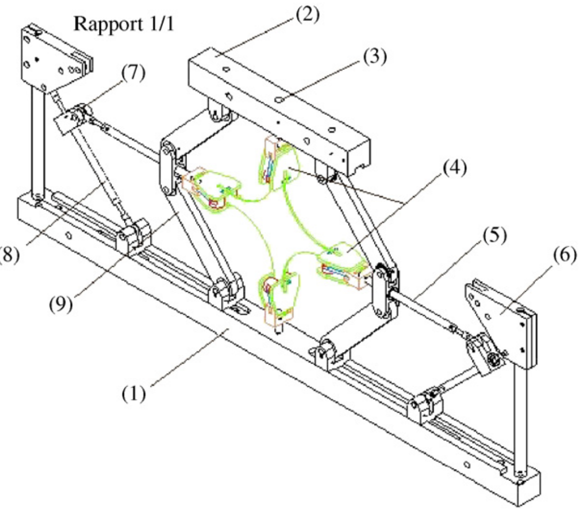

Fig. 2. A schematic of biaxial tensile test fixture.

A T slot is provided on the base (1) for easy alignment and reconfiguration of the fixture for required stress ratios. Two identical and foldable major links (9) are provided for accommodating the grips and the sample. Pin joints are provided for connecting the major and minor links. The minor link (7) is specifically designed to provide sliding motion to the transverse axis grip rod (5), and to simultaneously keep the transverse axis parallel to the base to avoid any unbalanced forces and bending moments. A horizontal shaft (not shown in the diagram) is also provided for the same purpose, which passes through the major links (9). The specimen is required to be fixed in this hexagon along with the grips (4) which can be pulled from all the four directions by the action of the cross arm and the fixture mechanism. To minimize friction, linear bush bearings are used in the minor link. All the shafts are hardened, ground and chrome plated. The inclined shaft is fitted at an angle of 45° to provide equi-biaxial stress on the specimen. Any mismatch in the assembly can be compensated by the bearings provided at the shaft ends. As the foldable major link moves in the axial direction, the slider (minor link) slides on this shaft and a proportionate motion is achieved in the transverse direction. This motion is synchronized between axial and transverse directions. In this way, when the moving crosshead goes up, the vertical upper grip moves with a velocity "v" whereas the vertical bottom grip is motionless. During this time, the horizontal grip also moves up with a velocity of "$v/2$" and simultaneously moves apart in the horizontal axis in opposite directions (reverse front walk) with a velocity of "h". The relation between v and h is given by the angle "φ", which is formed by the inclined bars with the horizontal. The part of adjustment (part 6) as shown in Fig. 2 makes it possible to vary φ in order to get different stretch ratios (r).

$$\tan\varphi = 1, 2, 3 \text{ or } 4$$
$$\Leftrightarrow \begin{cases} \text{equi}-\text{biaxial tension } (r=1): h = v \\ \text{biaxial tension } (r=2): h = 2v \\ \text{biaxial tension } (r=3): h = 3v \\ \text{biaxial tension } (r=4): h = 4v \end{cases} \tag{1}$$

where h and v are the horizontal and vertical velocity displacements and r is the ratio between these displacements ($r = h/v$).

In this way, the stretch obtained by such a mechanism could be related to

$$\lambda \text{ and } \beta = 1 + \frac{\lambda - 1}{r}, \tag{2}$$

where λ and β are the strains in the vertical and horizontal directions.

The load measurement is carried out in the following way. As the vertical top grip is fixed to the load cell through the vertical draw bar (part 3), the link between this grip and the load cell makes it possible to obtain a measurement of the stress in the vertical direction. The two horizontal grips are fixed on the horizontal draw bars (part 5) and the biaxial specimen is instrumented with rosette strain gages in order to measure the load in the horizontal direction of tension as per Ash [12]. Thus, the load in both the vertical and horizontal directions is evaluated. The strain in the center of the specimen is measured with the use of a video extensometer.

2.1. Assembly of the test fixture

All the subassemblies of major and minor links, base support structure (1,2) and grips were assembled into one complete system as shown in Fig. 3. The top base (2) of the fixture was mounted onto the cross arm of an Instron Material Testing System 5582 through a specially machined coupling. The fabricated and assembled fixture is shown mounted on the Instron 5582 in Fig. 4.

