REVISTA Mundi
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INSTITUTO FEDERAL
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# DEVELOPMENT AND TESTING OF A NEW COUPLING DEVICE FOR PERFORMING IN-PLANE BIAXIAL TENSILE TESTS WITH CRUCIFORM SPECIMENS

## DESENVOLVIMENTO E TESTE DE UM NOVO DISPOSITIVO DE ACOPLAMENTO PARA REALIZAÇÃO DE ENSAIOS DE TRAÇÃO BIAXIAL NO PLANO COM CORPOS DE PROVA CRUCIFORMES

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**Abstract:** Biaxial tensile tests provide more reliable information regarding the analysis of damage initiation and failure mechanisms, when compared to uniaxial tensile tests, for the characterization of materials, such as anisotropic, hyperelastic and heterogeneous ones, as they approximate conditions more realistic, which will be subject in practice. One of the most referred approaches in the literature to form the test configuration is the development of devices to be coupled in uniaxial machines. Therefore, analyzing the current needs, for the constant improvement of the test, a new coupling device to carry out biaxial tensile tests in the plane with cruciform specimens, was proposed in this work. The design methodology used includes the informational, conceptual, preliminary, detailed, and manufacturing and testing design phases. The numerical-experimental model, Finite Element Method (FEM), was used for the stress analysis of the mechanism. In addition, a functional prototype, printed in 3D, was developed to obtain a full-scale model in order to facilitate the analysis of its functionality. The device allows carrying out tests with variations in the loading rates between the two drive axles, in addition to being able to generate a state of plane deformation in the center of the specimen. The mechanism presents a reduction of components and a simplification in the manufacture and construction, in comparison with those found in the literature that allow test configurations similar to those that will be presented in this work. Due to the innovative character of this coupling device, the project generated a patent deposit.

**Keywords:** Biaxial, Cruciform, Device, Tensile.

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**Resumo:** Os ensaios de tração biaxial fornecem informações mais confiáveis quanto a análise de início do dano e dos mecanismos de falha, quando comparados com os ensaios de tração uniaxial, para a caracterização de materiais, como os anisotrópicos, hiperelásticos e heterogêneos, pois os aproximam de condições mais realistas, as quais estarão sujeitos na prática. Uma das abordagens mais referidas na literatura para formar a configuração do teste é o desenvolvimento de dispositivos para serem acoplados em máquinas uniaxiais. Portanto, analisando as necessidades atuais, para o constante aperfeiçoamento do ensaio, foi proposto neste trabalho um novo dispositivo de acoplamento para realização de ensaios de tração biaxial no plano com corpos de prova cruciformes. A metodologia de projeto utilizada inclui as fases de projeto informacional, conceitual, preliminar, detalhado e de fabricação e teste. O modelo numérico-experimental, Método de Elementos Finitos (MEF), foi utilizado para a análise de tensão do mecanismo. Além disso, um protótipo funcional, impresso em 3D, foi desenvolvido para obter um modelo em escala real de modo a facilitar a análise de sua funcionalidade. O dispositivo permite a realização de ensaios com variações nas taxas de carregamento entre os dois eixos de tração, além de ser possível gerar um estado de deformação plana no centro do corpo de prova. O mecanismo apresenta uma redução de componentes e uma simplificação na fabricação e construção, em comparação com os encontrados na literatura que permitem configurações de teste semelhantes às que serão apresentadas neste trabalho. Devido ao caráter inovador deste dispositivo de acoplamento, o projeto gerou um depósito de patente.

**Palabras-clave**: Biaxial, Cruciforme, Dispositivo, Tração.

# 1. INTRODUCTION

Biaxial tests arose from the need to obtain more realistic predictions of the mechanical behavior of certain types of engineering materials, such as anisotropic, heterogeneous and hyperelastic materials, which, under complex multiaxial stresses, present different responsed from those provided by standard tests, such as of uniaxial tensile. Due to its ability to provide more reliable information on the onset of damage and failure mechanisms of these materials, biaxial test have become of great interest to automotive, naval, aeronautical and Aerospace industries.

Within the biaxial test field, in-plane loading with a cruciform specimen has become the most used technique for the study of changes in stress curves and linear and non-linear stress states, because unlike to other methods , bending stresses and/or friction forces are not present (Zhao, K. *et al*., 2019). Thus, an equipment has been used to generate a homogeneous stress-strain state in the center of the cruciform specimen by pulling the arms of the sample in two perpendicular axes.

These equipments can be divided into two groups, which are autonomous machines and coupling devices to be coupled to universal machines (Hannon, A., Tiernan, P., 2008). Despite the fact that initial studies used a test configuration composed of an autonomous biaxial machine (Shiratori, E., Ikegami, K., 1967), a greater number of researches were directed to the study of the biaxial stress field using devices that could be attached to conventional uniaxial universal testing machines already used in mechanical testing laboratories. Among the main reasons for this choice, we can mention the high cost of manufacturing autonomous machines, the difficulty to synchronize the actuation of pairs of actuators on the same axis and, consequently, to keep the center of the specimen immobile.

The first studies with biaxial testing devices were carried out by Ferron and Makinde (1988). Their system was a pantographic mechanism composed of eight binary links and six rotation joints, with a fixed part at the base of the machine, and another movable part, coupled to the actuator, which, when pulled in the vertical direction, is responsible for transmitting the second movement in the orthogonal direction. Terriault, Settouane and Brailosvki (2003), aiming to test Ti-Ni specimens that would be subjected to different temperatures, presented a similar mechanism that works with the approximation of the two fixing points to the machine, simulating a compression test, with the mechanism responsible for providing tensile on both axes of the cruciform sample. Vezér and Major (2008) developed a device with planar motion, composed of a system of rigid bars and cylindrical joints, capable of testing elastomeric materials. Andrusca *et al*., (2016), also developed a more robust device with planar motion, whose objective was to analyze the behavior of metallic and composite materials.

Other researchers have devoted their efforts to the development of devices that would make it possible to carry out tests with different loading rates on each axis. Rohr, Harwick and Nahme (2005) developed a biaxial tensile device to investigate the stress-strain behavior of polyamide fabrics, which resembles a simplification of the mechanism proposed by Terriault, Settouane and Brailovski. To subject the sample to different loading rates, the authors used different lengths of tension bars. In the project conceived by Brieu, Diani and Bhatnagar (2007), for the analysis of the behavior of hyperelastic materials, differently from what was proposed by Rohr, Harwick and Nahme, the change of the rate is performed without the need to change the components. It happens simply by adjusting the inclination angle of oblique cylindrical bars to provide a different displacement in each axis. Abu-Farha and Khraisheh (2010) designed a mechanism composed of sets of gears and racks, which allows changing the load by changing the transmission ratio of the gears. Dongsheng *et al*., (2021) developed a mechanism capable of performing quasi-static and dynamic biaxial tests, in order to analyze the mechanical properties of aluminum sheets. Different strain rates are obtained by altering the inclination angle of the side faces of a pyramidal wedge, used as a drive part for guide cars. In addition, a condition of flat deformation in the center of the specimen, with load ratios of 1:0 or 0:1, was also obtained by other researchers (Shao, Z. *et al*., 2016; Zhao, K. *et al*., 2019) by means of the fixation of two opposing arms of the sample.

In the above mentioned works, several configurations were proposed since, generally, such devices are dimensioned to be coupled to specific machines, which have different forms of load application, and to work with specimens with singular geometric characteristics for each type of material. In addition, improvements are constantly undertaken to better requirements, such as symmetry in each tensile axis, structural rigidity, use of different loading rates, sufficient field of view to monitor the deformation of the specimen and cost reduction.

Therefore, in this work the design of a new device will be presented to meet the main requirements already mentioned and generate comparable results for different test strategies. Soon, a working prototype will be manufactured by 3D printing, using PLA. Device validation tests were performed using a hyperelastic silicone rubber specimen. Digital imaging correlation (DIC) was used to analyze the homogeneity of the stress-strain field in the zone of interest and finite element method (FEM) was used to corroborate the results obtained in the test.

