Bulletin of the *Transilvania* University of Brasov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 17(66) No. 2 – 2024
https://doi.org/10.31926/but.fwiafe.2024.17.66.2.6

EVALUATION OF TENSILE AND COMPRESSION BENDING MOMENT OF L-TYPE JOINTS WITH 3D PRINTED CONNECTORS

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Abstract: *The paper investigates the bending moments under diagonal tensile and diagonal compression loads of L-type corner joints made of three wooden parts corresponding to the leg and the two stretchers used in chair construction. The wooden parts were jointed together with a 3D printed connector made of polylactic acid (PLA) filaments using Filament Fused Fabrication (FFF) as additive manufacturing technology. Larch (Larix decidua Mill.) wood was used to manufacture the wooden elements. In order to assess how the model orientation on the build platform influences the mechanical performance of the printed connector, two print positions were taken into account during the additive manufacturing (AM) process, namely horizontal and vertical. Mechanical testing under diagonal tensile and compression loads of the L-type corner joints, followed by the microscopic investigation of the fractured connectors with magnifications 50X, 80X, 100X were employed in this study. The results were compared with those of the reference L-type corner joint consisting of common mortise-tenon jointed wooden elements. The results show that the vertical orientation of the model on the build platform of the 3D printer is preferred for a better mechanical performance. The microscopy of the fractured connectors revealed the interlayer delamination of the filaments, especially in the case of the horizontal orientation of the model, which caused the wooden parts to slide out of the connector and record low values of the maximum failure loads.*

Key words: *Polylactic acid (PLA), additive manufacturing, larch wood, connector, L-type corner joint.*

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1. Introduction

Filament fused fabrication (FFF), as a part of AM, has a multitude of applications, being one of the most accessible and inexpensive 3D printing technologies. PLA filaments are often used for large applications, being manufactured in a variety of colours that can bring an attractive design to 3D printed objects [8, 25]. In the traditional furniture manufacturing industry, the possibilities of designing wooden components generate a series of constraints on the production in this field, limited by the execution of the joints between the wooden parts to 90º angles, rarely connecting more than two pieces in the same joint [5]. The use of 3D printed parts in the structure of furniture allows the design without the limitations of wood jointing and avoids the difficult technological processes of wood [14]. By using AM, functional structures with difficult geometries can be obtained through the deposition of successive layers of extruded thermoplastic filament [21]. There are several advantages of using AM in the production of furniture parts: improving the degree of fit, reducing the difficulty of parts manufacturing and the production time, easing the assembly process, allowing the secondary recycling of furniture and prolonging its service life with a positive impact on the environment [16, 27].

The creation of a 3D model is the first step before 3D printing an object. Computer-aided design (CAD) software, such as AutoCAD, Rhino, SolidWorks, Autodesk 3ds Max, and Maya, is used for this purpose. The 3D model is saved as a (.stl) file and then transferred to the printer software. The software slices the data file into individual layers which are sent as instructions to the printing device that adds overlapping layers of material, until the object is printed completely.

The most used materials for printed parts in furniture manufacturing are the filaments made of acrylonitrile butadiene styrene (ABS) and PLA, and FFF technology is employed to print them. The costs of these two materials are similar, but the filaments made of ABS have a slightly toxic exudate and they are sensitive to thermal deformation, whilst the PLA filaments are safer and more environmentally friendly [5]. Based on the literature review, some researchers [18] reached the conclusion that layer thickness and raster width should be minimal for improving the mechanical strength of the specimens and temperature plays a significant role in PLA filament bonding. The increased thickness of the printed layer decreases the manufacturing time of the specimen [4], but it has a negative impact on the quality of the printed surface, by increasing its roughness [22]. PLA filaments have similar mechanical properties with the printed specimens, so an assessment of the filament could predict the behaviour of the specimen [7]. The SEM examination of printed specimens with different coloured PLA filaments [26] indicated that colorant additives could play a role in the size of the inter-layer gaps, due to the fact that some colorants restrict heat flow and could lower the ultimate tensile strength, as in the case of white PLA, which had larger gaps in its structure compared to the natural material. In order to support the piece, in the case of complex geometries, it is necessary to add material to create a structure that supports the geometry of the piece in the correct position during the printing process [2]. Once the object is created, a variety of finishing activities are needed [19, 24].

Several attempts are presented in the literature related to the manufacture of 3D printed connectors for furniture, using FFF or the selective laser sintering (SLS) method of AM technology [1, 2, 5, 9, 10]. The application of AM in the development and research of furniture parts relies on a comprehensive analysis based on evaluation tests. There are few methods applied in the literature for the assessment of the mechanical strength of the assembly with 3D printed connectors, or of the product itself. The corner joint is often used to assemble chair parts using mortise-tenon joints [17] and one evaluation method is to subject the L-type corner jointed parts to diagonal compression and diagonal tensile loads [3, 6, 13, 15, 23] and to calculate the bending moments. Another method is to assess the strength and durability of the chair seat and back by applying perpendicular forces to their middle points [1, 9].