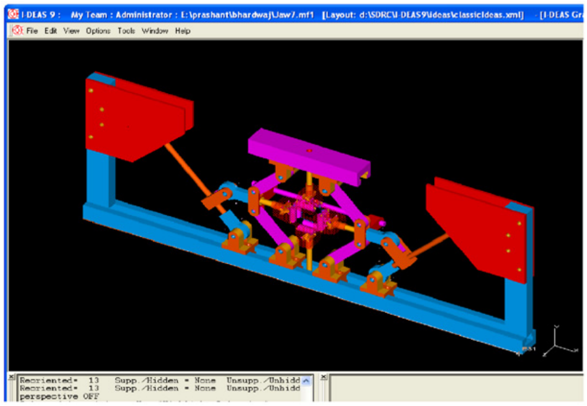

Fig. 3. Assembly of biaxial test fixture.

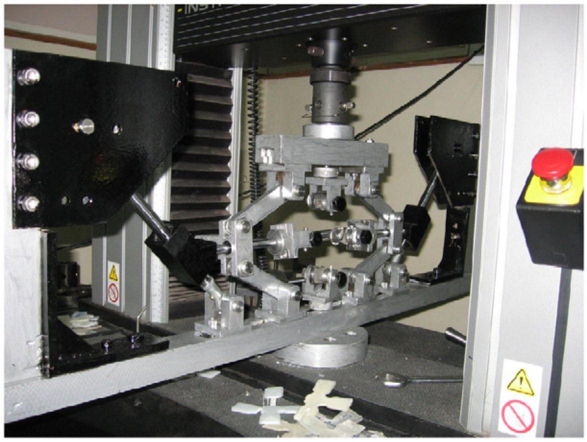

Fig. 4. Assembly of biaxial test fixture on an Instron material testing system.

3. Experimental validation

The experimental portion of this study began by identifying the specimen that could potentially be tested successfully. To be considered a successful biaxial test, the ultimate failure must occur in or around the gage section of the test specimen. Biaxial strengthening effects exhibited by composites can make this a difficult objective to obtain in certain laminates, which in particular was a concern for the quasi-isotropic laminate. Biaxial strengthening refers to the fact that most laminated composites exhibit higher failure strengths under biaxial loading conditions compared to uniaxial loading. Examining the shape of most of the higher-order failure theories could easily identify this phenomenon. In general, this failure envelope shape can be described as an elliptical surface with the major axis

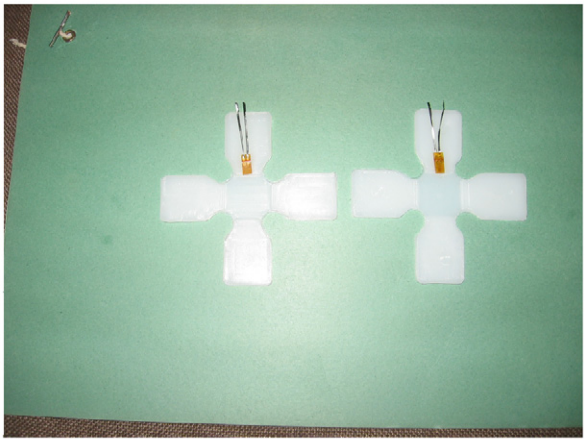

Fig. 5. Biaxial test specimen with strain gauge.

along a 45° line between the first and third quadrants in σ_1–σ_2 stress space when plotted in rectangular coordinates. Using biaxial cruciform specimens, it is reasonable to expect unacceptable failures to occur in one of the loading arms (which are loaded uniaxially) rather than in the biaxially loaded gage section. The specific thickness-tapered cruciform biaxial test specimen geometry used in the present study was evolved to limit the biaxial failure in a narrow zone. Because cruciform-shaped specimens have two intersecting loading directions, there exists the possibility of load sharing between adjacent loading arms. That is, it is possible that all of the applied load in one direction may not be directed into the gauge section, leading to inaccurate stress level predictions in the biaxially loaded gage section. Fortunately, it is possible, but not trivial, to quantify the levels of load sharing for each material system and specimen geometry, referred to as the bypass correction factor. This value gives an indication of the amount of applied force that bypasses the thickness-tapered gage section. Daniel [13] suggested the specific bypass ratios of 1.3 and 1.55 for the cross-ply and 1.67 for the quasi-isotropic laminates in 1995. The procedure for generating ultimate biaxial strength values by instrumenting several specimens with uniaxial and biaxial strain gauges is shown in Fig. 5.