# 2. MATERIALS AND METHODS

## 2.1 Design methodology for the development of the biaxial device

The methodology adopted for the device’s development followed that proposed by Maribondo (2000) divided into six phases: informational design, conceptual design, preliminary design, detailed design, manufacturing and testing, as illustrated in Figure 1.

Initially, in the informational design phase, an extensive bibliographic research was carried out, where the database had 20 models of mechanisms that provide an updated basis both on the design and operational characteristics of the devices present in the literature as well as their limitations.

It is important to mention that in Brazil few studies were directed to the performance of in-plane biaxial tensile tests with cruciform specimens, and up to now, this work, an autonomous machine (Suzin, C. M., 2019), for membrane analysis, and a coupling device (Silva Filho, W. B., 2017), for validation of an already proposed mechanism (Rohr, I.; Harwick, W.; Nahme, H, 2005).

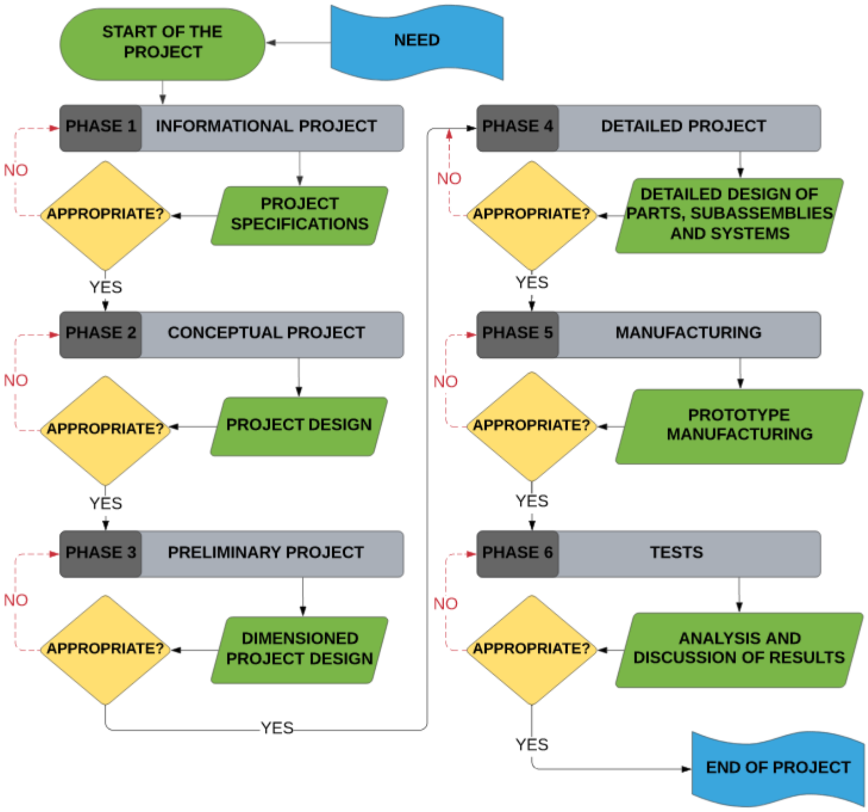


**Figure 1:** Project methodology flowchart.

Therefore, it is of fundamental importance to have a device that can meet the main needs of in-plane biaxial tensile. When designing a new device, criteria such as structural rigidity, application of different biaxial loading rates without the need to change components, generating a plane deformation state in the center of the specimen, manufacturing process and cost and coupling capacity on the available uniaxial machine need to be evaluated. In addition, it is critical for biaxial tests with cruciform specimens that the center of the sample remains immobile during the tests.

Therefore, in this phase, a comparative analysis was carried out between the mechanisms present in the database, considering the criteria mentioned for this project. As a result, the ones that most suited the requirements were those presented by (Brieu, M.; Diani, J.; Bhatnagar, N, 2007; Rohr, I.; Harwick, W.; Nahme, H, 2005; Zhao, K. *et al*., 2019).

After the study carried out in the informational design phase, the conceptual design phase, which allows the visualization of ideas from schematic drawings, diagrams or sketches of the devices, took place. The design of the new device began by adopting as the main structure the model proposed by Rohr, Harwick and Nahme (2005), in which the mechanism works with the application of a vertical force at the top, causing the load to be distributed between four bars, coupled to guide cars, moving with the aid of linear guides (Fig. 2(a)). Also based on the design of Brieu, Diani and Bhatnagar (2007), a cross-shaped machine coupling part (Fig. 2(b)) was proposed so that different loading rates could be achieved by changing the angulation of the bars, without the need to dismantle the device and replace parts, thus facilitating manufacturing, assembly and subsequent tests.

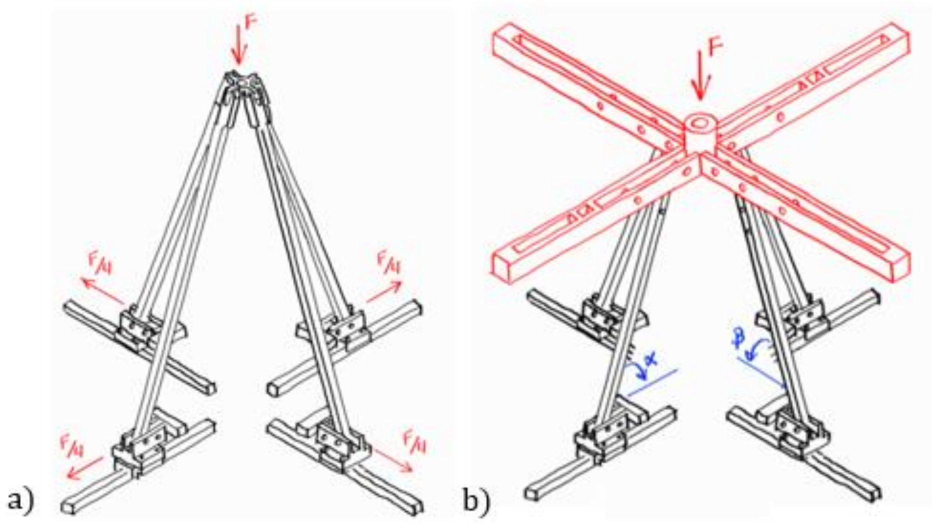


**Figure 2:** Sketches made for the idealization of the biaxial device.

The crosshead design was based on the dimensions required in the device, so that it was possible to test different materials, from elastomers to thin metal sheets. Thus, the inclination angles of the bars were selected according to the load that will be applied to each tensile axis, in order to generate different loading rates but without significantly affecting the maximum load supported by the device. Considering that a force Fz = 10 kN is applied on the crosshead (Fig. 3), we have the following force distributions reported in Table 1.

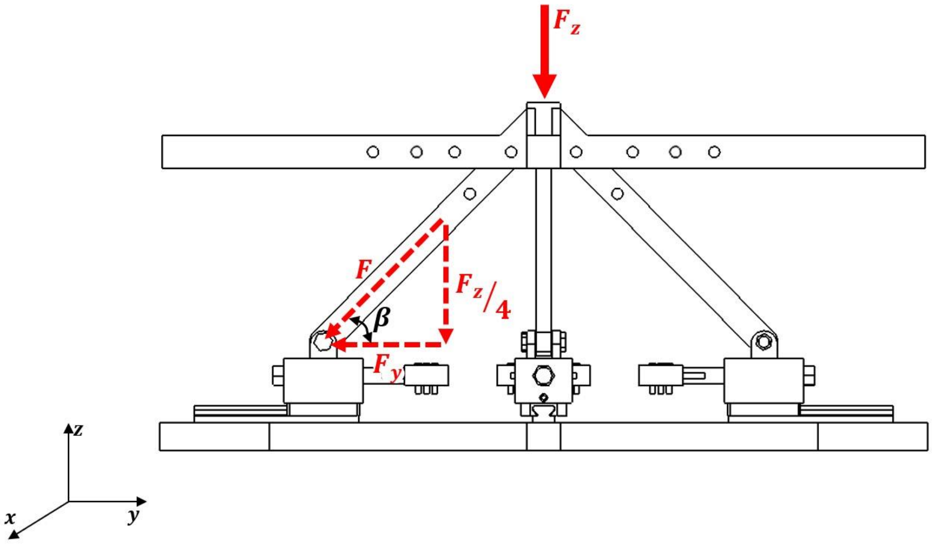


**Figure 3:** Forces acting on the biaxial device.

Where the F and Fy components can be calculated by the following equations:

