A Device for Biaxial Testing in Uniaxial Machines. Design, Manufacturing and Experimental Results Using Cruciform Specimens of Composite Materials

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BRIEF TECHNICAL NOTE

A Device for Biaxial Testing in Uniaxial Machines. Design, Manufacturing and Experimental Results Using Cruciform Specimens of Composite Materials

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Abstract The present study deals with the design and manufacturing of a mechanical device to perform biaxial testing in universal (uniaxial) testing machines. A review of previous definitions of similar devices is carried out and a new device is conceived and developed. The main improvement with the present device is that it allows different types of biaxial loadings (tension-compression) to be performed with few manipulations. The device allows variable displacement ratio to be used in each loading direction, giving then rise to variable loading ratios. Biaxial tension-tension tests on cruciform specimens made of composite material were carried out using very brittle samples in which the fibre direction was perpendicular to the loading plane. Strain gages were used to monitor the percentage bending parameter so that the correct alignment of the loading could be checked. Values below 5% for the bending parameter were achieved at the moment of failure.

Keywords Biaxial loading · Cruciform specimens · Composite materials · Percentage bending

Introduction

Multiaxial testing of materials is a fundamental task, especially for those materials where failure mechanisms and the associated failure criteria are still under discussion and research, as is the case for composite materials. In the framework of fibrous composite materials, there exist several failure criteria [1], some of the most important discussions surrounding the role of a secondary transversal tension in the interfibre failure of these materials [2, 3].

Multiaxial testing machines are typically much more expensive than uniaxial machines, mainly because their frame is more complex and therefore more actuators and associated devices are needed [4, 5]. This is the reason why multiple options for devices which can create a biaxial loading state from its use in a uniaxial testing machine are available in the literature.

A comprehensive review of different devices for introducing biaxial loading is summarized in [6], both for devices with actuators in each loading direction [7–9], as well as devices for use in uniaxial machines [10–13]. Other approaches for introducing biaxial loading using rings and disks [14, 15], planar mechanisms [16], 3D mechanisms [17], or other mechanisms [18], are available in the literature.

The objective of the present study is to conceive, design and manufacture a mechanical device, which allows biaxial testing of cruciform specimens to be used in the frame of a uniaxial testing machine. The device allows, with very simple manipulations, tension-tension (compression-compression) and tension-compression biaxial tests to be carried out. It also allows, in any of the three previously mentioned loading configurations, variable loading ratios (e.g. tension-compression 1:0.5, or tension-tension 1:0.75).

The device was used in the biaxial loading of cruciform specimens of composite materials. Strain gages at the centre of the sample, at both faces and in both loading directions were used to measure the percentage bending parameter, following ASTM E1012 [19] as a measurement of the eccentricity of the loading mechanism of the device. The bending parameter for all tests proved to be below 5%, which indicates an excellent alignment in the manufactured loading device.

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It is important to notice that the device was originally conceived to apply a biaxial loading state in a unidirectional laminate, but with the fibres oriented perpendicularly to the plane of testing. If we define x_1 as the fibre direction, the biaxial load state will be applied in the x_2-x_3 plane, plane in which a unidirectional thermoset composite is extremely delicate, its strength being some orders of magnitude lower than in the fibre (x_1) direction. A correct alignment of the loading device being mandatory for representative results to be obtained. Obviously, the conceived device allows the typical standard biaxial testing of cruciform samples with the fibre contained in the plane of the laminate.

Design and Manufacturing of the Biaxial Device

The main novelty of the device developed in the present study is the possibility of being able to perform tension-tension (or compression-compression tests) (Fig. 1(a)) as well as tension-compression tests manipulating the mechanism as little as possible. It also allows a tension (in the straight direction of the sample) and surface compression (transversal to the plane of the sample) loading state to be carried out, not only in cruciform samples, but also in standard straight samples by substituting the gripping system by flat indenters (Fig. 1(b)). Nevertheless, in this test configuration, and at certain levels of the surface compression, friction might produce some shear effects at the contact surface, which may be avoided by using some lubricant. It is also possible to perform any of these tests with different loading ratios, by simply varying the length, and corresponding angle, of the loading inclined arm.