The strain data generated using this instrumentation are not necessary to directly determine the ultimate biaxial strength, but rather to determine the appropriate bypass ratio for each laminate configuration. Once instrumented, each cruciform specimen was loaded into the biaxial testing fixture

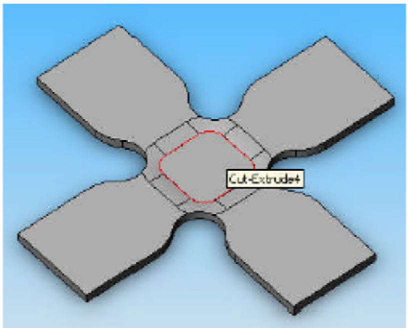

Fig. 6. A solid model of biaxial tensile test specimen.

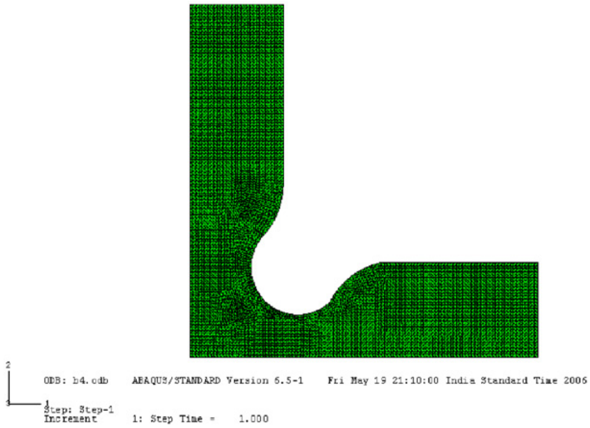

Fig. 7. Finite element mesh of one quarter of the 3D model (>50,000 elements).

as shown in Fig. 5. Each specimen was then loaded at a rate of 2.0 mm/min while maintaining the appropriate stress ratio of 1.0 until ultimate specimen failure occurred. As a case study for validation of working of the fixture, random glass reinforced polyamide (PA) (with 33% short random glass fibers) was tested and the specimen failed as per the predicted results of FE simulations using Abaqus V 6.5. As shown in Figs. 6–12, the failure predicted by the FE analysis occurred in the specimens. It was observed during the experiments that the failure starts at a radius between the arms of the specimen and then grows inwards to the center of the specimen. Stress whitening was observed in every failure, indicating plasticity. The strain obtained by the strain meter closely follows the strain value recorded by the Merlin software of the Instron material testing system in the vertical and horizontal direction when measured independently. This validated the biaxial test fixture workability.

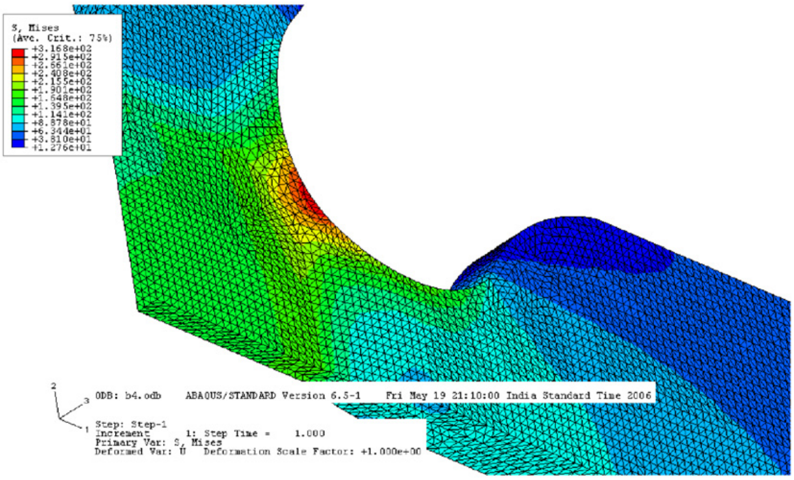

Fig. 8. Von Mises stress indicating the failure stress at the radius in biaxial loading.

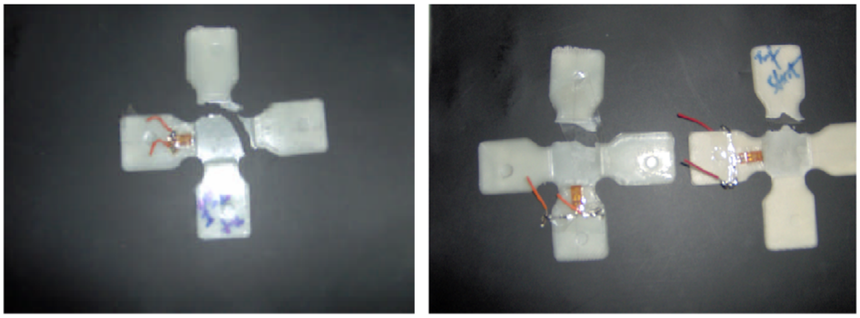

Fig. 9. Failed biaxial specimens as predicted.