$$F = \frac{F_z}{4.sen(\alpha)} \tag{1}$$

$$F_Y = \frac{F_z.\cos(\alpha)}{4.sen(\alpha)} \tag{2}$$

**Table 1:** Calculation of the forces acting on the device as a function of the angle α.

| $\alpha$ | Fz (kN) | F (kN) | Fy (kN) |
|---|---|---|---|
| **45º** | 10 | 3.54 | 2.5 |
| **50º** | 10 | 3.26 | 2.09 |
| **55º** | 10 | 3.05 | 1.75 |
| **60º** | 10 | 2.88 | 1.44 |
| **65º** | 10 | 2.76 | 1.17 |
| **70º** | 10 | 2.66 | 0.91 |
| **75º** | 10 | 2.59 | 0.67 |
| **80º** | 10 | 2.53 | 0.44 |
| **85º** | 10 | 2.51 | 0.22 |
| **90º** | 10 | 2.5 | 0 |

From Table 1, that presents the decomposition of the forces as a function of the inclination angle of the bars, adjustments of the inclinations of 45º, 55º and 75º in an axis (Fig. 4(a)) and 45º, 65º and 90º in an orthogonal axis (Fig. 4(b)), allow to perform different combinations of load application onto the specimen.

Therefore, the ratio of displacements between the axes can be 1:0, 1:1.5, 1:2 and 1:3. It is also important to point out that, as in other works (Rohr, Harwick and Nahme, 2005; Brieu, Diani and Bhatnagar, 2007), for the highest strain rate to be achieved, the dimensions of the measurement area must be observed at a given displacement.

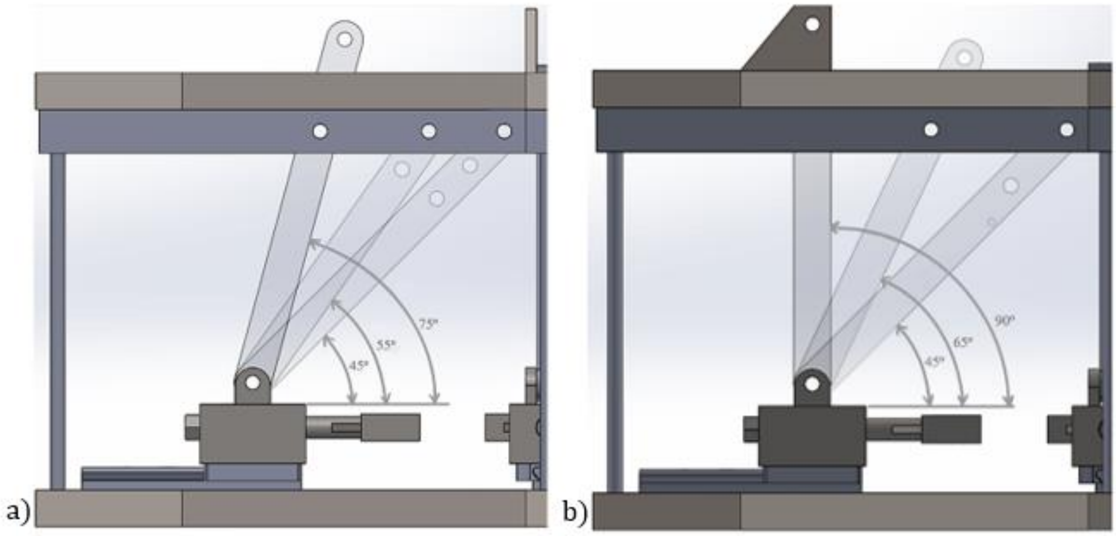


**Figure 4:** Schematic representation of test configurations for the biaxial test.

Once the crosshead design was completed, the device design was carried out with the help of SolidWorks software, for a better understanding of the mechanism's operation (Fig. 5). In addition, Figure 5 shows that a system of vertical guide axes, composed of cylindrical bars, were added to ensure greater stability of the mechanism and the simultaneous activation of the bars. Thus, it was necessary to design two parts, a base for fixing the uniaxial machine and a coupling support for the cylindrical bars. Thus, one concludes that, in addition to ensuring greater strength of the structure, having the movement guided by vertical and horizontal guides provides greater stability in the deformation measurement zone.

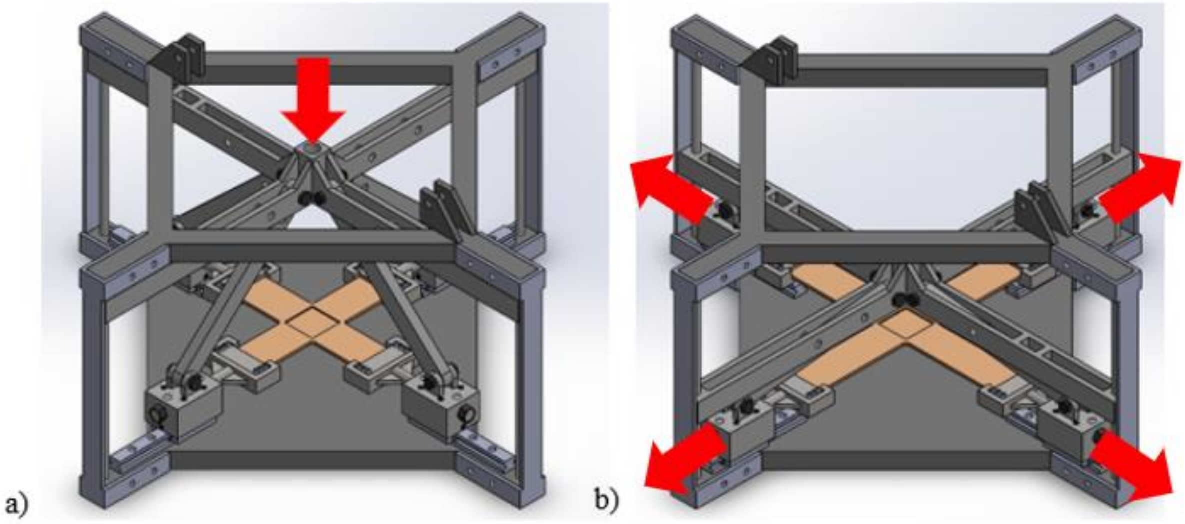


**Figure 5:** Schematic representation of the device.

The test configuration with the bars positioned at an angle of 90º (Fig. 6(a)) on an axis makes it possible to generate a state of plane deformation in the specimen, as proposed by Zhao *et al*., (2019). With the bars fixed to the cylindrical bars coupling support, located above the crosshead, two opposing guide cars are locked, preventing the specimen arms from moving along the same axis (Fig. 6(b)).

