BIAXIAL TESTING OF COMPOSITES IN UNIAXIAL MACHINES: MANUFACTURING OF A DEVICE, ANALYSIS OF THE SPECIMEN GEOMETRY AND PRELIMINARY EXPERIMENTAL RESULTS

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Abstract

The present work deals with the transverse failure in fibre reinforced composite materials under biaxial loading and is divided in three main aspects. The first one is the design and development of a reliable low-cost biaxial device to be used in any standard uniaxial testing machine. The second one deals with the details of the design of a composite cruciform specimen with the fiber perpendicular to the testing plane to promote failure in the biaxial stressed area. The third presents preliminary results of the device to check accuracy of the loading ratio with the cruciform specimen. The device has shown to be quite accurate in transforming the uniaxial loading in a biaxial one and is ready to be used in the biaxial study of transverse failure of cruciform composite specimens under different loading ratios.

1 Introduction

Biaxial testing of composites is becoming increasingly important to asses failure in bi-dimensional stress states, as results of uniaxial testing can not fully provide information for failure induced by a bi-dimensional stress state. Although biaxial testing machines are commercially available, they are very expensive compared with uniaxial ones. In particular, testing of unidirectional specimens under transverse biaxial loading is especially interesting for the study of matrix/inter-fibre failure, a mechanism of damage that has already been numerically studied by the authors in previous works [1].

The aim of this work is to present the design and manufacturing of a device for performing biaxial testing using a uniaxial testing machine. It is also the aim of the work to present additional discussions about the design of a test specimen, made of fibre reinforced composite material, to be employed in transverse biaxial loading tests for the study of matrix/inter-fibre failure of unidirectional laminates. The design is carried out based on a cruciform geometry (a typical one which is much more easy to test compared, e.g., to the tension-torsion tube specimens). To the authors' best knowledge, such transverse biaxial testing has not been addressed previously in literature and particular issues have to be discussed when designing this particular test geometry. The specimen designed is aimed to guarantee a uniform 2D stress state in the area of interest and avoid premature failure both at the gripping area and at the geometrical transition between the uniaxial loading areas and those near the center of the specimen.

The device allows, by very simple manipulations, to carry out, tension-tension, compression-compression and tension-compression biaxial tests. 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).

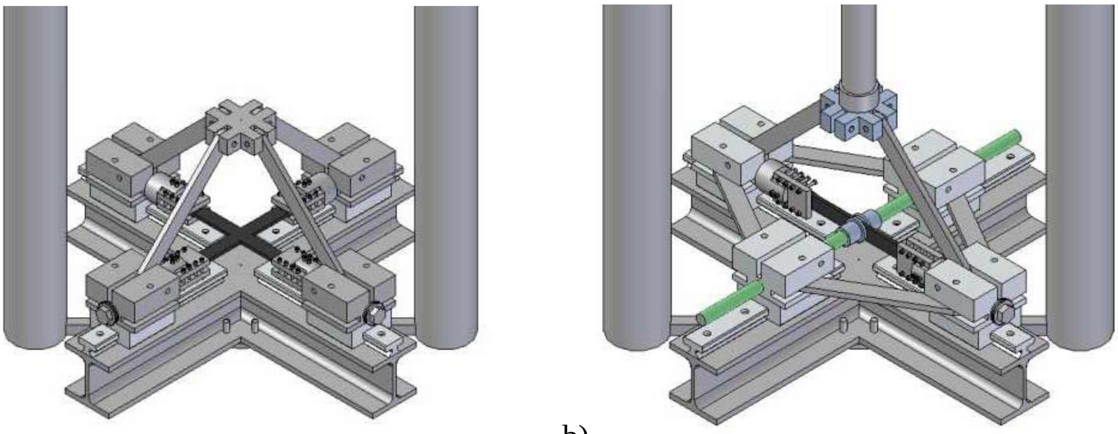
The present solution, as well as many other previous fixtures proposed in literature, does not intend to substitute the accuracy and robustness of a commercial biaxial testing machine, but it allows exploring the influence of secondary stress components on the failure of biaxial stress states in composite laminates, with a reasonable degree of accuracy.