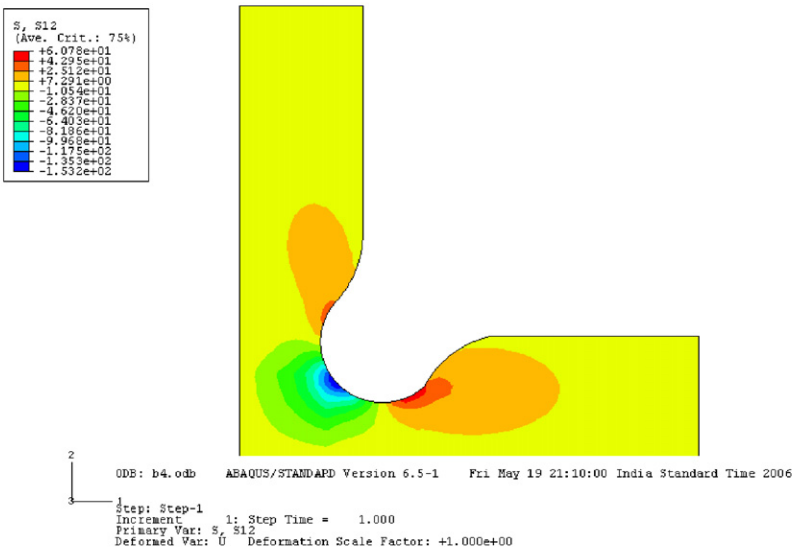

Fig. 10. The shear stress at the zone of onset of failure is negligible indicating a pure state of biaxial stress.

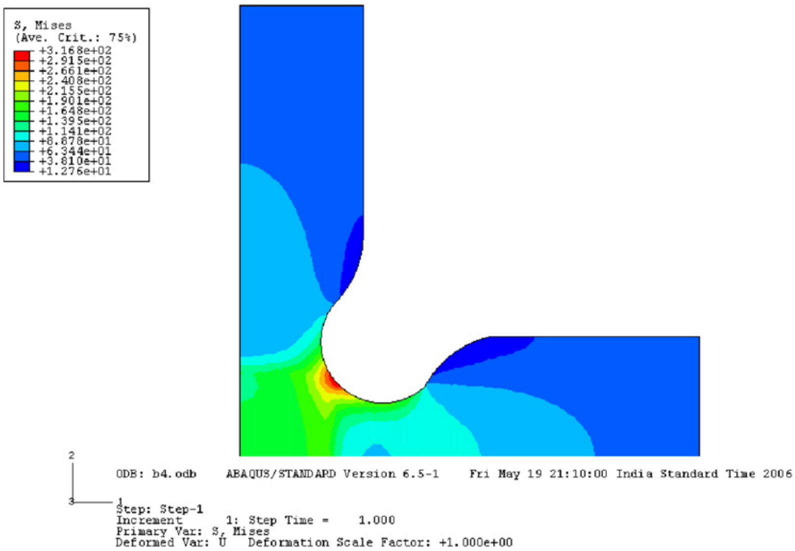

Fig. 11. The Von Mises stress at the onset of failure indicating equi-biaxial stress.

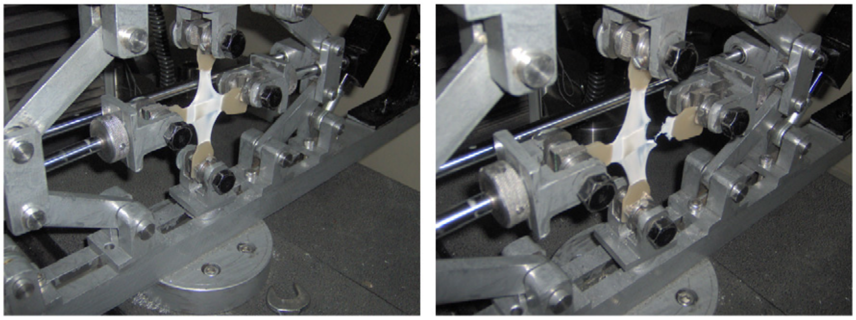

Fig. 12. A progressive failure of hyper plastic nanoclay based PP under equi-biaxial loading showing first failure in the transverse direction.

4. Conclusions

1. A new low-cost biaxial-testing fixture was successfully developed and validated with sample tests.
2. Equi-biaxial and non-equi-biaxial stresses with different stretch ratios can be incorporated in the new biaxial fixture design.
3. The fixture could be very useful for the estimation of interaction coefficient between the two principal stresses, typically for any orthotropic or fiber-reinforced material system.

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