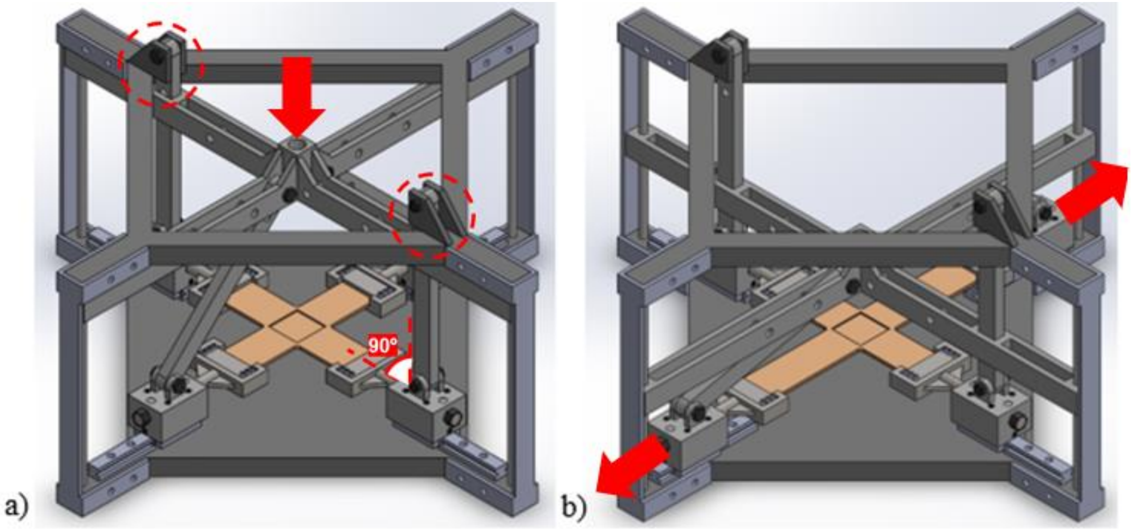


**Figure 6:** Schematic representation of test setup for plane strain state.

In order to meet the design specifications and established requirements, the structure was divided into five subsystems for a better understanding of the mechanism, and thus facilitate the design steps. The specifications of the parts that make up each subsystem are illustrated in Figure 7 and detailed in Table 2.

The first subsystem is the fixing base on the uniaxial machine, where the horizontal and vertical guides (1) will be mounted. The second subsystem is the load distribution subsystem, consisting of the cross (3) that will be coupled to the uniaxial machine actuator. The third subsystem is the axis displacement, formed by four tensile bars (4) and (5), by the linear guide (7) and (8), by four cylindrical bars (10), which will provide the alignment of the cross, and by the support of the specimen fixing claw (6). The fourth subsystem is the specimen fixation subsystem, consisting of four fixation claws (9), which are joined to the claw supports. The fifth subsystem is the structural support, consisting of the support of the cylindrical bars (2) and four lateral structural supports (11), responsible for providing greater rigidity to the device.

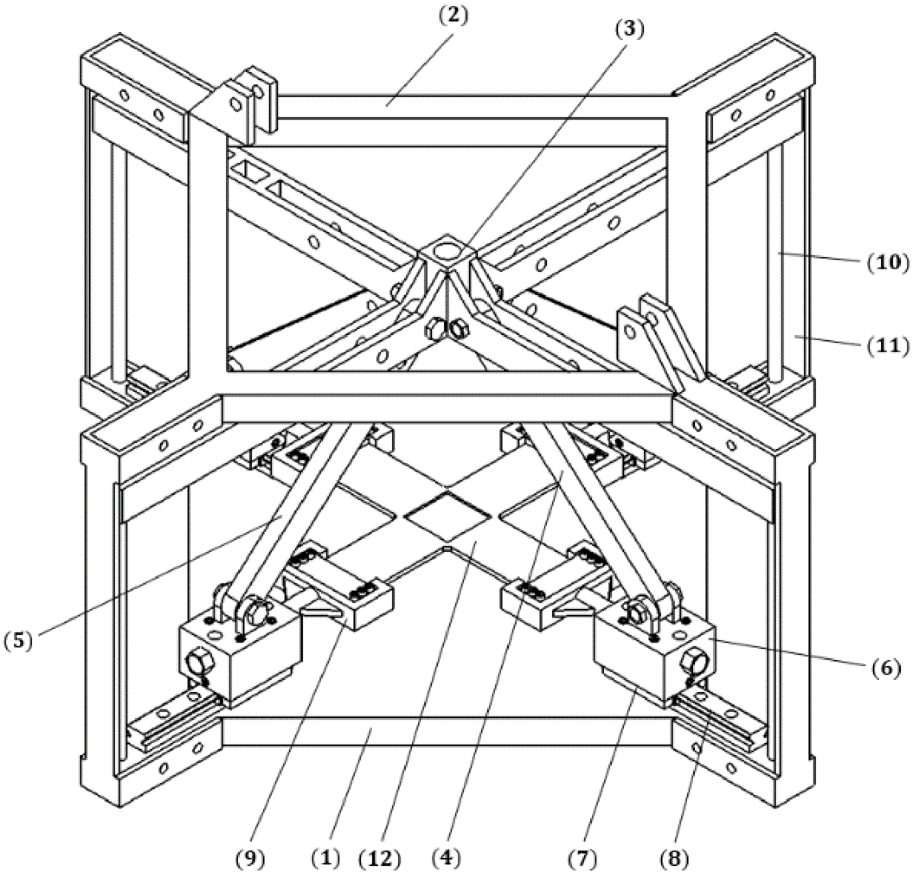


**Figure 7:** Detailed drawing of the biaxial device.

**Table 2:** Specifications of the parts that make up the biaxial device.

| **Item No.** | **Description** | **Qty.** |
|---|---|---|

| | | |
|---|---|---|
| (1) | Machine fixing base | 1 |
| (2) | Support for cylindrical bars | 1 |
| (3) | Cross | 1 |
| (4) | Bar with adjustment 45º/65º/90º | 2 |
| (5) | Bar with adjustment 45º/55º/75º | 2 |
| (6) | Specimen clamp support | 4 |
| (7) | Guide car | 4 |
| (8) | Linear guide | 4 |
| (9) | Specimen clamp | 4 |
| (10) | Cylindrical bar | 4 |
| (11) | Structural support | 1 |
| (12) | Cruciform specimen | 1 |

With the realization of the ideas, the preliminary design phase began in order to execute the correct dimensioning of the parts that make up the project so that the requirements already exposed are met. The stress distribution analysis used the computational numerical model, Finite Element Method (FEM), considering AISI 1020 steel as material for all device components. For the crosshead, the part that will be coupled to the machine's actuator, the load stipulated for the project, of 10 KN, was considered. The maximum stress of 204.5 MPa was achieved at the joint of the arm reinforcements (Fig. 8), using the 45º/75º configuration, with a loading ratio of 1:3. In the simulations of the other parts, vertical forces of 2.5 KN were applied, due to the force of 10 KN being distributed among the four bars, for a configuration of 45º/45º in order to obtain a maximum horizontal force. The pieces that showed the highest tension were the specimen clamp (Fig. 9), with an intensity of 73.25 MPa, followed by the clamp support (Fig. 10), with 62.14 MPa. Adopting the yield strength of the selected material of approximately 350 MPa and assuming that the maximum stress is obtained at the crosshead, a minimum safety factor of 41.6% is considered acceptable.