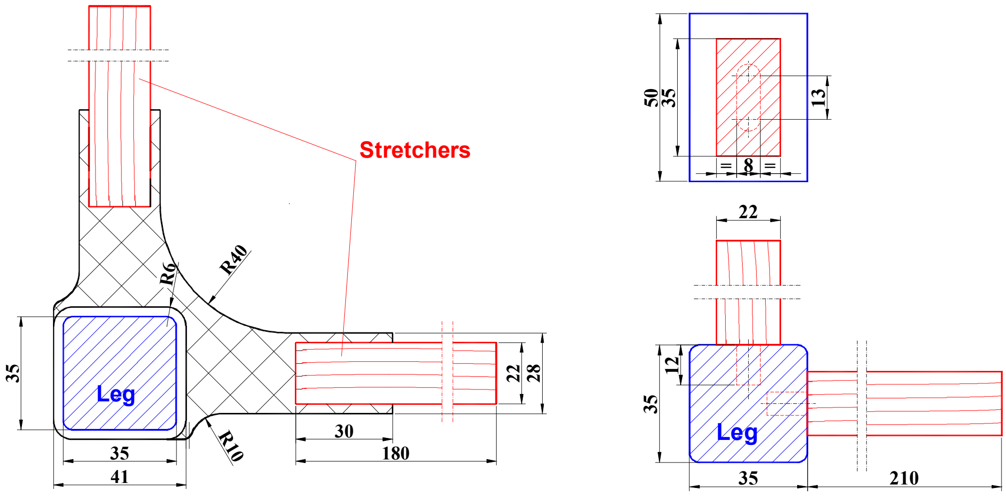
There are not many studies available regarding the assessment of the mechanical strength of 3D printed connectors for furniture. The present paper investigates the behaviour under diagonal compression and diagonal tensile loads of L-type joints between wooden elements assembled with a 3D printed connector made of white PLA. The experimental research reveals the influence of the orientation of the model on the build platform of the 3D printer upon the bending moment of the tested L-type corner joints under diagonal compression and diagonal tensile loads. Larch wood (*Larix Decidua* Mill.) was selected for the experiment, which is a species with moderate resistance used in the construction of chairs. This choice is intended to allow for a gradual progression in the research, avoiding the oversizing of the connector, as would be the case when joining more resistant wood species like beech or oak.

2. Materials and Methods

2.1. L-type Corner Joints

Larch (*Larix decidua* Mill.), wood with a moisture content of 9.2% and density of 607 kg/m^3 was used as raw material for the wooden parts. Two different L-type corner joints were designed for the mechanical tests: the first one included a 3D printed connector, and the second one was a common mortise-tenon joint between the three wooden elements, and was taken as reference sample. The adhesive used for the mortise-tenon joint was the commercial Novobond D2 polyvinyl acetate. The construction types and sizes of the L-type corner joints are presented in the cross sections from Figures 1a and 1b.

The density of the larch wood, determined by the calculation of the moisture content of 9.2%, was 607 kg/m^3. An adherent joint was used between the wooden parts and the 3D printed connector, and no adhesive was used. The piece of wood corresponding to the leg of the chair was completely inserted into the square section of the connector, and the stretchers were inserted 30 mm into the void spaces designed for them. The 3D model of the connector was designed using the SolidWorks 3D CAD software, version 2016, developed by Dassault Systèmes, France, and exported to the printer software as a (.stl) file.



a. b.

Fig. 1. *L-type corner joints used for the experimental work with: a. a 3D printed connector; b. a common mortise-tenon joint*

2. Additive Manufacturing

FFF technology was employed to print the connectors, and white PLA filament (S.C. Atelier Concept&Design Studio, Bucharest, Romania) was used as material for the 3D print. The characteristics of the filament, as resulted from the technical data sheet of the supplier, are presented in Table 1.

Table 1

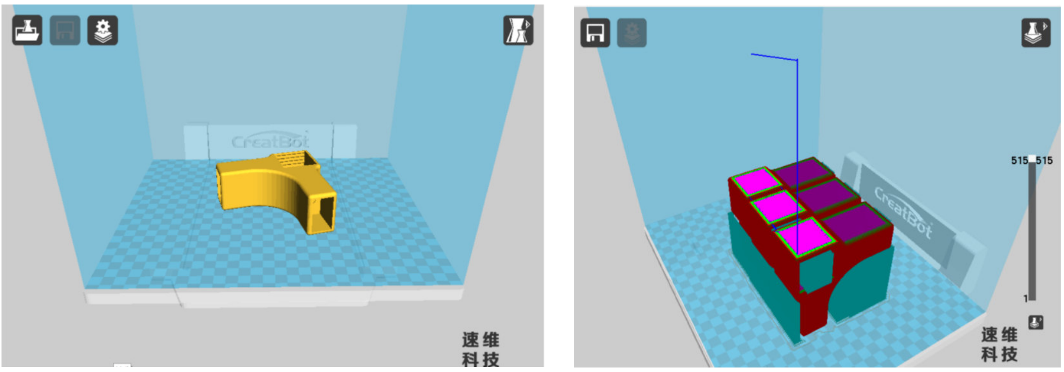
Characteristics of the white PLA filament used to print the experimental connectors