2 Design and manufacturing of the biaxial device

A first step to reduce the cost of the acquisition of a biaxial testing machine is adapting an independent actuator as done, for example, by Hoferlin et al [2]. A step forward is achieved by simply using a device to perform biaxial tests using uniaxial testing machines without additional actuators, Ferron and Makinde [3] presented a tension-tension fixture, an analogous fixture was proposed by Tasan *et al.* [4], Fraunhofer [5] a device for tension-tension with lower mechanical links and Bhatnagar et al [6] proposed a device allowing equibiaxial and non-equibiaxial tension over a short range.

The device designed and manufactured in this work allows tension-tension and compression-compression (see Fig. 1a) as well as tension-compression (see Fig. 1b) with different loading ratios to be introduced. It is also useful for tension-compression tests with standard (non-cruciform) test specimens, by the substitution of the gripping system by two flat indenters (Fig 1b). In Fig. 1, the two cylindrical columns represent the load frame of typical uniaxial testing machines, the dimensions of the device having been designed to be used in an Instron® 4481 or any other with a higher clearance between the machine load frames.

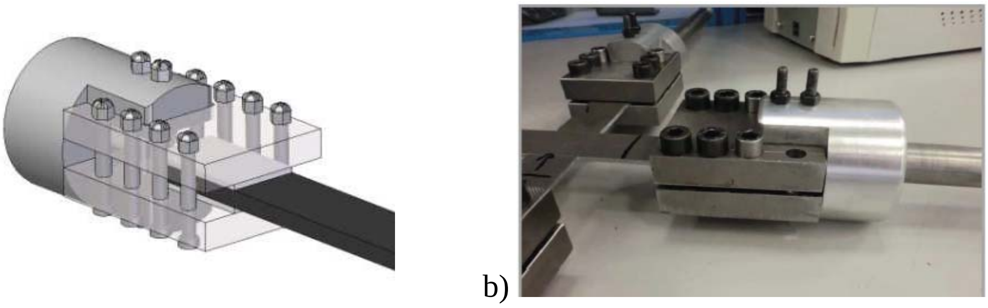
The device shown in Fig. 1 has four DryLin® T linear guide system, with an allowable vertical load of 14 KN. The dimensions and drill positions of the fixture over the carriage have been designed to minimize the bending moment perpendicular to the carriage axis. The final design allows axial loading of the specimen to be applied up to 14 KN.



a) b)

Figure 1. Schematic representation of: a) tension-tension on a cruciform specimen and b) tension-compression on a standard straight specimen.

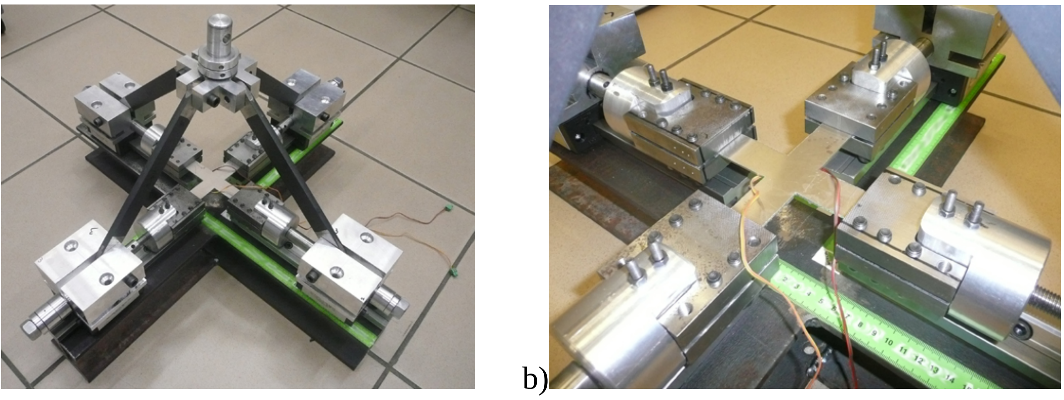
The reduced dimensions of the device have forced to build a manual gripping system (Fig.2) with at least the same loading capacity than the sliding elements (14 KN). This load is above the estimated ultimate load for the materials under analysis.



a) b)

Figure 2. a) Schematic representation of the gripping system and b) the real manufactured gripping system.

The final disposition of the device for a tension-tension test is shown in Fig. 3a whereas a detail of the cruciform specimen and the gripping system is shown in Fig. 3b. The dummy cruciform specimen in Fig. 3b has strain gages at both arms to check the strain (loading) ratio.



a) b)

Figure 3. a) Set-up for the tension-tension test b) detail of the cruciform specimen.

