Development of a biaxial tensile device in the plane for monotonic mechanical tests and cruciform specimens

Desenvolvimento de um dispositivo de tração biaxial no plano para ensaios mecânicos monotônicos e de corpos de prova cruciformes

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ABSTRACT
This work deals with the development of a coupling device for performing biaxial tensile tests with cruciform specimens. For the project, a methodology consisting of six phases was used, that is, informational design, conceptual design, preliminary design, detailed design, manufacturing and testing. Thus, the design and sizing of two coupling devices was carried out, and the model chosen for manufacturing was based on that proposed by Rohr, Harwick, and Nahme. In addition, the design, sizing and fabrication of cruciform specimens in MDF and PS, with geometry similar to that of ISO 16842:2014, was also carried out for the device validation tests. The tests were divided into 1) device stiffness

test and 2) specimen deformation test for equibiaxial testing. The proposed test setup was designed to test cruciform specimens with dimensions up to 350 x 350 x 4 mm and support a maximum vertical load of up to 30 kN.

Keywords: Biaxial testing, Cruciform specimens, Coupling Device, Tensile properties

1 INTRODUCTION

Biaxial tests are employed for the study of several engineering materials, such as fiber-reinforced composites, sheet metal, elastomers, or polymers, emerging as a primary technique for the characterization of anisotropic, hyperelastic, and heterogeneous materials. The in-plane biaxial test allows the investigation of mechanical responses for different stress states, providing considerably important information for a prior identification of the material behavior when loaded, by describing more accurately the local anisotropic properties [1].

Among biaxial loading methods, four are highlighted, which are the bubble, punch, Marciniak and cruciform methods. Amid these, in-plane loading with a cruciform specimen is the most widely used for studying the changes in stress curves and linear and nonlinear stress states, because unlike the other methods, flexural and/or frictional forces are not present [2].

Cruciform specimen design has become one of the most challenging aspects for biaxial testing. Several studies were conducted in order to find the best geometry of the specimen, which could guarantee stress-strain homogeneity in its central area. One of the first investigations regarding the geometry of the cruciform specimen was performed by SHIRATORI and IKEGAMI [3] using a specimen with the arms area smaller than the central area to analyze the nominal stress distribution in the plastic deformation field. PASCOE and VILLIERS [4] proposed a specimen with reduced thickness of the central section on both sides in the form of spherical caps aiming to avoid the rupture of the arms, submitting it to cyclic tensile loading and biaxial compression. HAYHURST [5] proposed a geometry with uniform reduction in the thickness of the central area, aiming to enable a greater deformation and, consequently, rupture at that place, and having grooves in the arms in order to avoid stress concentration in the contours between the arms, which made the stress distribution in the central area larger and more homogeneous. MERKLEIN and BIASSUTI [6] performed tests on specimens also with reduced thickness in the central area to estimate the standard deviation of stress and strain in the region transversal to the central area.

However, the design of these specimens is more complex and increases the manufacturing costs, as machining is needed to reduce the thickness of the central area. KUWABARA, IKEDA and KURODA [7] then presented a uniform specimen with grooves in the arms aiming to better understand the elastic-plastic deformation behavior of a cold-rolled steel sheet with low carbon content. SHIMAMOTO, SHIMOMURA and NAM [8] performed static and dynamic biaxial tests on specimens with a hole in the center of the test area to act as a stress concentrator and thus evaluate the behavior of the stress field around the hole.

In the works mentioned above, it could be noticed that, regardless of the geometry proposed by the researchers, with or without reduction of the thickness of the central area, all presented difficulties to generate a uniform stress field in the central area of the specimen. Therefore, optimization techniques of the specimen were also employed [9-12] to establish criteria to improve test data acquisition. HANABUSA, TAKIZAWA and KUWABARA [12] proposed to analyze the geometry parameters of the specimen and to find the best position to perform the deformation measurement in the test area, aiming to reduce stress field measurement errors. The study served as a model for the creation of the ISO 16842:2014 standard.

It should be noted that the effectiveness of these investigations also depends on the type of configuration used to perform the biaxial tests. Several types of equipment have already been developed to generate biaxial loading, and these have been divided into two groups: standalone machines and devices to be coupled to universal machines. The autonomous machines developed will have different formats and force application systems, and may have one [13], two [14], or four hydraulic actuators [3, 4, 8, 9, 15], spindle actuators [6, 10, 16], electromechanical [17], manual [18, 19], and a dead weight configuration [5].