Characteristics	Value	Test method
Thickness [mm]	2.85 ± 0.10	
Print temperature [°C]	180 – 220	
Build platform temperature [°C]	60 – 70	
Print speed [mm/s]	40 – 80	
Impact strength [kJ/m^2]	7.5	ISO 180/A
Tensile strength [MPa]	110 (MD)	ASTM D882
Tensile modulus [MPa]	3310 (MD)	ASTM D882
Elongation at break [%]	160 (MD)	ASTM D882
Flexural modulus [MPa]	±2392.5	

The initial filament deposition is the perimeter, which defines a closed contour for the deposition of the subsequent layers of the 3D printed connector. The infill pattern, alternating in the X and Y direction at an inclination angle of 45º relative to the direction of the perimeter and perpendicular to the previous layer, was selected according to the literature recommendation, in order to obtain superior results concerning the compressive or tensile properties [11, 20]. The parameters used to print the connectors were, as follows:

- Print speed of 50 mm/s;
- Print temperature of 250°C;
- Layer height of 0.2 mm;
- 100% filling density.

Two orientations of the model on the build platform were considered, as shown in Figure 2. In "position 1" from Figure2a, the part is printed horizontally and does not need a support material. In "position 2" from Figure 2b, the connector is printed in a vertical position and the deposition of the layers needs a support material which is removed after the printing process is over. As seen in Figure 2b, a set of three pieces were printed at the same time.



a. b.

Fig. 2. *Orientation of the model on the build platform: a. Position 1 (horizontally); b. Position 2 (vertically) with support material, colored in green*

The printer used to manufacture the connectors was CreatBot DX Plus-3D (manufacturer Henan CreatBot Technology Limited, Zhengzhou City, Henan Province, China). This printer has the following characteristics: filament diameter of 2.85 mm, nozzle temperature up to 260°C, open filament system, maximum print speed of 200 mm/s, build area of 250 mm x 300 mm x 520 mm, layer height between 0.05 and 0.5 mm, and resolution of 0.05 mm.

3. Mechanical Strength of the L-Type Corner Joints

The L-type corner joints were tested for both diagonal compression and diagonal tensile loads using models described in the literature [3, 12, 28]. The tests were performed on the Zwick/Roell Z010 universal testing machine (Ulm, Germany) for five samples of each category. The compression loads tend to open the joint, while the tensile forces tend to close the joint, and bending moments occur in the corner joints under these loads.

The bending moments under the tensile (M_t) and compression (M_c) loads were calculated using Equations (1) and (2), respectively:

$$M_t = \frac{F}{2} \cdot L_t \quad [N \cdot m] \qquad (1)$$

$$M_c = F \cdot L_c \quad [N \cdot m] \qquad (2)$$

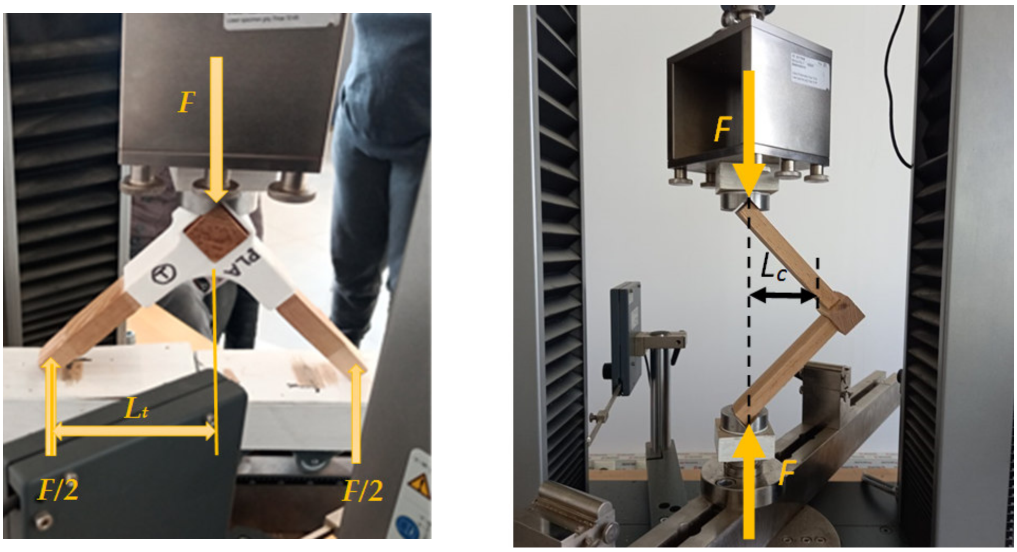
where:

L_t and L_c are the moment arms under tensile and compression loads [m];

F – the maximum failure load [N].