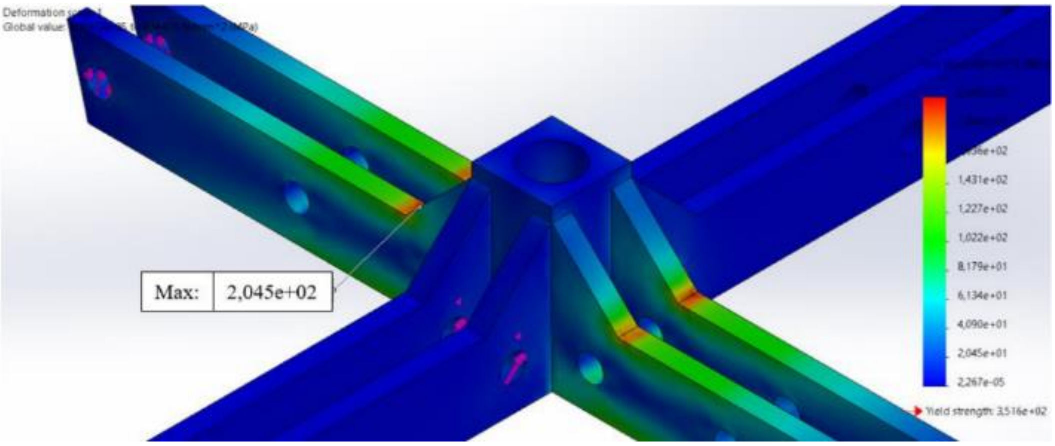


**Figure 8:** Analysis of stress distribution on the crosshead.

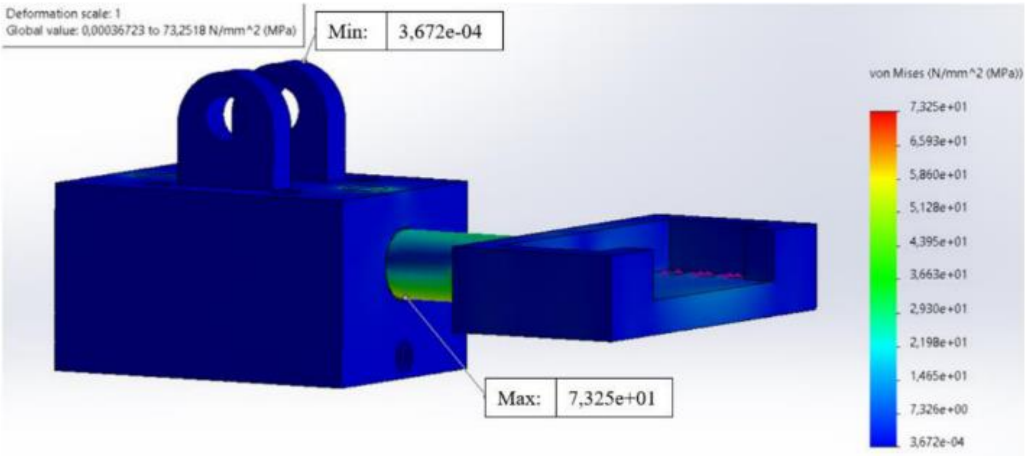


**Figure 9:** Stress distribution analysis in the specimen clamp.

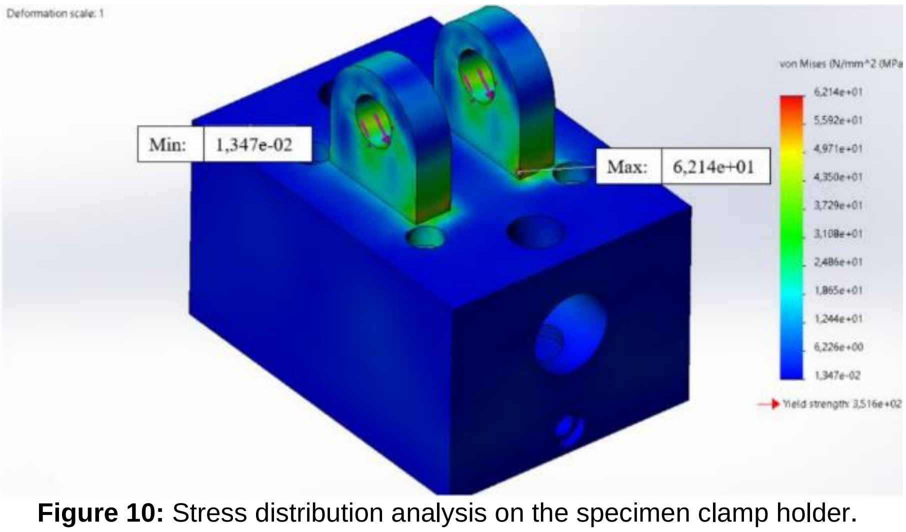
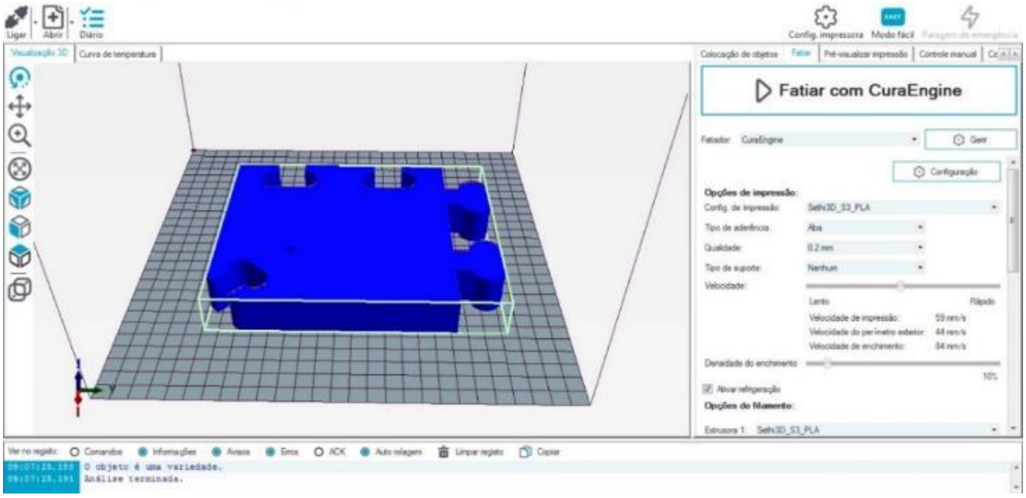


**Figure 10:** Stress distribution analysis on the specimen clamp holder.

After completing the structural analysis using the CAE software, the technical information for the fabrication and assembly of the parts involved in the project were presented in the detailed design phase. Analogously to what is reported in the literature (Medellín, L. F. P. *et al*., 2019; Vigueras, E. M. R. *et al*., 2019), the design of a prototype made of a thermoplastic polymer, polylactic acid (PLA), by additive manufacturing was defined. The fabrication was carried out at the Innovation and Prototyping Laboratory (LIP) of the University of Fortaleza (UNIFOR), with the Sethi S3 printer. The software used to generate the programming was Cura (Fig. 11). Due to the dimensions of some parts being larger than the printing table (25x25 mm²), such as the machine fixing base, cross, and support for the guide axes, these were manufactured in parts. Since the crosshead is the part subjected to the greatest efforts, the density used for its printing was 100%. In the other pieces, densities of 5% to 30% were used.