To reduce the cost associated with building stand-alone test machines, coupling devices have been designed for use in universal machines. The first device presented for this purpose was developed by FERRON and MAKINDE [20], and is composed by a set of binary links and rotation joints, forming a pantographic mechanism that, when pulled in the vertical direction by a uniaxial machine, provides a second movement, in the horizontal direction. TERRIAULT, SETTOUANE and BRAILOVSKI [21] presented a similar device, with the difference that, while the first [20] works with the distance between the two fixation points on the testing machine, the second [21] works with the approximation, simulating a compression test and, in this case, the mechanism is responsible for providing tension in both axes. In the device developed by ROHR, HARWICK and NAHME [22], a remarkable simplification of the number of interconnections was obtained by the use of linear guides. These authors [22] also proposed a modification to perform non-equibiaxial tests by changing the length of the bars on one of the axes. Later, devices similar to this one appeared, such as the one developed by BARROSO et al., [23] and by MARCELO and ANDRÉS [24]. VEZÉR and MAJOR [25] presented a device with planar movement, composed of a system of bars and cylindrical joints to perform monotonic and cyclic tests. ZHAO et al., [2] developed a device capable of promoting variable load ratios through different tilt angles (45º, 60º and 90º) of a set of interchangeable wedges. The use of wedges with a 90º angle also allows obtaining a flat deformation condition in the center of the specimen in tests with loading rates of 1:0 or 0:1. HANABUSA [26] and MEDELLÍN and LA PEÑA [27], dedicated themselves primarily to the design of easy to manufacture and assemble low-cost devices.

However, these devices only allow tests with the same loading rate in both axes to be performed, which is a disadvantage compared to autonomous machines. Also, when it is possible to change the load distribution, partial disassembly of the device is necessary, making it difficult to perform subsequent tests. Other researchers, managed to present a device that could perform tests with different loads on each axis and promote this change more efficiently. BRIEU, DIANI and BHATNAGAR [28] developed a device, later used for the characterization of polymeric composite materials [29], that allows the change by adjusting two oblique bars that pass through sliding bearings, originating a different displacement in one of the axes.

Therefore, although different specimen geometries and load transmission equipment were proposed, the nature of the material and the test setup adopted may dictate specific restrictions in the test procedure.

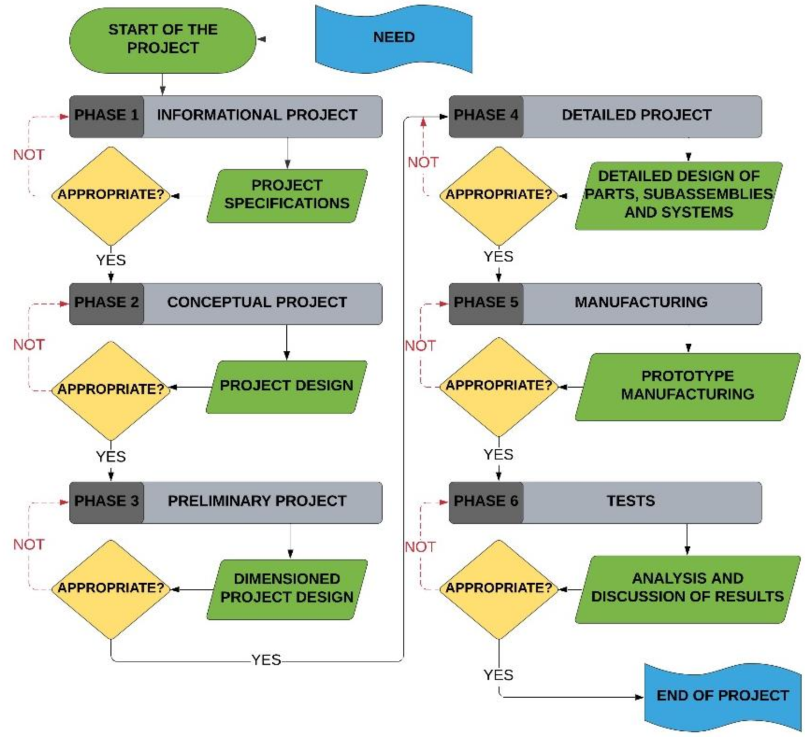
Thus, the main objective of the present work is to develop and test an in-plane biaxial tensile coupling device for monotonic mechanical tests, starting from the premise of adopting solutions from devices found in the literature while overcoming their limitations, in order to produce comparable results for different test strategies. In addition, the design and fabrication of the cruciform specimens to perform these tests are presented, along with additional discussions of device stiffness and specimen deformation.

2 METHODS

The biaxial tensile test, unlike other tests already established in the scientific environment, such as uniaxial tensile tests, bending and uniaxial compression tests, is still under development, especially with respect to the results that can be extracted from the test, in view of the fact that few research centers in the world are using it in their scientific work.

The need for developing the coupling device to perform biaxial tensile tests was to analyze anisotropic and isotropic materials, which will be subject to loading in more than one direction. Thus, the design of the equipment began, adopting a methodology divided into six phases, as shown in Figure 1.

Figure 1: Flowchart



- Informational Project: In-depth analysis of the design and operational characteristics and limitations of the devices present in the literature;
- Conceptual Project: Visualization of ideas from diagrams, sketches, and schematic drawings to better meet the project's objective;
- Preliminary Project: Dimensioning of all the parts that compose the project, specifying the materials that will be used in the manufacturing stage.
- Detailed Project: Drawings and parts, subsets and assemblies, presenting all the technical information for the manufacture and assembly of the parts involved in the project;

- Construction: Stage of manufacturing the components, for the assembly of the full-size prototype;
- Testing: Performing the tests and analyzing the results for the validation of the device.

