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# MECHANICAL PROPERTIES OF L-TYPE CORNER JOINTS CONNECTED WITH 3D PRINTED CONNECTORS USING FUSED DEPOSITION MODELLING TECHNOLOGY

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***Abstract:***

*The paper presents the study of L-type corner joint between three wooden elements connected with a 3D printed connector obtained by applying fused filament fabrication (FFF) method as additive manufacturing and black polylactic acid (PLA) filament as material. The solid wood elements are made of beech (Fagus Sylvatica L.) and their jointing simulates the connection between leg and two stretchers (rail) of a chair. The corner joints with 3D printed connectors were subjected to mechanical testing under tensile and compression loads and the results were compared with those of the classical mortise-tenon jointed assembly of the same components, considered as the reference one. The results have shown that the assembly with the 3D printed connector was more resistant to tensile load than the reference, but couldn't reach the performance of the classical mortise-tenon joint when it was subjected to compression load. The analysis of the defects occurred in the connectors after mechanical testing revealed a good interlayer adhesion, but fractures in the structure of the PLA material, specific to hard and breakable materials. Instead, the wooden elements were less affected in this case compared with the classical joints, where large fractures of wooden components occurred, both for the leg and stretcher elements. The conclusion is that the 3D printed connector protects the wooden components from breaking in case of applying tensile and compression loads, being the first affected by the stresses occurred in the joint.*

***Key words:*** *Polylactic acid (PLA); fused filament fabrication (FFF); beech wood; 3D printed connector.*

## INTRODUCTION

Fused Filament Fabrication (FFF) is the most used method in additive manufacturing (AM), due to its simplicity, low cost and accessibility. It is used in modelling, prototyping, but also in the production of objects with various applications. It consists in depositing at a constant rate the material under constant pressure through a nozzle, and afterwards the extruded material completely solidifies, adhering to the previous material layer (Popescu *et al.* 2018). In the case of complex geometries it is necessary to add material to create a structure to support the geometry of the part in the correct position during the printing process, which is subsequently removed, in some cases with some difficulty (Aydin 2015). Currently, the materials from which filaments for FFF are made are thermoplastic materials, such as nylon, acrylonitrile-butadiene-styrene (ABS), polyethylene terephthalate (PET), polycarbonate (PC), polylactic acid (PLA) and thermoplastic polyester (TPC), and they are used to produce complex geometries (Shahrubudina *et al*. 2019). At present, the commonly used materials for filaments in FFF technology are ABS and PLA, especially for their low cost, but ABS filaments have as drawbacks the slightly toxic exudate and their sensitivity to thermal deformation, whilst the PLA filaments have the advantage of being environmentally friendly, allowing green production and new possibilities of development (Chen *et al.* 2023, Jarža *et al.* 2023). PLA filaments used in 3D printing have a variety of colours and can create an attractive design (Felek 2020), including hybrid furniture, where the wood in combination with other different colours of 3D printed components have an attractive appearance, without limitations of shapes and design, bringing also advantages, such as: ease of the technological processes especially for wood jointing, reduction of the production time and especially of the time allocated for the assembly process, manufacture dismountable furniture and thus allowing the secondary recycling of the wooden components, prolonging in the same time the furniture service life with a positive impact on the environment (Yang and Du 2022).

In the traditional manufacturing process, there are constraints in the execution of the joints between the wooden parts, which are usually limited to 90º angles and two components in the same joint (Magrisso *et al.* 2018) and that's why the 3D models of the printed connectors can be designed without any restriction of shape or number of jointed components. The 3D models can be created using Computer-aided design (CAD) software, such as AutoCAD, SolidWorks, Autodesk 3ds Max, Maya, Blender or Rhino, and as (.STL) files they are imported by the printer software, which slices the model into individual layers and send the information to the printer, which adds layers of material to obtain the printed object.