Fatiador: CuraEngine

Opções de impressão:
Config. de impressão: Sethi3D_S3_PLA
Tipo de aderência: Aba
Qualidade: 0.2 mm
Tipo de suporte: Nenhum
Velocidade:
Velocidade de impressão: 59 mm/s
Velocidade do perímetro exterior: 44 mm/s
Velocidade de enchimento: 84 mm/s
Densidade do enchimento: 10%
☑ Ativar refrigeração
Opções do filamento:
Estrusora 1: Sethi3D_S3_PLA

```
09:07:25.100 O objeto é uma variedade.
09:07:25.191 Análise terminada.
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**Figure 11:** G code slicing software for 3D printers.

## 2.2 Methodology for the manufacture of specimens

Due to the print density that was used to manufacture the biaxial device, the material selected to be tested was a high flexibility silicone rubber. It is important to emphasize that the objective of the test is not to obtain the material rupture, but to analyze the stress-strain paths in the center of the specimen for the validation of the biaxial device. Therefore, the selected material will provide a greater displacement of the specimen arms and, consequently, a greater deformation.

The geometry of cruciform speciments for hyperelastic materials has not been normalized yet. Up to now, only the ISO 16842:2014 standar for metallic materials has been established. The geometry used in the present work was that suggested by Seibert, Scheffer and Diebels (2015). Therefore, considering the proper proportions for carrying out the tests with the proposed device, we used the cruciform specimens geometry shown in Figure 12.

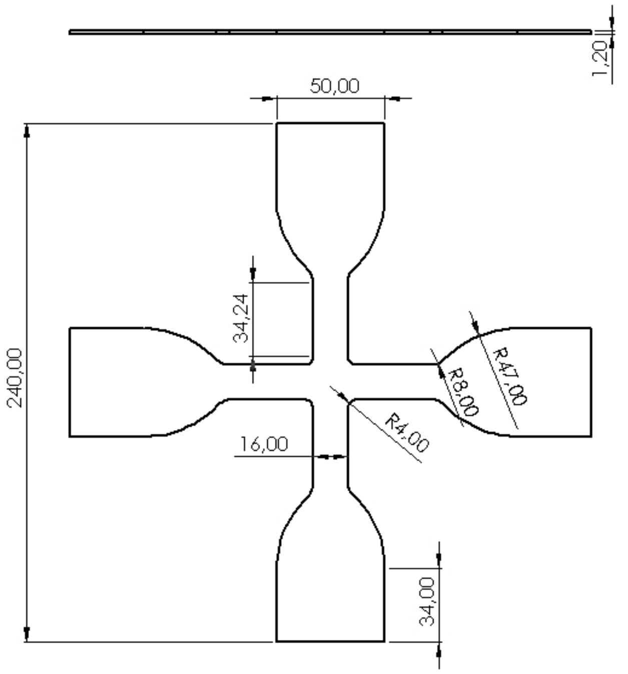


**Figure 12:** Cruciform specimen geometry.

For manufacturing the sample specimens, initially a mold (Fig. 13(a)) was printed with a thermoplastic polymer, polylactic acid (PLA), using the Sethi S3 3D printer, at the Innovation and Prototyping Laboratory (LIP) of the University of Fortaleza (UNIFOR).

The ratio of silicone/catalyst mixture to obtain the specimen was based on the instructions provided by the manufacturer, i.e., 0.03 g of catalyst for 1 g of silicone. This mixture was added to the mold (Fig. 13(b)) and the specimen removed after a curing time of 1h, with the total curing of the part being achieved after 24h (Fig. 13(c)).

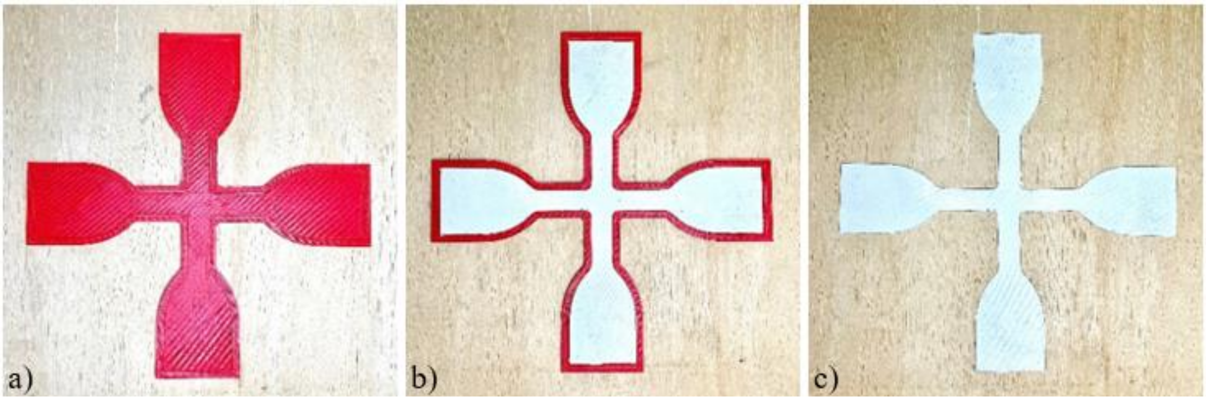


**Figure 13:** Methodology adopted for the manufacture of the specimen.

## 2.3 Method for stress-strain field analysis

Digital Image Correlation (DIC) was the technique chosen for measuring the homogeneous stress-strain distribution because not only does it allows for measuring the deformation of a larger field but it does not influence the conditions imposed in the tests and because it is a simpler technique that requires less equipment. Only a reording camera, proper lighting, printing patterns on the specimen and software for image processing are needed.

Filming was performed with the aid of an iPhone, with a resolution of 4000x3000 pixels and 24 fps. The camera was directed to a mirror positioned at a 45º angle to the base of the device (Dongsheng, L. *et al*., 2021).