For the development of the device, we used the design and simulation software Autodesk Inventor 2017 Student Edition, where detailed drawings and static load simulation of each part was performed.

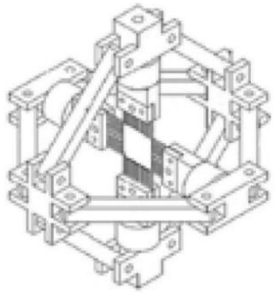
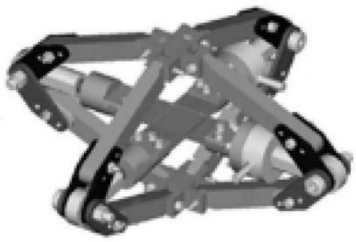
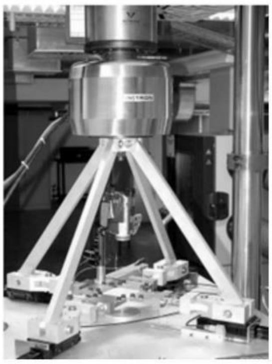
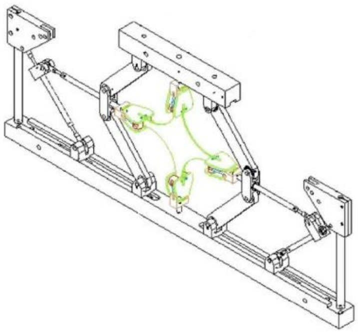
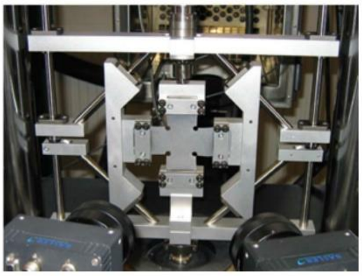
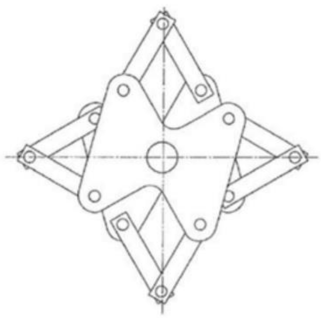
The manufacturing of the parts and the tests took place at the Machine Tools Laboratory of the Federal Institute of Science and Technology of Paraíba (IFPB), at the Cajazeiras Campus.

3 DEVICE DESIGN AND MANUFACTURE

In this section, we show the design of the coupling device, with all the subsystems that compose it, as well as its operation. In addition, we detail the evolution of the project and the reasons for the selection of the final device. Finally, we present its main features, dimensions, and workload.

The design phase of the device initially required a thorough literature review about different test configurations to perform the biaxial tests with cruciform specimens [30]. Thus, several subsystems that make up each mechanism were analyzed and those that best met the project's specifications were chosen. Table 1 shows the devices explored for the project.

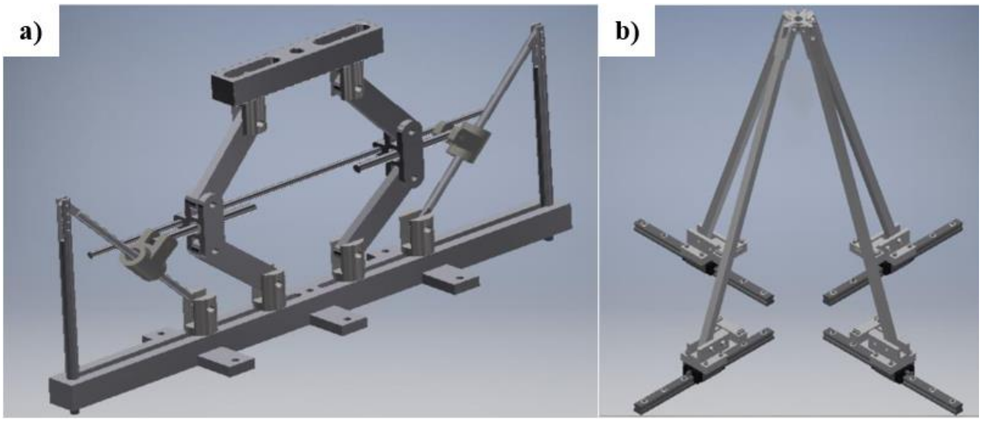
Table 1: Coupling device design variables

Ferron e Makinde, 1988.	Terriault, Settouane e Brailovski, 2003.	Rohr, Harwick e Nahme, 2005.
		
( ) Load change flexibility	( ) Load change flexibility	(x) Load change flexibility
Brieu, Diani e Bhatnagar, 2007.	**Vezér e Major, 2008.**	**Hanabusa, 2014.**
		
(x) Load change flexibility	( ) Load change flexibility	( ) Load change flexibility

Considering the presented table, the following factors were evaluated for the choice of the device, such as 1) testing several types of materials; 2) using available machinery; 3) applying different loads in each axis; 4) performing simultaneous movement of the four arms of the specimen; 5) manufacturing process and 6) interchangeability.