The set-up for the device (tension-tension) is shown in (Fig. 1(a)), and is conceptually similar to that introduced in [10] (see also Fig. 12 on Ref. [6]) but with the improvement that the device can easily turn into a tension-compression (transversal) loading by simply removing two bars and adding four bars between the four linear guides, as depicted in (Fig. 1(b)).

The device shown in Fig. 1 has four linear guides, with an allowable vertical load of 14 KN for each guide, corresponding to a maximum vertical load introduced by the uniaxial testing machine of 56 KN. The dimensions and drill positions of the fixture over the carriage were designed to minimize the bending moment (M in Fig. 2) perpendicular to the carriage axis (Fig. 2). The forces involved in the equilibriums (F the compression force of the device load arm, and the horizontal and vertical components, F_1 and F_2,) are depicted in Fig. 2.

For the gripping system, several alternatives were explored.

a) A double-pin, to try to minimize any misalignment in the device, but this alternative proved to be very sensitive to the hole drilling of the sample, generating bending in it.
b) A clamping device, resulting in an acceptable but extremely tedious procedure, with 6 screws per loading arm (24 in total).
c) Steel wires were used together with glass fibre tabs in the sample, the procedure was also tedious, but was mainly discarded by the problems in introducing the tensile

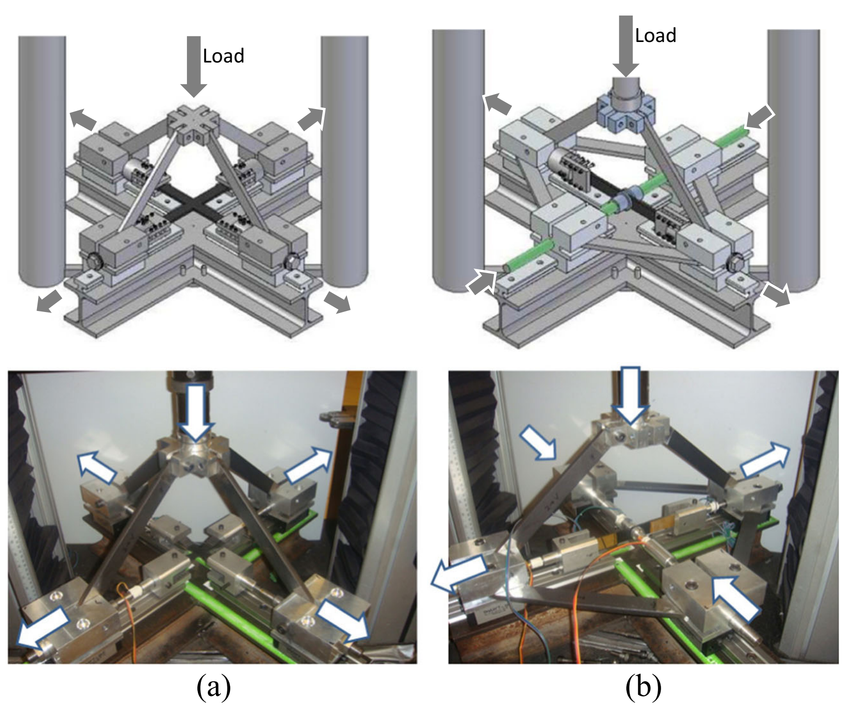

Fig. 1 Diagram (up) and real prototype (down) of the device set-up for (**a**) tension-tension loading in cruciform samples, and (**b**) tension-compression (transversal) loading in standard samples

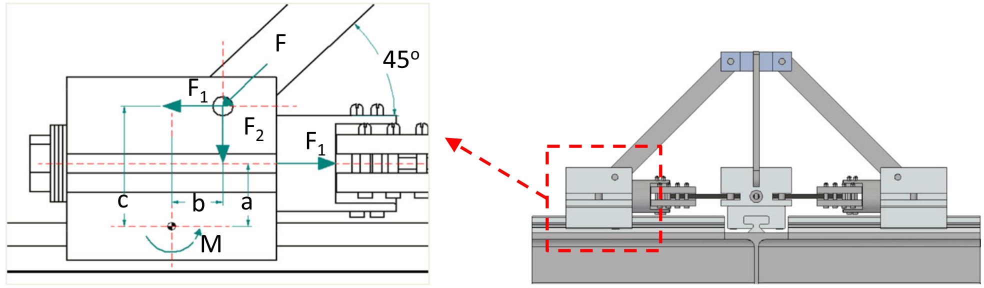

Fig. 2 Dimensions and detail of the position of holes on the device over the linear guide, to minimize the bending moment on the carriage axis

loading ratio due to the difficulties in adjusting the real length of the wire under tension.