The DIC software chosen for image processing was based on a comparative study between six existing softwares (Beleza, S. C. A., 2017). In this comparison, the softwares were analyzed, taking into account aspects such as: installation; loading images; operation; analysis speed; results presentation; etc. Gom Correlate Pro software was choses for this work as i was the one with the best classification in the study reported by Beleza (2017).

The methodology for analyzing the stress-strain field was divided into three main steps (Fig. 14), which are: 1) position the mirror with an inclination of 45º, with respect to the specimen; 2) record the process with the aid of a camera; 3) transfer the footage to a computer to be processed by correlation software.

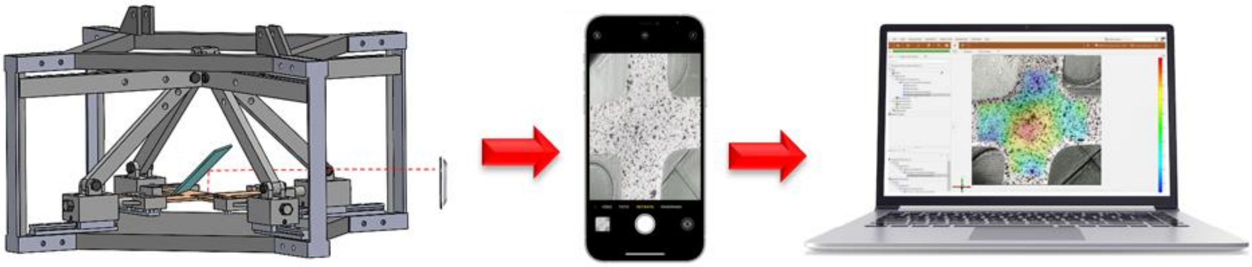


**Figure 14:** Digital image correlation method.

## 3. RESULTS AND DISCUSSION

The validation of the device was carried out by tests at the Laboratory of Mechanical Tests of UNIFOR. The device was coupled to an Instron 4484 machine (Fig. 15(a)) and the instrumentation for filming the deformation consisting of an iPhone and an LED lamp was positioned (Fig. 15(b)). As already mentioned, in order to process the images using the correlation software, a mirror was placed on the specimen with an inclination of 45º relative to the base.

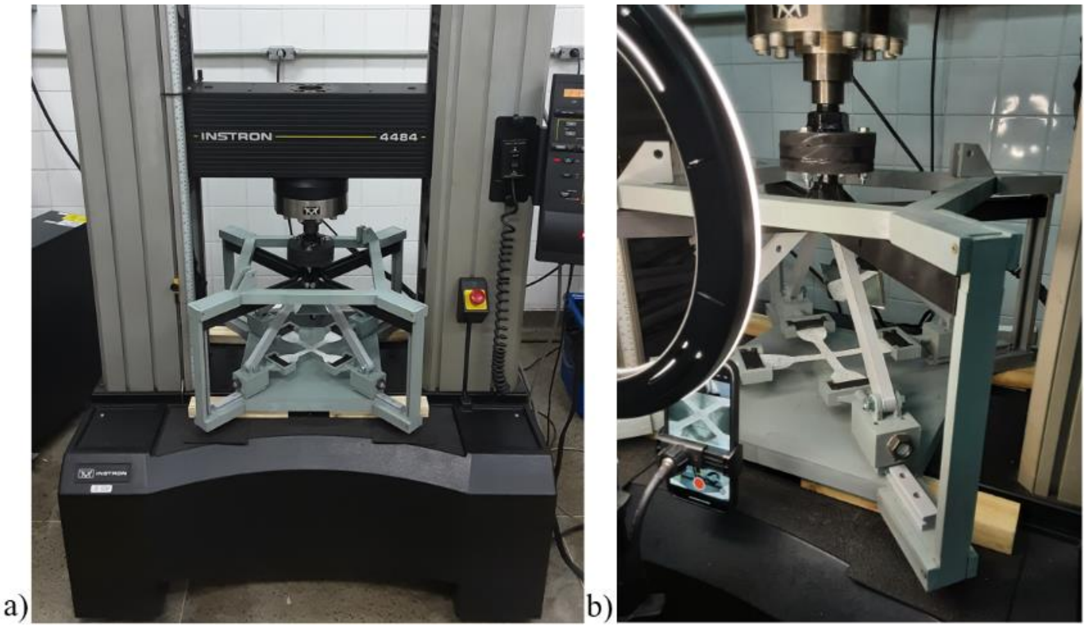


**Figure 15:** Biaxial test setup.

Five specimens were manufactured to be used in different biaxial configurations, which were classified according to the angulation of the bars in the two orthogonal axes and performed in the following sequence: 1) 45º/45º; 2) 45º/55º; 3) 45º/65º; 4) 45º/75º; 5) 45º/90º. The first two tests, with load application rates of 1:1 (Fig. 16) and 1:0 (Fig. 17), were performed with a strain rate of 0.1 mm/min and the remaining tests at gradually higher rates, last test is carried out with a 10 mm/min strain rate, to verify the instability of the mechanism.

The first test carried out was the equibiaxial test, with the tension bars on both axes initially positioned at an angle of 45º and a 1:1 axis displacement ratio. For this configuration, the rupture of the specimen occurred at a position close to the maximum displacement provided by the device, which is 130 mm per axis. Figure 16(b) shows that the maximum stress was reached in the center of the specimen, with the rupture forming an angle of 45º relative to the tensile axis, as mentioned by Shimamoto, Shimomura and Nam (2003), demonstrating the uniformity of the stress-strain field in this region. In the other tests conditions, the device reached the limit of its course before specimen rupture.

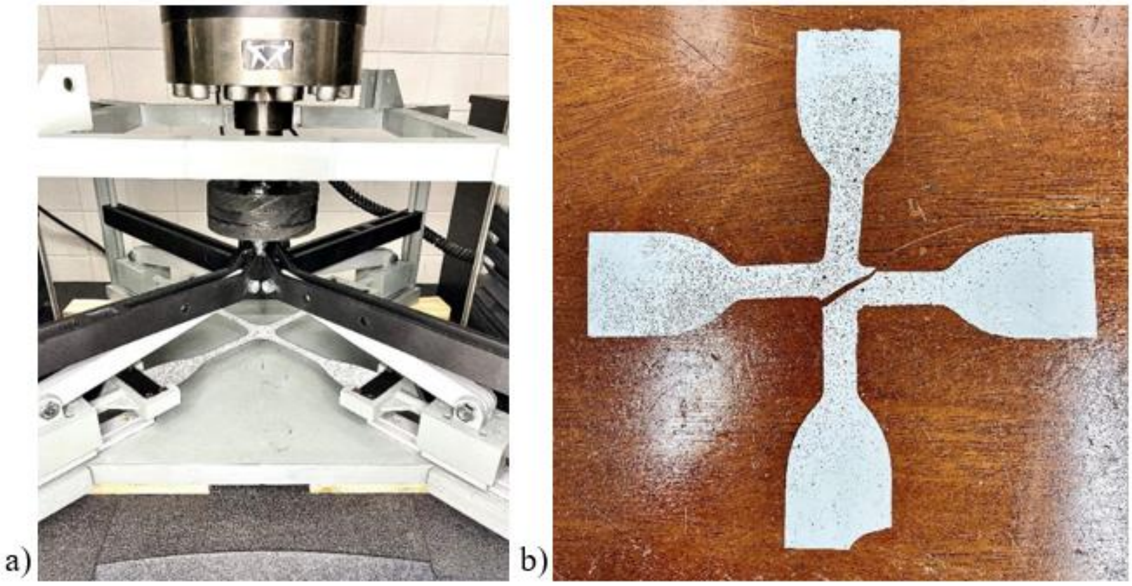
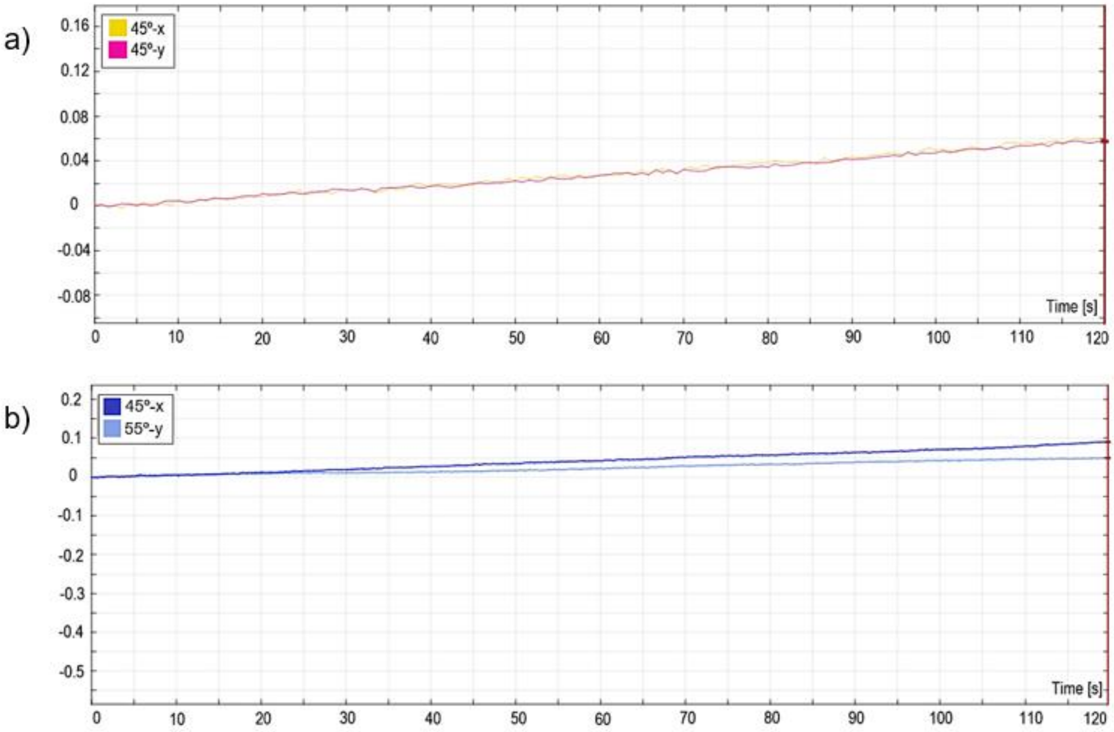


**Figure 16:** Deformation of the specimen for the equibiaxial test (1:1).

**Figure 17:** Test setup for in-plane deformation state (1:0).

Sample strain analysis was carried out with Gom Correlate Software monitoring two points in the central area so that the X-Y strain behaviour could be observed. The results for each test are shown in the graphs of Figure 18, in the same sequence of execution.



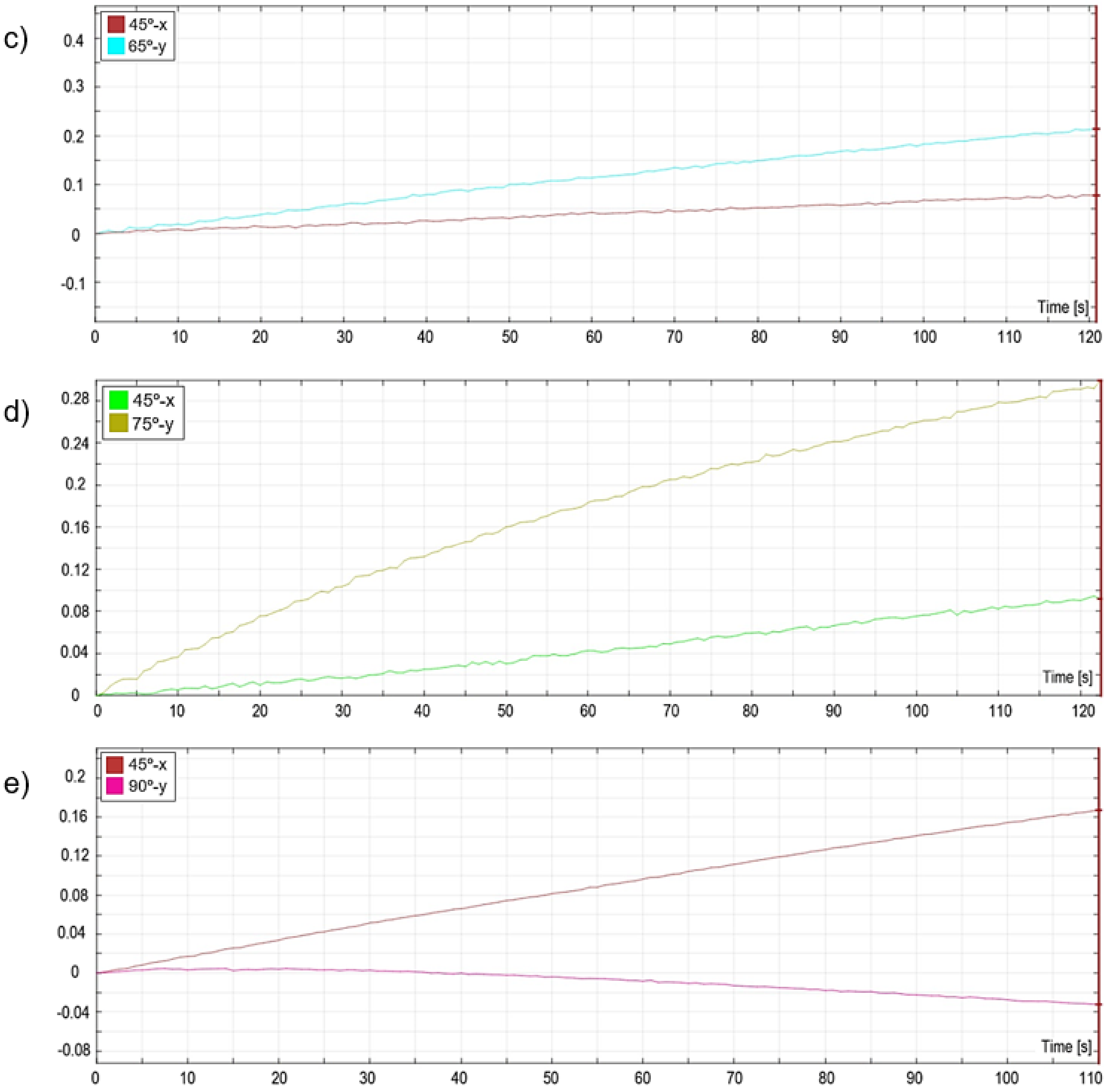