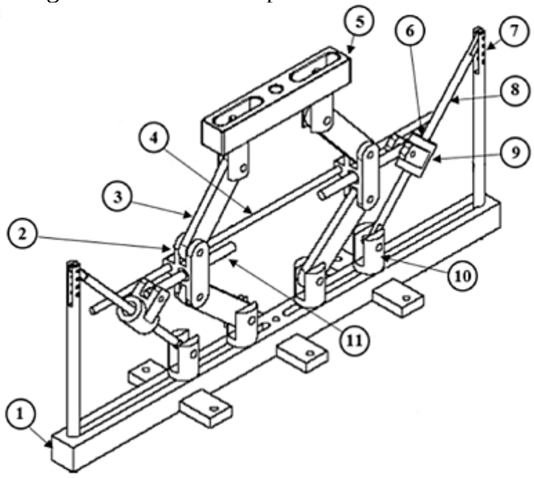
The only ones that fitted the specifications of the project were those presented by BRIEU, DIANI and BHATNAGAR [29] and ROHR, HARWICK and NAHME [9]. Then, from the analysis of the authors' works, drawings of the devices [31, 32] were made for a better understanding of the subsystems that compose them and the movement of the mechanisms, initiating the conceptual project phase. Figure 2 shows the schematic representation of the devices.

Figure 2: Schematic representation of the mechanism proposed by (a) Brieu, Diani and Bhatnagar and (b) Rohr, Harwick and Nahme



The device selected to be the basis of the research project was the one presented by Brieu, Diani and Bhatnagar, due to the fact that it allows changes in the load ratios in a more efficient way. Initially, it was divided into four subsystems in order to facilitate its design, i.e., machine mounting base, shaft displacement, load distribution, and specimen clamping. Figure 3 shows the mechanism with its respective components.

Figure 3: Schematic representation of the device proposed by Brieu, Diani and Bhatnagar



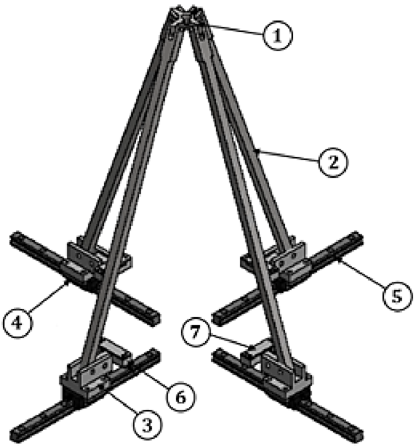
Item No.	Description	Qty.
1	Fixed crosshead	1
2	Horizontal bar guide	2
3	Link bar	4
4	Alignment bar	1
5	Moving crosshead	1
6	Linear bearing	4
7	Vertical support	2
8	Inclined bar	2
9	Inclined bar guide	2
10	Support	6
11	Horizontal bar	2

For the design, a working load of 30 kN was selected, which was sufficient for the rupture of the materials chosen for making the specimens. Then, the simulation of static loading was performed for each component and the assembly test of each subsystem for interference analysis.

However, during the manufacturing phase of the device, it was not possible to perform certain machining steps, which made it impossible to complete the project. Therefore, it became more feasible to design a new device, modelled on the one presented by Rohr, Harwick and Nahme, consisting of a symmetrical system with rotation joints.

The new coupling device, like the one by Brieu, Diani, and Bhatnagar, was divided into four subsystems: machine mounting base, shaft displacement, load distribution, and specimen clamping. Figure 4 shows the mechanism with its components listed and described in the table with their respective dimensions.

Figure 4: Schematic representation of the device proposed by Rohr, Harwick and Nahme.

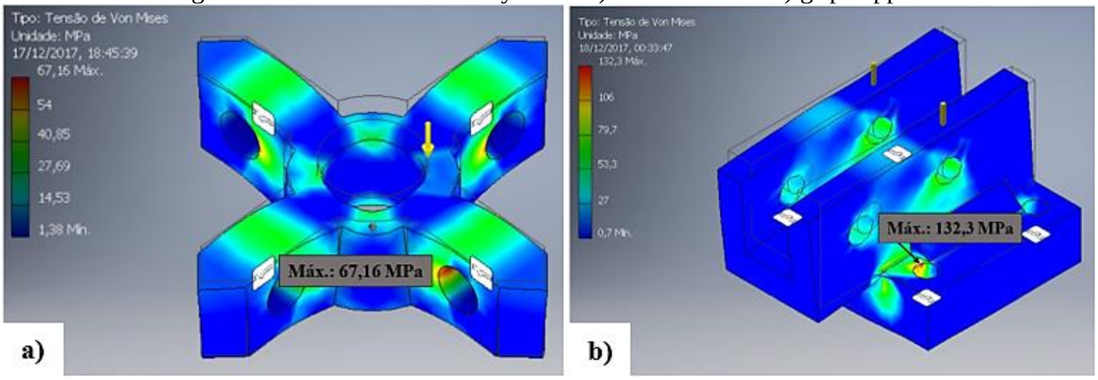


Item No.	Description	Qty.	Dimension (mm)
1	Moving crosshead	1	62 x 62 x 19,05
2	Bar	4	770 x 28 x 19,05
3	Grip	4	62,5 x 80 x 19
4	Specimen clamp	4	26 x 80 x 6,35
5	Guide support	4	88 x 76 x 55
6	Linear guide	4	-
7	Linear rail	4	400 x 25 x 22