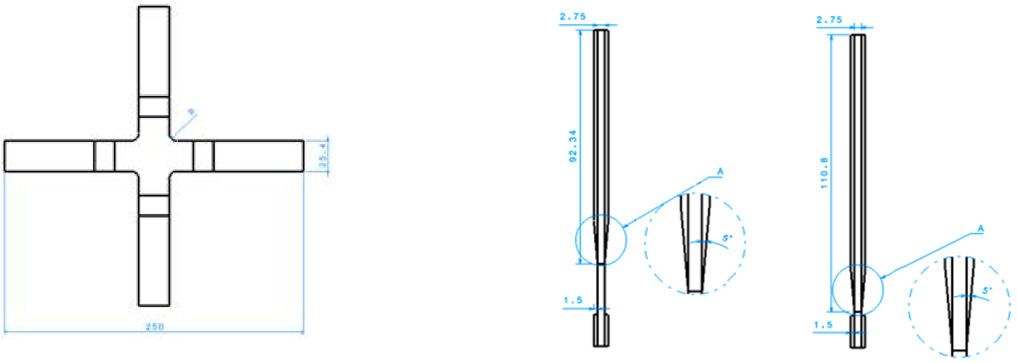
3. Design of the specimen

3.1 Model

To avoid premature failure of the specimen outside the zone of interest it is necessary to perform a preliminary design of the cruciform specimen to be tested under tension-tension biaxial load. There exists a considerable amount of studies in literature about cruciform specimens [6-11], both for metals and fibre reinforced laminates, though it is not easy to find a specific design for unidirectional laminates to be subjected to transverse loads (i.e. 90º specimens).

The design of the specimen suitable for biaxial transverse load testing is based on a main objective: it must assure that the failure takes place at the central zone of the specimen (the area really subjected to biaxial load); besides, stresses at this zone should be uniform and cover a wide enough area. Additionally, geometrical features should not promote or increase undesirable effects such as stress concentrations.

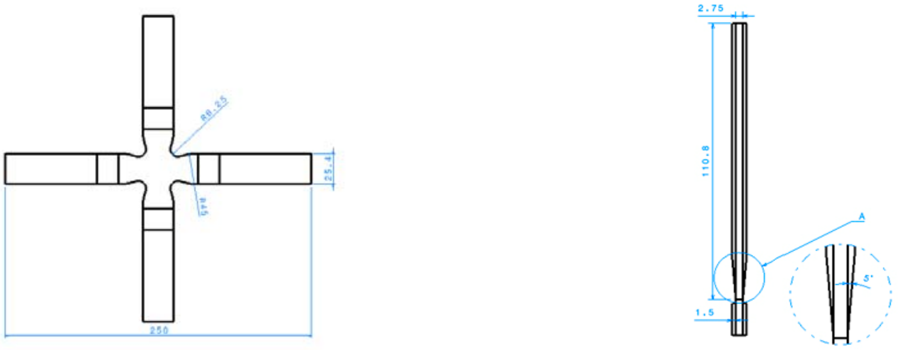
Following the aforementioned premises four different geometries have been considered until the present moment (specimen types A, B, C and D, Fig. 4) and Finite Element models designed based on them in order to analyze the stress state occurring when subjecting them to tension-tension biaxial load.



Types A (R=1.5 mm), B (R=6.25 mm), C (R=19.97 mm)

Type A

Types B and C



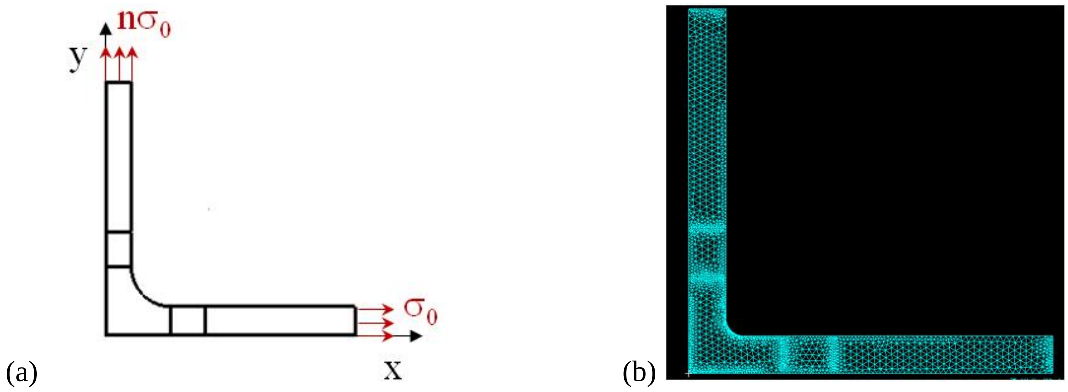
Type D

Type D

Figure. 4. Types of specimen considered.