Figure 3a shows how the test was conducted under tensile load in the case of the white PLA connector and Figure 3b shows the test under compression load for the reference L-type corner joint.

The same test speed of 7 mm/min was applied both for the L-type corner joint with connector and for the reference sample.



a. b.

Fig. 3. *Mechanical tests: a. under diagonal tensile load; b. under diagonal compression load*

4. Microscope Investigation

The microscope investigation of the fractured connector after testing under diagonal tensile and compression loads was conducted on two microscopes: the optical microscope OmniMetBuehler (Tokyo, Japan) with 50x and 100x magnification power and the Emspira 3 Digital Microscope (Leica Microsystems, Danaher Corporation, Washington DC, USA) with 26×, 40×, and 80× magnification power. The optical microscope was used to investigate the cracks occurred in the connectors printed in position 1, and the Emspira 3 Digital Microscope with an 8:1 zoom ratio with 26×- 206× magnification range was used to analyse the damage of the connectors printed in position 2. The micrographs were taken on the longitudinal and crosscut sections of the 3D printed connectors where cracks and fractured areas occurred after mechanical testing.

5. Results and Discussion

5.1. Strength of the L-Type Corner Joints

Both the reference and L-type corner joints with 3D printed connectors were subjected to diagonal compression and tensile tests and afterwards the results were compared for the maximum failure loads (Table 2) and for the bending moments calculated using Equations (1) and (2) together with the recorded displacements during the test (Figure 4). The average values of the results recorded for five samples and the standard deviations (values in the parentheses) are presented in Table 2 and in the graph from Figure 4.

Table 2

Average values of maximum failure loads, recorded for all experimental L-type corner joints

L-type corner joint/print position	Maximum failure tensile loads (F) [N]	Maximum failure compression loads (F) [N]
White PLA connector/position 1	613.5 (92.3)[1]	377.0 (30.1)
White PLA connector/position 2	1124.0 (161)	592.7 (27)
Reference (mortise-tenon joint)	464.6 (91.8)	357.4 (36)

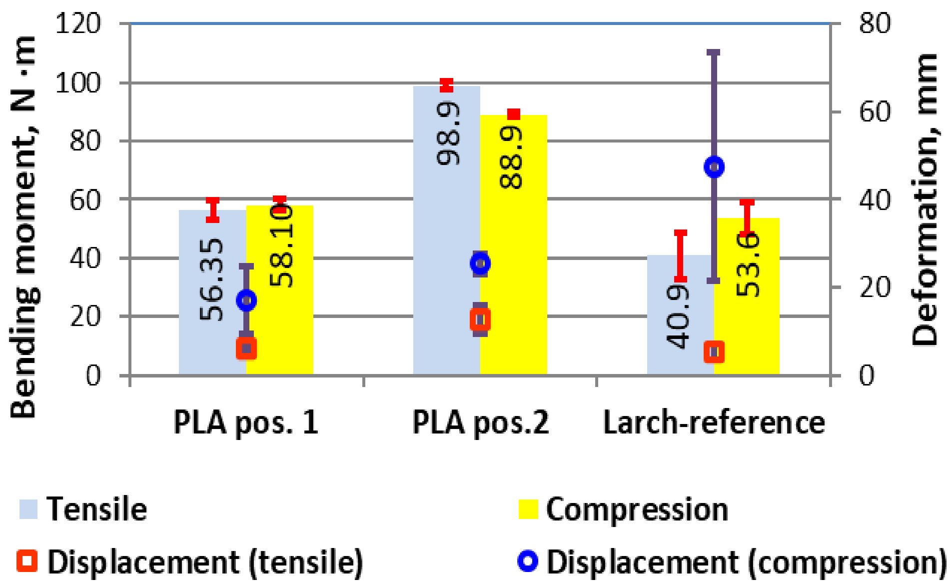
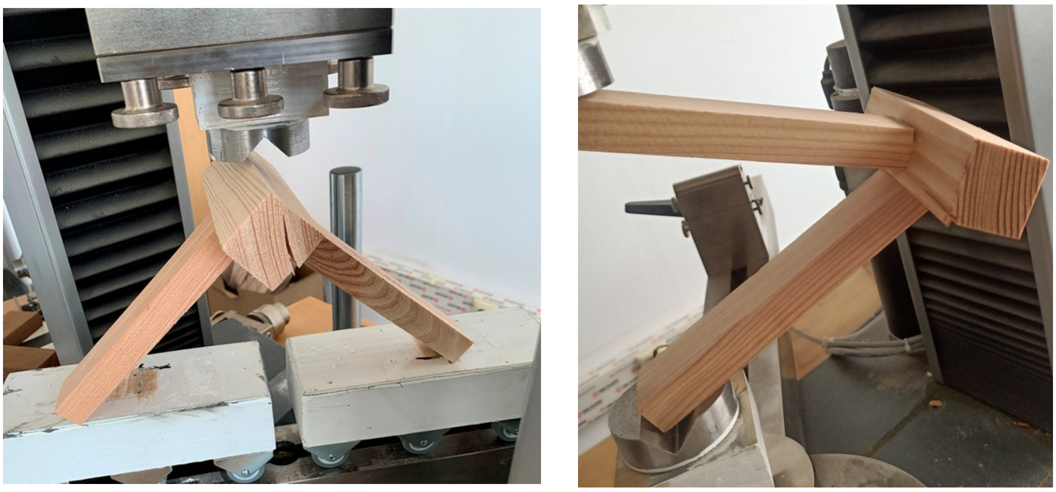