The machine mounting base subsystem is composed of a cross-shaped piece fixed to the uniaxial machine table. The axis displacement subsystem, consisting of the bars (2), linear guides (6), and the supports for attaching the bars to the guides' skids mounted on it (5). The other end of the bars are connected to the load distribution subsystem, composed of a part (1) attached to the machine actuator, responsible for transforming the compression force into four tensile forces, imposed to the specimen by the specimen clamping subsystem.

The simulation analysis of the stress distribution in each component was determinant for the selection of the material used in the manufacturing. Sizing of the device followed the same criteria base adopted for the mechanism in Figure 2(a). Thus, the maximum working load stipulated was 30 kN. Figure 5 shows the Finite Element Method (FEM) load analysis for the crosshead (Fig. 5(a)) and the sliding support of the clamping jaw (Fig. 5(b)), parts with high level of mechanical stress. For the crosshead, a part fixed to the universal machine actuator, a 30 kN load was applied in the center with, obtaining a maximum stress of 67.16 MPa. In the support simulation, however, a load of 20 kN was used, because the main force was distributed among the four axis displacement bars. In this case, the maximum stress obtained was 132.3 MPa.

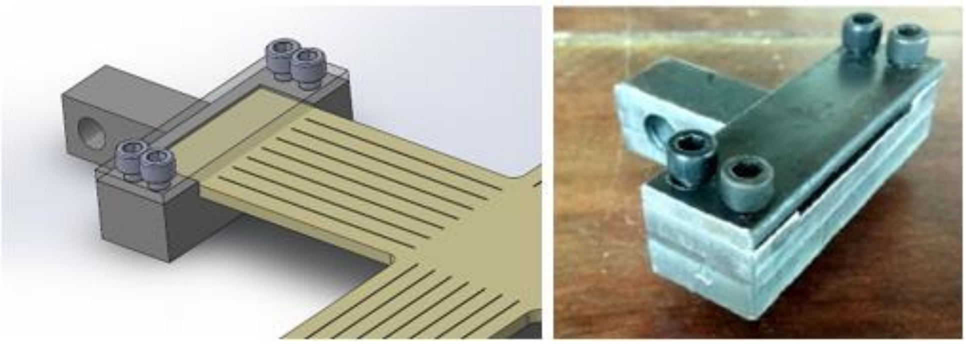
Figure 5: Maximum stress analysis for a) crosshead and b) grip support



After analyzing the stress distribution of the components, SAE 1020 steel was chosen for the manufacture of the mechanism, due to the maximum stress obtained being below the yield strength of the material. The model selected to compose the linear guide system was the DFH25A, with a capacity of approximately 24.5 kN.

The selection of the kind of gripper that will compose the clamping subsystem of the specimen is a basic requirement for biaxial tests because it is responsible for establishing the mechanical connection between the specimen and the testing machine, directly influencing the reliability and precision of the results. Therefore, a new clamping jaw model was proposed [31], aiming to facilitate its manufacture and the adjustment of the specimen, ensuring good adhesion. The fixation is generated by friction, due to the compression of two parts, clamp (Fig. 6 (a)) and clamping block (Fig. 6 (b)). The union between the two parts is promoted by four socket head cap screws, with ¼" hexagonal BSW, which allows a free adjustment between the clamps. The load capacity selected for the clamps was 20 kN, the same load established for the parts that compose the shaft displacement subsystem.