**Figure 18:** Deformation x Time graph for settings: 45º/45º; 45º/55º; 45º/65º; 45º/75º; 45º/90º.

The results provided in the tests with the DIC technique indicate that small deviations in the strain rates were obtained in some tests. This may have occurred due to improper adjustment of mirror inclination as the mirror was moved at each new test as the specimen was changed, leading to a more accelerated increase in the deformation in one of the axes during reading by the software. In addition, the graph in Fig. 18(e) shows a condition very close to in-plane deformation, because even with two opposing arms of the specimen locked, the regions close to the central area can still almost imperceptibly deform by visual inspection (Zhao, K. *et al*., 2019). Despite the deviations observed in some tests, the comparative analysis of the stress field reproducible results, making the device able to perform different tests of biaxial tensile.

The results obtained from the stress field for each test are shown in Figure 19. It is important to highlight that the behaviors of the silicone rubber observed here show similar trends to the results provided by numerical modeling (Fig. 20), which means that the new device satisfactori-ly generates the deformation paths stipulated in the project.

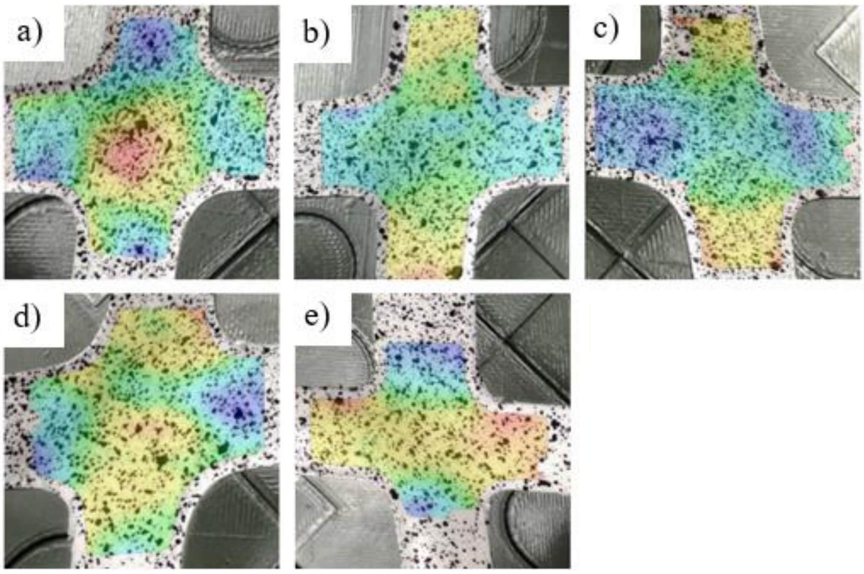


**Figure 19:** Von Mises yield criterion by Gom Correlate for configurations a) 45º/45º; b) 45º/55º; c) 45º/65º; d) 45º/75º; e) 45º/90º.

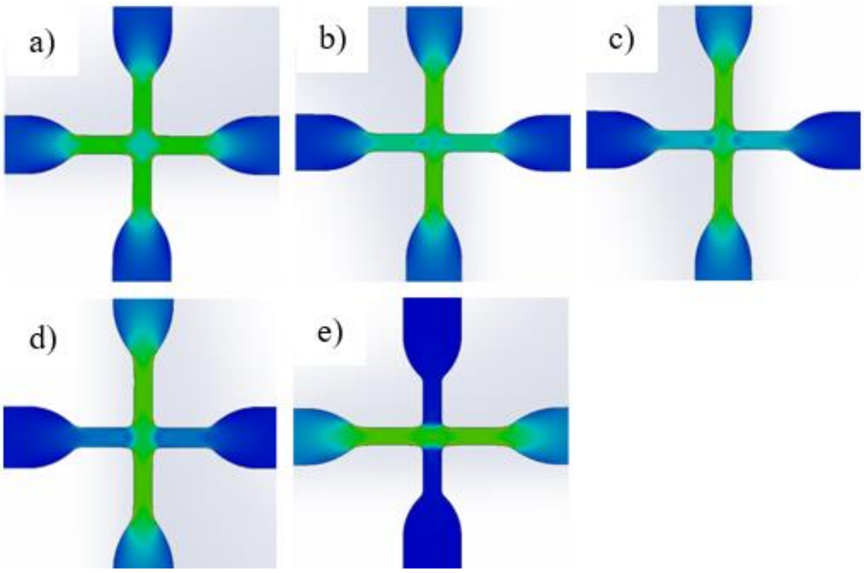


**Figure 20:** Von Mises yield criterion by SolidWorks for configurations a) 45º/45º; b) 45º/55º; c) 45º/65º; d) 45º/75º; e) 45º/90º.

## 4. CONCLUSION

It was possible to conceive, simulate, manufacture and test a new type of biaxial test device capable of applying different biaxial loading rates (1:1; 1:1.5; 1:2; 1:3), in addition to generating a state plane strain (1: 0). When compared to the devices by Shao, Z. et al., 2016 and Zhao, K. et al., 2019, which propose similar test configurations, the present mechanism does not require replacement of components to change the load distribution between the axles, facilitating subsequent tests. In addition, it presents a considerable reduction in the number of components, reducing the manufacturing cost and the assembly complexity. In the analysis of the von Mises yield criterion, the data generated by the optical method and CAE software were compared, which showed good correlation between the results. As for the deformation measurements through the correlation software, the graphs of the test configurations showed that the deformation rate between the axes was practically the same as that stipulated in the design. This device, due to its innovative character, motivated the patent claim BR102021024262-0.

## 5. ACKNOWLEDGEMENTS

The authors thank the Coordination for the Improvement of Personnel and Higher Education (CAPES). We also thank the University of Fortaleza (UNIFOR) for the assistance provided for the development of the project and, in a special way, the head of the Innovation and Prototyping Laboratory (LIP), Clarissa Ribeiro Pereira de Almeida, and the specialist technician in 3D printing, Erikson Queiroz Costa.

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