Fig. 4. *Bending moments and displacements under tensile and compression loads for the L-type corner joints with 3D printed connectors made from white PLA in position 1 (PLA pos.1) and position 2 (PLA pos.2), and for the common mortise-tenon joint made of larch wood, taken as reference (Larch-reference)*

The behaviour of the reference L-type corner joint during the test is highlighted in Figure 5a for the tensile load and in Figure 5b for the compression load.



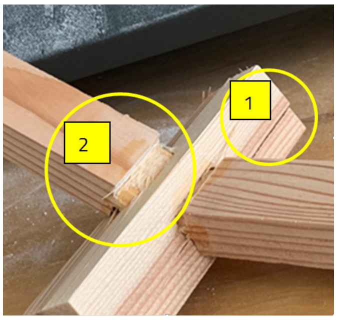
a. b.

Fig. 5. *Behavior under tensile (a.) and compression (b.) loads of the reference L-type corner joints*

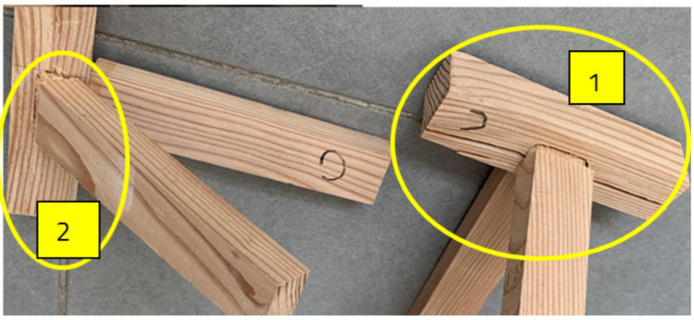
The lowest F value was recorded for the reference sample under compression load (357.4 N), and the highest was recorded for the L-type corner joint with the connector printed in position 2 under the tensile load (1124 N), as seen in Table 2. The data in Table 2 show that the recorded *F* values were higher under tensile than under compression loads, whilst the displacements had an opposite trend (Figure 4), namely lower under tensile than under compression loads. The same trend of the displacements was noticed for the L-type corner joints made of wood-based panels [23], approximately 1.5 times higher under compression load compared to tensile load. The lowest value is accompanied by the highest displacement value (47.3 mm) of the reference sample under compression load, as the diagram in Figure 4 and the image from Figure 5b show. In this case, the higher deformation of the L-type corner joints under compression load resulted in the occurrence of cracks, both on the piece of leg and on the stretchers, seriously affecting the mortise-tenon joint (Figure 6b) and ultimately the low recorded *F* values. In Figure 6, the marked circles marked with 1 show the deep cracks that occurred on the leg and the circles numbered with 2 highlight the fracture mode of the mortise and tenon joint.

While the mechanical tests damaged the wooden elements in the case of the reference sample, they remained unaffected after testing the L-type corner joints with the connectors (Figure 7). During the tests, the cracks occurred at the edges of the connectors, because of the forces exerted by the stretchers on the connectors.

Overall, the bending moment capacities of the L-type corner joints with connectors were higher than those of the reference, both under tensile and compression loads, as can be seen in the diagram in Figure 4. These findings highlight the benefit of using connectors instead of common mortise-tenon joints for chair production, because in addition to the other advantages related to the reduced production times and ease of manufacturing [16, 27] they also bring the advantage of higher strength than the wood itself.



a.