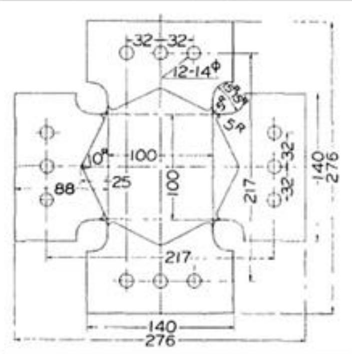
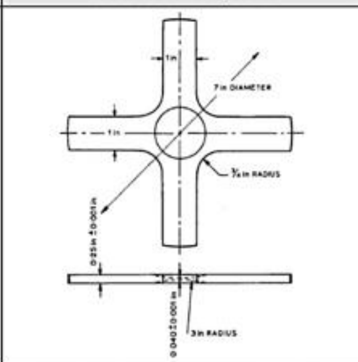
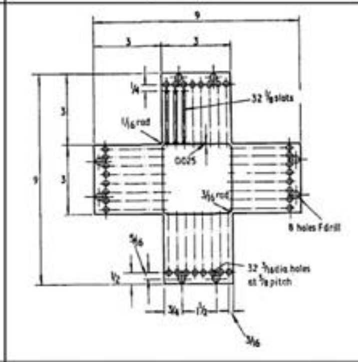
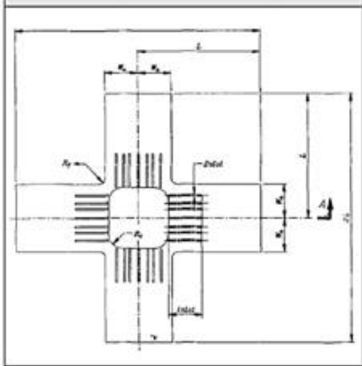
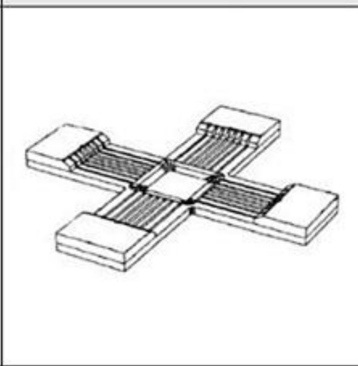
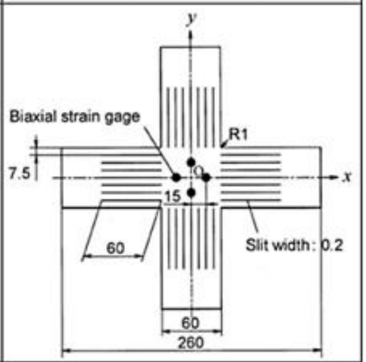
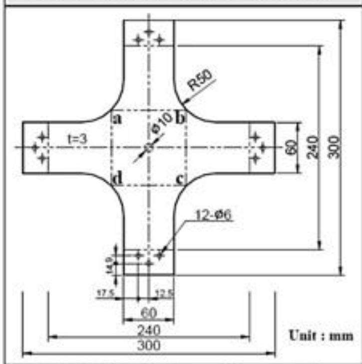
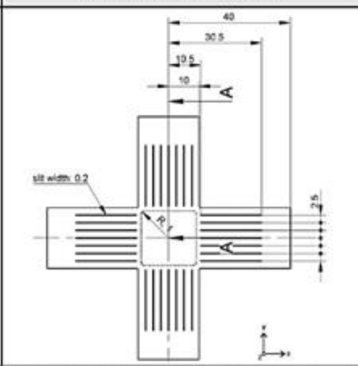
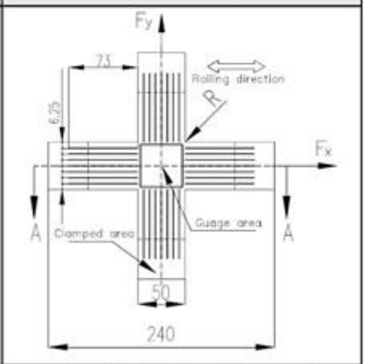
Figure 6: New specimen clamping clamp model.



4 SPECIMEN DESIGN AND FABRICATION

One of the most challenging aspects during biaxial test characterization is the design of the cruciform specimen, as the relationship between biaxial stresses is directly linked to its geometry. When designing it, it is of great importance to consider two factors in the design, i.e., the homogeneity of stress-strain within the central area, which enables stress determinations with the smallest possible deviation, and to avoid deformation and stress concentration in other regions of the specimen [17]. Table 2 presents the main geometries found in the literature, giving special attention to the principles cited.

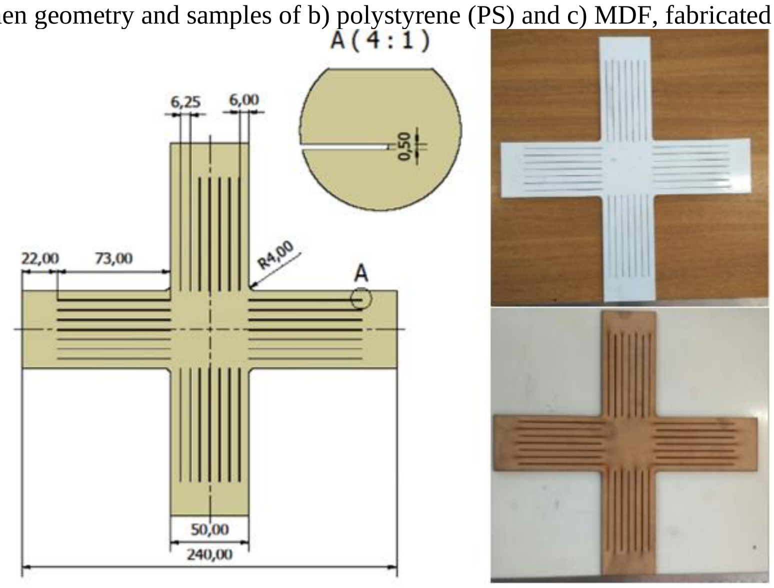
Table 2: Test specimen design variables

Shiratori e Ikegami, 1967.	Pascoe e Villiers, 1967.	Hayhurst, 1973.
		