d) Rigid steel rings demonstrated the best behaviour in all senses, as the installation procedure was quick, the curvature of the rings acted as a self-alignment mechanism and the loading ratio was easily controlled. The rings are individual chain links with a thread and a nut to allow the quick connection between the device and the sample (which has holes at the tabs for this purpose). This option was chosen as the best one to introduce loading under tension.

The use of tabs is necessary, in the particular case of the present study, because the cruciform samples used for the tests are made of unidirectional carbon fibre, with the fibre direction oriented along the thickness direction, perpendicular to the plane of the sample. As a result of this, the sample is extremely brittle.

Although the device can be used with any cruciform sample, Sample Preparation and Testing Section summarizes some details for the preparation of the sample of composite material under the scope of the present study.

Sample Preparation and Testing

Figure 3 shows the steps followed to prepare the composite cruciform sample. The correct cruciform shape of the contour of the samples, specifically designed for this test configuration by [20], including the curvatures, was manufactured by lateral machining, using a metallic pattern previously machined using a numerical control machine (Fig. 3(a)). Both sides of the sample were polished (Fig. 3(b)). Location of the center (Fig. 3(c)) was an important step to correctly apply the loading and avoid secondary bending moments. Figure 3(d) shows the bonding of the tabs, (Fig. 3(e)) the hole drilling and (Fig. 3(f)) the installation of the strain gages.

A biaxial rosette was bonded at each side of the sample in order to measure the strains at each loading direction and at each side, and consequently, to have the bending parameter following ASTM 1012 [19]. Notice that each load axis has a percentage bending (PB) measurement and a pair of strain gages.

Figure 4 shows the definition and plots the absolute value of the PB measurements for both loading axes (PB1 and PB2 respectively) in a particular cruciform tension-tension test. Although the device was built only for measuring mechanical