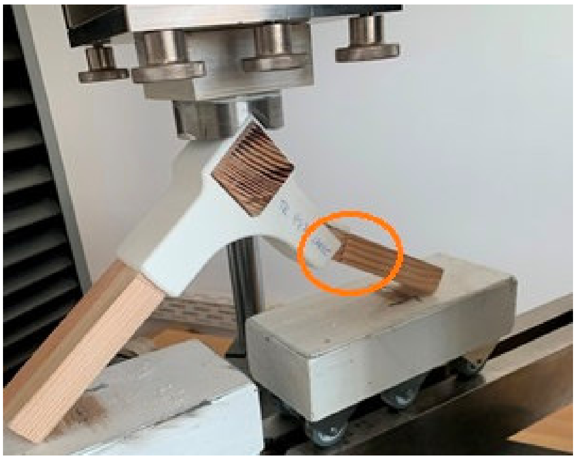
b.

Fig. 6. *The fracture mode of the reference L-type corner joint under tensile (a.) and compression (b.) loads*

The results presented in the diagram from Figure 4 clearly show that the orientation of the model in position 2 is preferable for a better mechanical performance of the L-type corner joint with a 3D printed connector. Thus, for the connector printed in position 2, *F* was 1.8 times higher for tensile load and 1.6 times higher for compressive load, compared to the L-type corner joint with the connector printed in position 1. The M_c value for the L-type corner joint with the connector in position 2 was 88.9 Nm, very close to the value of 95.54 Nm obtained in a previous study [3] for the mortise-tenon corner joint (250 mm x 250 mm long and 20 mm thick made of beech wood) used in the construction of a chair.

In the present research, no adhesive was used to bond the wooden parts to the 3D printed connector. In this case, the mechanical strength was based only on the friction forces and the assembly forces, but failed because of delamination which occurred between the 3D printed layers at the connection with the wooden stretchers, as can be seen in Figure 7, where these types of fractures are circled.

Cracks at the edge of the connectors caused the stretcher to slide out of the joint more quickly in the event of a larger delamination or fracture. The delamination between the printed layers in position 1 was deeper than in position 2, because the deposition of layers in position 1 was in the same direction as the length of the stretcher, so the forces applied by the stretcher inside the connector could strain easily, affecting the adhesion between the printed layers. A similar conclusion was presented in the study [13] for fasteners used for corner jointing wood and wood-based composites, which showed that the main reason for joint damage was fasteners slipping out of sockets. When bonding 3D printed connectors (made of ABS filament) to join two beech wood rails with the intention to use these connectors in the construction of a chair [9], maximum failure loads between 790 N and 905 N were recorded, which were higher than those recorded in the present study, but 2.5 times smaller than the wooden mortise and tenon joint taken as reference. Even though the tests of the assembled chair showed that the seat was strong enough, the 3D-printed connectors at the back ended up breaking. So it is possible that the solution of gluing the connector to the wooden parts increases the strength of the corner joint and implicitly the strength of the chair produced with these joints. This solution can be considered for the continuation of the present research.



a.

b.

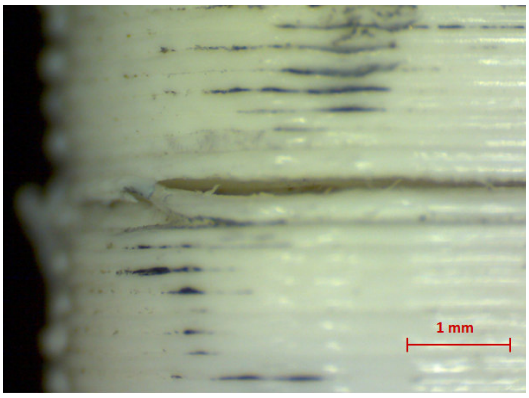
Fig. 7. *The fracture mode of the connectors after mechanical testing: a. under tensile load, print position 2; b. under compression load, print position 2*

5.2. Microscope Investigation

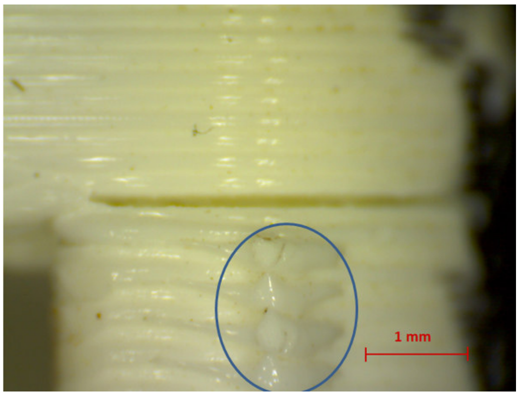
The microscope investigation was conducted in order to better highlight the fracture mode of the connectors after mechanical testing.