The four geometries chosen are composed by a main body, which represents the cruciform specimen itself manufactured from a unidirectional laminate, and 8 reinforcing tabs (one at each side of each “arm” of the specimen). These tabs pursue a double function: first, the assurance of the adequate fixing of the specimen to the machine grips during testing, and second, a thickness increase of the specimen out of the zone of interest, in order to promote failure initiation at the biaxial loading (central) zone of the specimen. The first three types of specimen use just one curvature radius defining the central zone (R=1.5 mm, R=6.25 mm, R=19.97 mm, respectively), whereas the fourth one uses two different radii. Geometrical specifications of the four specimens are detailed in Fig. 4. It is important to point out that latter manufacturing process of the specimens also needs to be considered in the final design of the specimen. In this particular case, the 90º orientation of the laminate is one of the critical features to be taken into account. The unidirectional laminate considered corresponds to a carbon-epoxy system (AS4/3501-6) whereas tabs are thought to be manufactured from glass fibre +45/-45 fabric.

Due to the symmetry shown by the four specimens considered only an eighth has been considered for the FEM analyses, by using the adequate boundary conditions. Different loading cases have been considered, all of them corresponding to a fixed value of the external tension σ_0 applied at the edge of the horizontal arm of the specimen (x axis) and different portions of σ_0 (characterized by a coefficient n=0.25, 0.5, 0.75 and 1) at the edge of the vertical one (y axis). σ_0 has been taken equal to the tensile strength associated to the laminate considered, 48 MPa in this case. The scheme of the problem described can be consulted in Fig. 5a for type C specimen, where a view of the mesh employed can also be observed (Fig. 5b).



(a) (b)

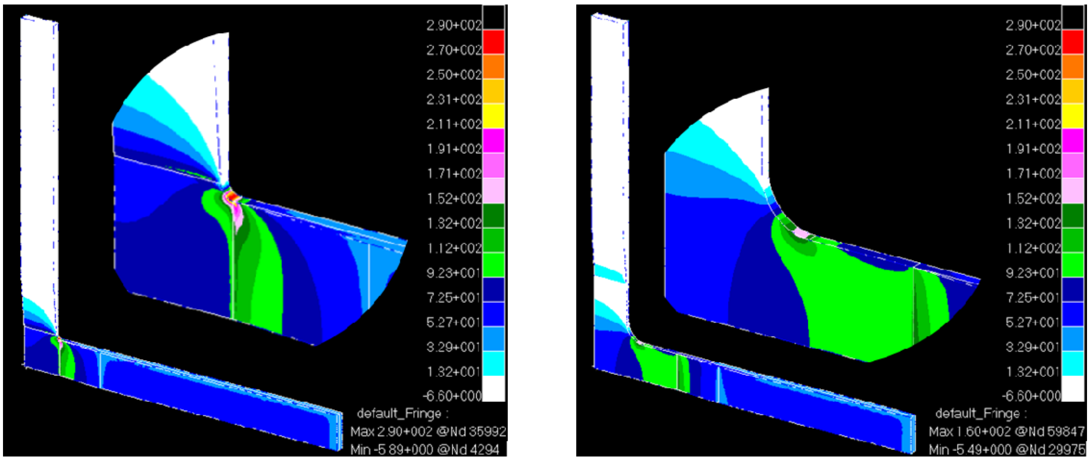
Figure. 5. Example of a) geometrical model, b) FEM model. (Type C specimen)