( ) With slit ( ) reduction of the central area	( ) With slit (x) reduction of the central area	(x) With slit (x) reduction of the central area
Makinde, Thibodeau e Neale, 1992.	**Demmerle e Boehler, 1993.**	**Kuwabara, Ikeda e Kuroda, 1998.**
		
(x) With slit (x) reduction of the central area	(x) With slit (x) reduction of the central area	(x) With slit ( ) reduction of the central area
Shimamoto, Shimomura e Nam, 2003.	**Merklein e Biasutti, 2013.**	**Xiao *et al.*, 2016.**
		
( ) With slit ( ) reduction of the central area	(x) With slit (x) reduction of the central area	(x) With slit (x) reduction of the central area

As a result, it was decided to employ a geometry similar to the one presented in ISO 16842:2014, due to the fact that it has a design with a higher level of optimization. The dimensions of the geometry were taken from the work presented by XIAO et al., [17], without reducing the thickness of the central area. Thus, a specimen with the geometry illustrated in Figure 7 was manufactured.

The material selected for the fabrication of the specimen used for the specimen deformation tests was polystyrene (PS). For the device stiffness test, the selected material was MDF, because its tensile strength is higher than that of polystyrene. During manufacturing, the material was laser cut to generate the grooves in the arms of the specimen, which are essential to reduce the effect of shear stress, something that would not be possible by conventional machining.

Figure 7: (a) Specimen geometry and samples of b) polystyrene (PS) and c) MDF, fabricated for testing.



5 RESULTS AND DISCUSSION

First, device stiffness and specimen deformation were determined by biaxial tensile testing for further analysis and device validation. To perform the tests, the device was coupled to a hydraulic press with a capacity of 150 t, operating under uniaxial compressive loads.

Coupling device stiffness test

To determine the stiffness of the device and ensure that no failures occur in future tests, the mechanism was submitted to the maximum vertical load stipulated in the design. The test specimen was made of MDF, 4 mm thick. Figure 8 shows the sample mounted on the coupling device.

Figure 8: Biaxial tensile test setup for device stiffness testing.

When the stipulated load of 30 kN was reached, disassembly and dimensional inspection of all components was performed. No visible deformation was detected. Thus, the test continued until rupture of the specimen, which occurred with a load of approximately 55 kN.

Testing the deformation of the test specimen

After performing the device stiffness test, the deformation of a polystyrene specimen, also 4 mm thick, was performed. Monitoring of the deformation of the central area of the specimen was performed by capturing images, taken at short load application intervals of 0.5 kN. The stretches of the sample arms were analyzed with the aid of a 300 mm capacity caliper with a resolution of 0.02 mm, as shown in Figure 9. Importantly, for measuring the strain during the tests, a technique of printing a checkered field in the central area was used (Fig. 10(a)), similar to the work of Rohr, Harwick, and Nahme.

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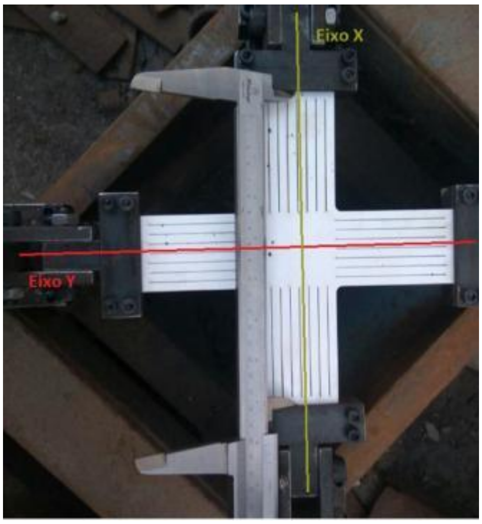
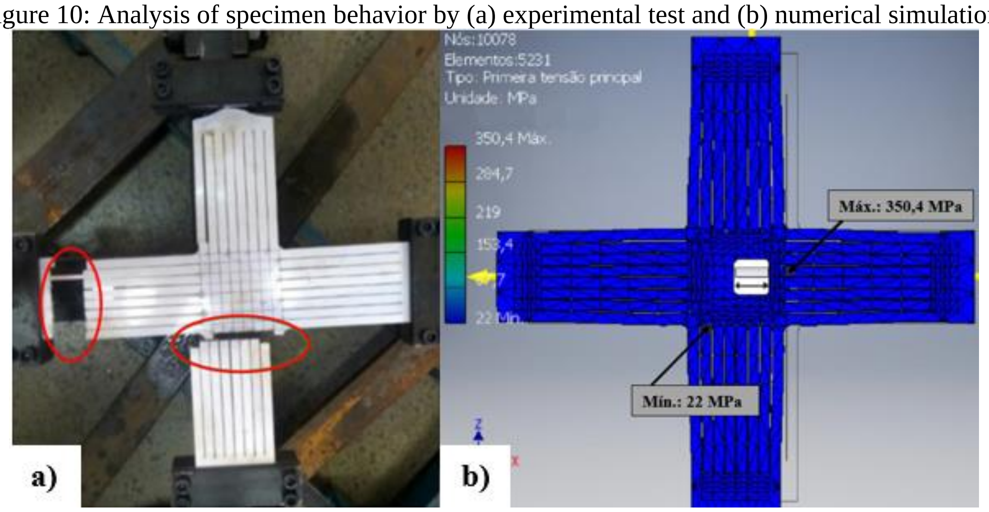
Figure 9: Demonstration of the strain measurement method.