The pictures were taken in the longitudinal direction, considered to be along the direction of the stretchers and transverse, which means perpendicular to the direction of the stretcher. The 100x magnification images shown in Figure 8 are illustrative of the connector fractures after testing under tensile load in the longitudinal (Figure 8a) and transverse (Figure 8b) directions. The pictures showed that the connectors failed by delamination

In Figure 8a, the delamination process in the longitudinal direction is highlighted. The delamination propagation continues in the transversal direction (Figure 8b) and the circled area indicates the protrusions caused by the overlap of the material during the AM process and the deformation of the deposition layers in this area. It is possible that the surplus of accumulated material in this area determined the stress of the upper deposition layer, which is why delamination occurred between the layers in this area, as a result of the tensile stress accumulated. The cause of this excess material may be the inertia generated by the print speed.



a.



b.

Fig. 8. *Process of delamination propagation in the connector printed in position 1, under tensile load: a. in the longitudinal direction, magnification 100X; b. in the transverse direction, magnification 100X*

The delamination of the filament layers in the longitudinal direction particularly affects the edges of the opening where the stretcher exits the connector, due to the fact that the filament layers are oriented parallel to the length of the stretcher. Also, a component of the tensile load acts perpendicularly, tending to detach first the layers near the opening edge and continuing the delamination both longitudinally and transversely over large distances, producing structural failure and sliding of the stretcher outside the connector.

In Figure 9a it can be seen that the delamination propagates over a measured length of 6.624 mm in the longitudinal direction and continues in the transverse direction for another 3.728 mm (Figure 9b). The details in Figures 9c and 9d show that the delamination affected only two adjacent layers and the stresses did not fracture the filament layer.

In the case of the connectors printed in position 1 and subjected to both compression and tensile loads, the failures were influenced by the insufficient adhesion between two adjacent layers, capable of resisting the forces that push the layers in a perpendicular direction from the inside to the outside. These forces tend to first detach the layers near the edge of the connector where the stretchers are inserted and then continue to propagate the delamination over several centimeters. The failure loads in this case recorded low values, but the wooden parts remained undamaged, and no fractures of the PLA layers were observed.

When changing the orientation of the model on the build platform in position 2 (Figure 2b), the maximum failure tensile loads were 1.83 times higher than those recorded for the printed connector in position 1, and the maximum failure compression loads were 1.57 times higher than the previous ones. The printed layers subjected to high tensile and shear stresses failed, and the delamination propagated over short distances accompanied by local fractures of the material, as seen in Figure 10a for the diagonal tensile test and in Figure 10b for the diagonal compression test. The local fractures allowed the tests to continue without slippage of the stretchers, so the strength contribution of the PLA material resulted in increased connector strength.

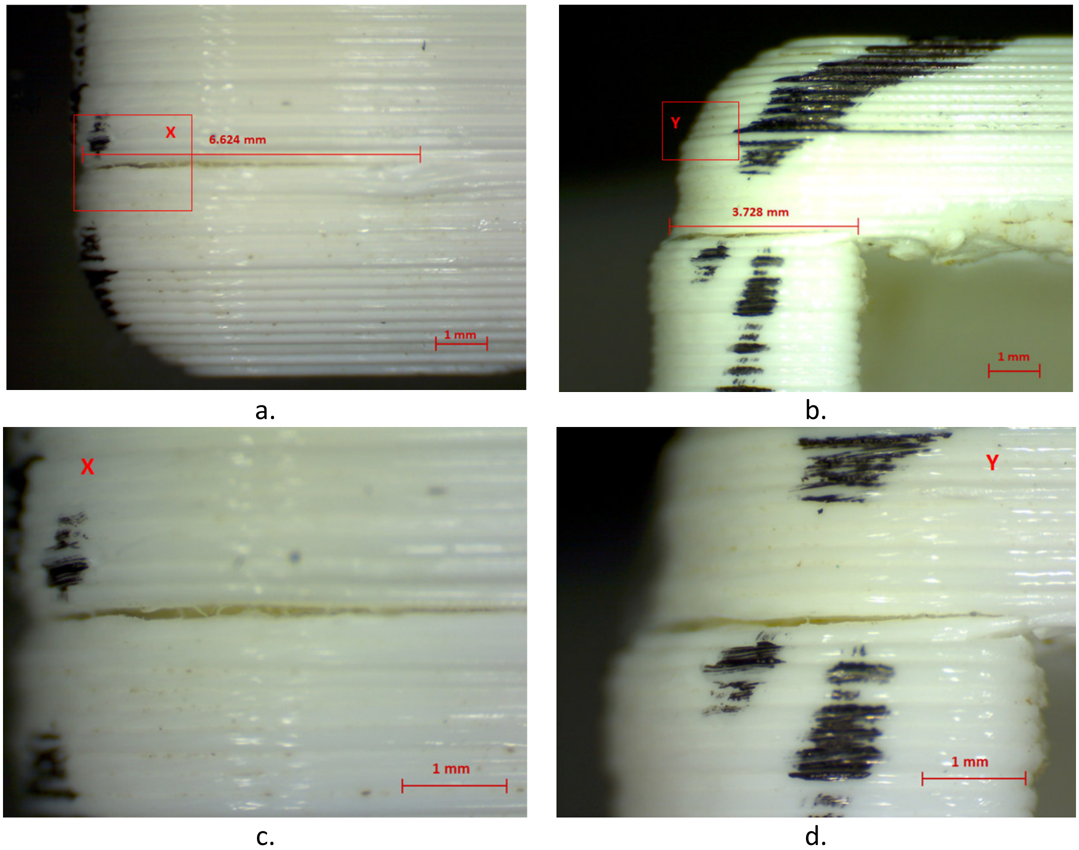
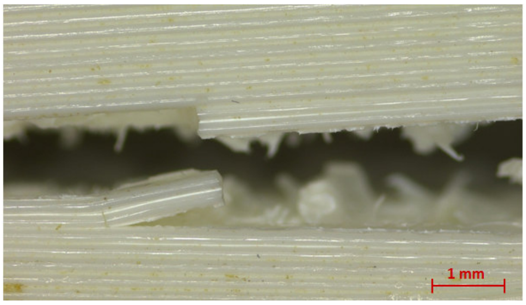
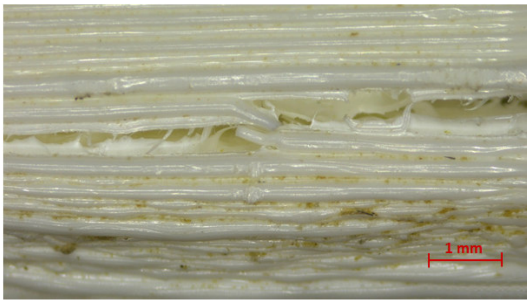