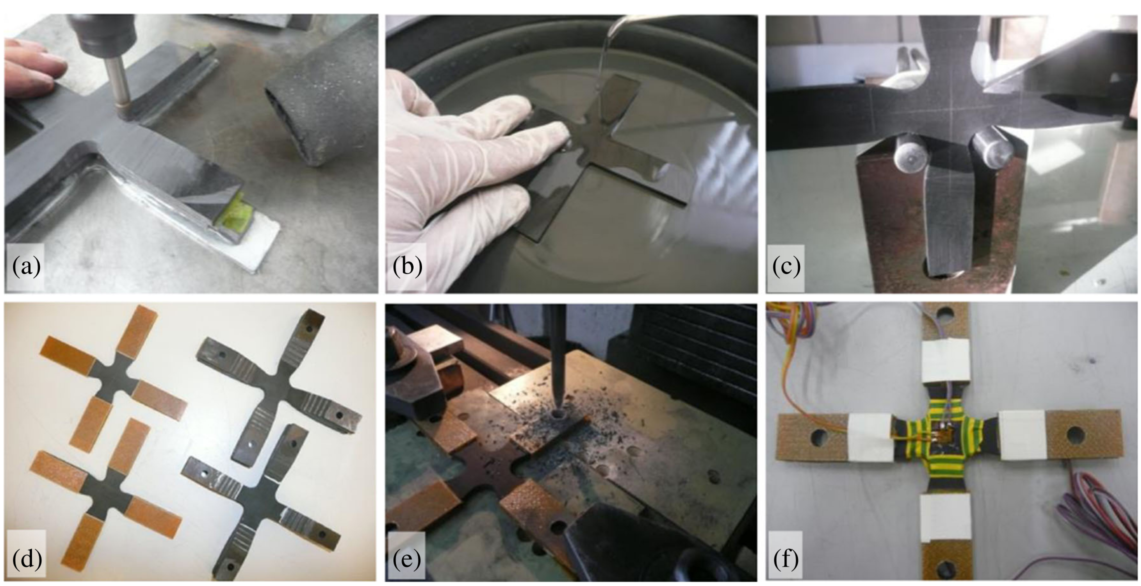

Fig. 3 Preparation of the samples. (**a**) lateral machining, (**b**) polishing, (**c**) centre location, (**d**) tabs bonding, (**e**) hole drilling, (**f**) strain gages bonding

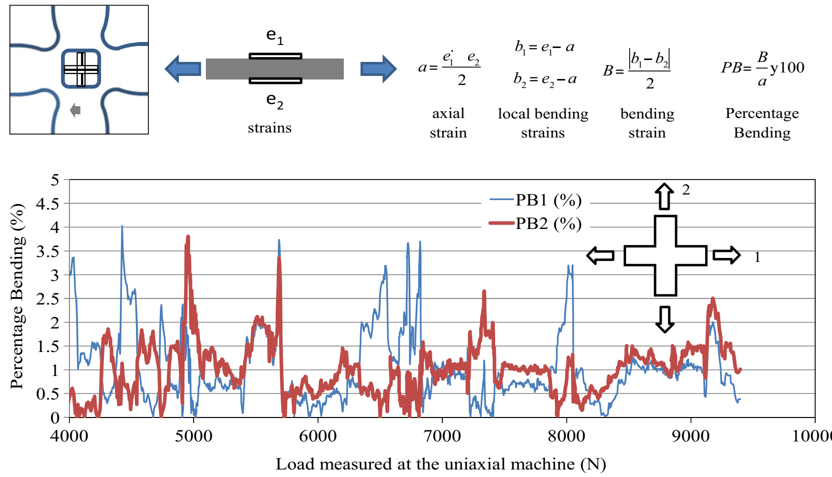

Fig. 4 Percent Bending (PB) measurements in a biaxial tension-tension test

properties of the materials at the instant of failure (strength measurements), percentage bending was recorded from approximately 40% of the failure load (4000 N in the case of Fig. 4).

For both loading axes, the percentage bending values are below 5%, which are, in absolute terms, excellent values. In the complete set of tests, which consisted of 21 cruciform samples (whose results fall outside the particular scope of the present study), the results observed were quite similar, the percentage bending parameter being below 5% in almost all cases and in all the measured range when the applied load was above 50% of the sample failure load. Lower values, <2%, were in any case systematically obtained at the instant of failure.

The self-alignment effect of the steel rings has proved to be efficient in controlling the load application. This self-alignment effect acts more efficiently as the load increases, the PB measurements being extremely satisfactory (low) at the instant of failure.

The steel ring (the individual chain link) connecting the sample to the device, particularly the curved part of it, contacts the specimen at two points, the upper and bottom part of the hole at the tab area. If the contact force is higher in any of these contact points, due to the curvature of the link, it will slip and will slightly twist, reorienting the ring and making the two contact forces being more equal and consequently, the bending moment being lower. This effect does not appear uniformly during the test due to friction, only when the tangential component of the contact force exceeds the friction, the slight reorientation occurs, giving rise to discrete changes (decrements) in the bending parameter measurements, as can be clearly observed in Fig. 4.

Conclusions

A mechanical device, conceived for its use in uniaxial testing machines, was designed and manufactured to generate biaxial loading states (tension-tension, compression-compression and tension-compression) in cruciform specimens with the possibility of variable loading ratios at each loading axis.

The device permits the use of standard (non-cruciform) specimens, for the tension-surface compression (transversal) loading state.

A complete set of tension-tension tests has shown that the manufactured device has an excellent alignment in the loading application, the percentage bending being below 5% at both loading axes.

The excellent alignment of the device has allowed the biaxial testing of cruciform samples of unidirectional composite laminates, with the fibre perpendicular to the testing plane, to be carried out. This testing configuration is, to the authors' knowledge, new in literature.

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