3.2 Results

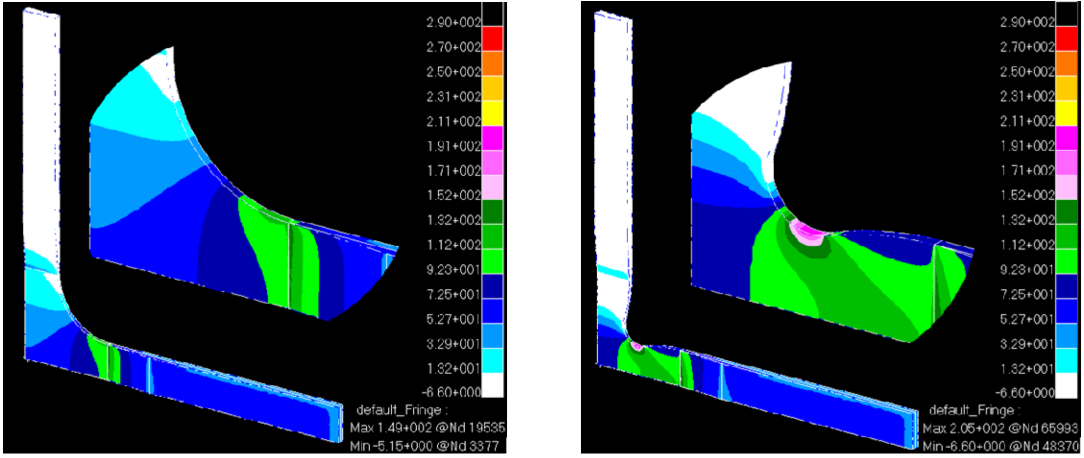
The stress state associated to the different loading cases considered has been analyzed for each type of specimen. Focusing our attention on the tension-tension (T-T) case (n=1) the results show that σ_{xx} and σ_{yy} are the dominant stresses, showing in fact identical distributions though reflected due to symmetry along the 45º line initiating at the centre of the specimen.

σ_{xx} distribution for the four types of specimens considered are shown in Fig. 6, where a zoom of the central zone is included. For comparison purposes the same scale of representation has been used for all cases, extending from the maximum tensile value obtained (occurring at type A specimen) to the maximum compressive value (occurring at type D specimen). Stress concentrations are found for the four specimens at the free edge, the maximum value occurring for type B (290 MPa) followed by types D (205 MPa), A (160 MPa) and C (149 MPa). Tensile values are found at all points of the central zone as well as the horizontal arm of the specimens, whereas very small (almost negligible) compressive values appear at the vertical arm of the specimens.

Looking at type A specimen, a uniform σ_{xx} distribution is detected in its central zone though its value being just a 25% of the maximun tension encountered at the free edge. Besides, higher tensions are also vertically distibuted along the horizontal tab border, which would eventually lead to a failure out of the biaxial zone. The use of a higher curvature radius, type B specimen, reduces the difference existing between σ_{xx} values at the central zone and the maximum σ_{xx} at the free edge, though still being quite significant (43%). Higher tensions are also distibuted vertically along the horizontal tab border but extending to part of the central zone in this case.



Type A Type B



Type C Type D

Figure. 6. σ_{xx} distribution (T-T case).

With reference to σ_{xx} distribution associated to type C specimen, this is very similar to that shown by type B though the stress concentration, and thus the maximum tensile value, moves towards the horizonatal arm. Besides, the stress value at the centre of the specimen is only a 36% of this maximun. Finally, type D specimen presents a relation between σ_{xx} value associated to the centre of the specimen and maximum σ_{xx} similar to that already encountered for type B specimen (42%); high σ_{xx} values are also found at the biaxial zone though do not reaching the centre of the specimen. The described results lead to the discarding of types A and C specimens as suitable designs for tension-tension biaxial transverse testing. Additional results obtained for types B and D specimens associated to the remaining loading cases (n=0.25, 0.5, 0.75) point to type D as the best design, since, for those cases and excepting the stress concentration, the aforementioned high σ_{xx} lateral area, occupies the whole biaxial zone. Anyway, the difference between the stress concentration at the free edge and σ_{xx} value at the centre of the specimen is still very remarkable, leading then to think in a necessary modification of type D geometry. This geometrical modification is shown in Fig. 7 (type E specimen) and consists in limiting the reduced thickness area just to the central zone of the specimen. This modification, at present under study and implying a change in the manufacturing process, is intended to minimize the effect of the stress concentration at the free edge and promote failure intitiation a the central zone.