Fig. 9. *Process of delamination propagation in the connector printed in position 1, under compression load; a. in the longitudinal direction, magnification 50X; b. in the transversal direction, magnification 50X; c. detail of the delamination in the longitudinal direction, magnification 100X; d. detail of the delamination in the transverse direction, magnification 100X*

The L-type corner joints with the 3D printed connector made of white PLA filaments recorded better results compared to the common mortise and tenon joint taken as reference. None of the tests performed on the L-type joints with 3D printed connectors affected the wooden parts of the assembly. Only connectors failed into delamination and fractures, but higher values of the maximum failure forces were recorded for these L-type corner joints compared to the one made of larch wood parts, mortise and tenon jointed, taken as reference. In contrast, the wooden parts of the L-type reference corner joint were partially or completely broken during the tests. This is the main advantage of using 3D printed connectors for L-type corner joints in chair production, as the wooden parts remain unaffected if the chair is overloaded and the connectors are damaged. The connectors can be replaced and the chair can be easily rebuilt by reusing the wooden elements. This is not the case with the wooden chair if the parts of the chair are broken, because the reconstruction of the chair with the same wooden elements is not possible.



a.



b.

Fig.10. *Fracture mode of the connectors printed in position 2, magnification 80X: a. under tensile load; b. under compression load*

The connector presented in this research is the first design concept. Based on the actual results obtained, further research will be done by changing the shape and size of the connector or using a different filament to increase its mechanical performance. The use of other wood species instead of larch is another direction of research. Finally, an optimized connector shape and size will be used to produce a chair and to test it for strength.

6. Conclusions

L-type corner joints with 3D printed connectors are potential solutions that can be applied in chair manufacturing.

In the L-type corner joint, the stresses under diagonal tensile and diagonal compression loads are transmitted to the connectors, which fail in delamination and fracture, protecting the wooden parts, which remain unaffected.

If larch is used for the wooden parts, the maximum tensile and compression failure loads of L-type corner joints with 3D printed connectors are higher than those of the common mortise and tenon joint.

Changing the print orientation of the connector from the horizontal position (position 1) to the vertical position with support (position 2) resulted in improved strength of the L-type corner joint under diagonal tensile and diagonal compression loads.

Diagonal tensile and compression loads applied to the L-type corner joint with 3D printed connector in the vertical position typically fracture multiple layers of the part with partial interlayer delamination, resulting in a tendency to maintain strength in the affected area and increase maximum failure loads.

The cost of the 3D printed connectorjoint may be covered by saving wood, due to shorter stretchers, by eliminating machining mortises and tenons for adhesive joints, eliminating gluing times and time for assembly, which is transferred to the client. In addition, the package will be smaller because of the dismountable construction, and implicitly, the cost of transportation will be lower compared to the adhesive jointed chair.

Further research will be conducted to adjust the size of the 3D printed connector for jointing beech wood partsand to build a chair using 3D printed connectors and assess its strength.

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