No apparent deformation in the central area prior to rupture of the specimen, which occurred before the applied load reached 1.5 kN, was observed. Rupture occurred at the intercession of the arm with the center of the specimen and at the ends of the arms, near the clamping jaw (Fig. 10(a)). The rupture at the intersection of the arm with the center of the specimen may have occurred due to the uniformity of the specimen thickness and the number of grooves present in the arm. It is important to emphasize that the fracture in this region matches the one with the highest stress presented in the finite element method analysis performed for the specimen (Fig. 10 (b)). The rupture in the contact region of the specimen arm with the clamping jaw may have been due to a possible accumulation of stress generated when tightening the clamp to the jaw.

Figure 10: Analysis of specimen behavior by (a) experimental test and (b) numerical simulation.



For a quantitative investigation of the actual strain level imposed, stretching measurements were performed before the sample rupture, at three different moments.

Figure 11 shows the relationship between the actual strain rate obtained in the test (ε_x: ε_y) and the theoretical strain rate (1: 1), represented by the red line, for equibiaxial tests.

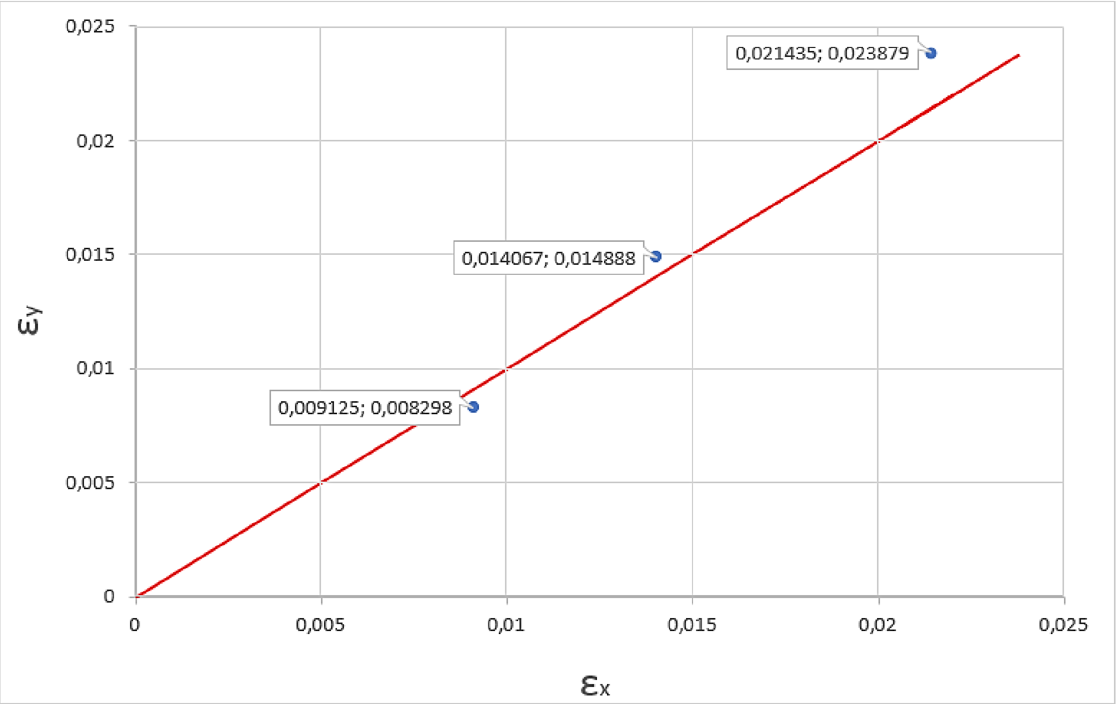
The actual strain values were obtained from equations 1 and 2.

$$\varepsilon_n = \frac{\Delta l}{l_o} \tag{1}$$

$$\varepsilon_r = \ln(1 + \varepsilon_n) \tag{2}$$

Where ε_n and ε_r are the nominal and actual strains, respectively, and Δl and l_o are the initial displacement and length of the specimen

Figure 11: Graph of the real deformation.



Analysis of the graph indicates that the biaxial strain ratio obtained from the test was close to the ideal. The standard deviation was calculated to allow future comparisons with the analytical performance criteria, presenting a value close to 10^{-3} mm, which shows a good reproducibility of the biaxial traction test.

6 CONCLUSIONS

A biaxial mechanical testing device with cruciform specimen was developed based on the mechanism presented by Rohr, Harwick and Nahme to be coupled to a universal tensile testing machine. The developed device can test specimens with dimensions up to 350 mm in length and thicknesses between 1 mm and 4 mm, and withstands a maximum vertical load of 30 kN. The tests demonstrate that the device has a good reproducibility for equibiaxial tests, with a strain rate (1:1).

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