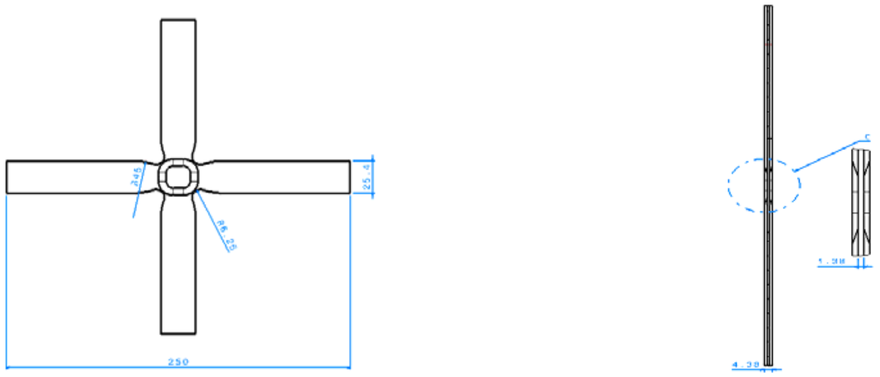


Figure 7. Type E specimen.

4 Preliminary results

Bearing in mind that the specimens have the fiber oriented perpendicularly to the testing plane, and thus a transverse failure is expected, the estimated failure load is moderate (around 3000N for the specimen arm dimensions of 25.4mm × 2.75 mm). Special care is then necessary to asses an accurate behavior of the fixture at moderate loads, where small clearances may make both axes not to develop the same loading level. It is also evident that this kind of devices only guarantees a displacement ratio, which will give the same load ratio only when testing an isotropic material. Notice that if the specimen had different stiffnesses in both in-plane directions, as would be the case of having the fiber aligned with one loading directions, the equal displacement ratio given by the fixture would give rise to a very different loading ratios in both directions, proportional to their stiffnesses ratio (E_{11}/E_{22}). Preliminary tension-tension tests using an aluminum test specimen are shown in Fig. 8 where the values of normal strains measured at the arms of the cruciform specimen are plotted *vs* the total vertical load applied at the top part of the device.

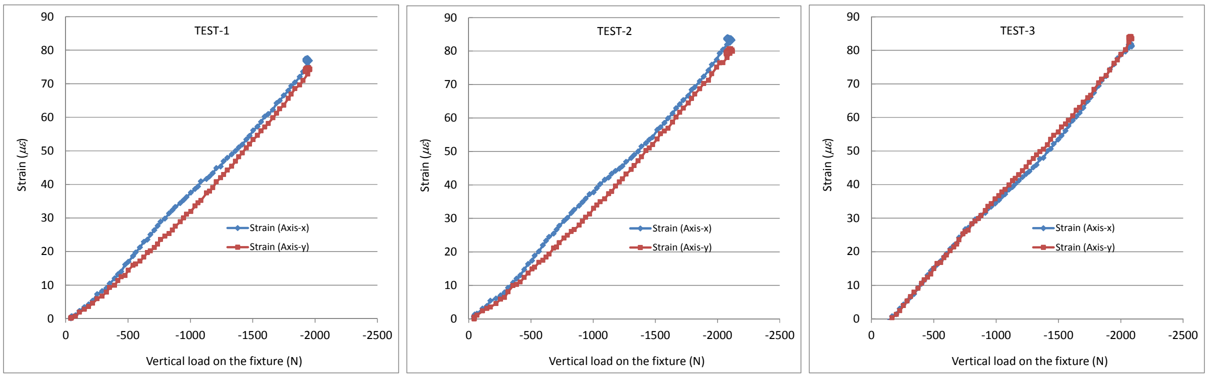


Figure 8. Preliminary results of a tension-tension cruciform specimen at moderate loads.

The results of three different tests show a good repeatability and accuracy with a reasonably constant strain ratio 1:1 in both axes at moderate loads.

Conclussions

A fixture for biaxial testing has been designed and manufactured allowing tension-tension, compression-compression and tension-compression to be carried out with a variable loading ratio. Preliminary experimental monitoring of the load ratios has been successfully checked even at moderate loads (<2000 N). The basic geometrical features of a cruciform specimen, suitable for transverse biaxial testing, have been established based on the conclusions derived from several FEM models.

Acknowledgements

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