To provide safety in the use of the furniture, the 3D printed connectors are subjected to mechanical evaluation tests on the corner (L-type) jointed elements for the diagonal compression and diagonal tensile loads (Derikvand *et al.* 2015, Smardzewski *et al.* 2016, Ayrilmis *et al.* 2020, Majewski *et al.* 2020, Krzyżaniak *et al.* 2021, Nicolau *et al.* 2023) or, in the case of using the connectors to assemble the chairs, the strength and durability of the seat and back can be determined by applying perpendicular forces to their middle points (Aiman *et al*. 2020, Hajdarevic *et al.* 2023). In order to improve the mechanical strength, the manufacturing time and the quality of the surface of the 3D printed specimens with FFF printers, the studies from the literature show that the layer thickness and the raster widths have to be minimal (Simion and Arion 2016, Chacón *et al.* 2017, Popescu *et al*. 2018), and the temperature influences the PLA filament bonding (Chen *et al.* 2023). The presence of colorant additives in the PLA filaments (Wittbrodt *et al.* 2015) indicated that the inter-layers gaps have different sizes, depending on the colorants used, some of them having the feature to restrict the heat flow and influence the adherence between the subsequent layers.

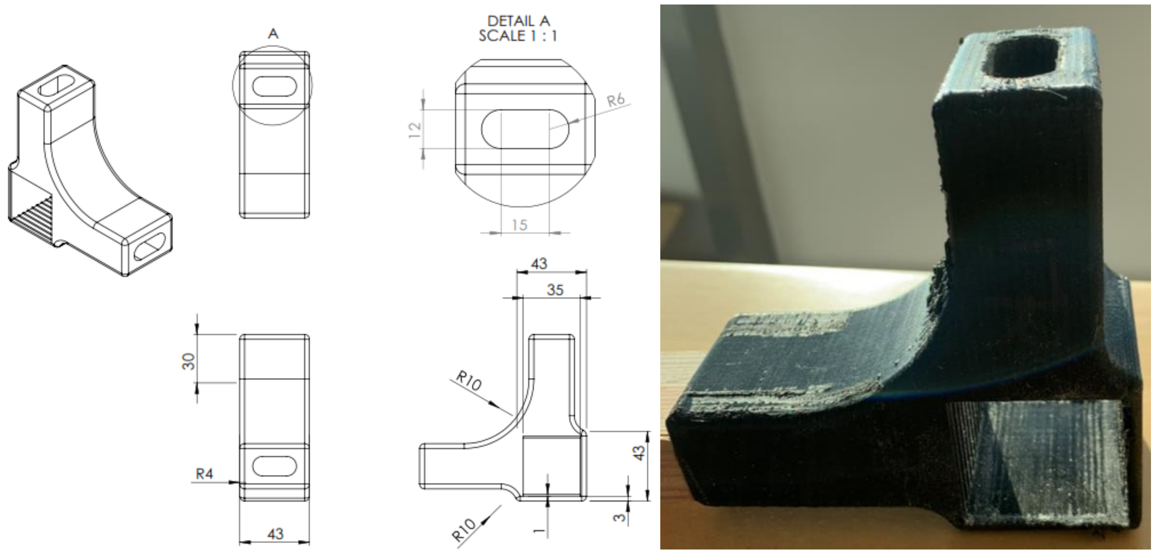
There is limited information available regarding the assessment of the mechanical strength of the 3D printed connectors for furniture and especially for the chairs, fact that influenced the motivation of the present study.

## OBJECTIVE

The objective of the present paper is to create in SolidWorks software a 3D model of the connector intended to be used for jointing the leg and two stretchers (rail) of a chair, to print the connector using black PLA filament as material and FFF technology for 3D printing, to assemble the beech wood elements and the connector and to test the formed L-type corner joints to diagonal tensile and diagonal compression loads and compare the results with the mortise and tenon jointed elements considered as reference.

## MATERIAL, METHOD, EQUIPMENT

The wooden components of the L-type corner joints were made from beech wood (*Fagus sylvatica* L.), with sizes of 50mm×35mm×35mm for the leg, and 210mm×35mm×22mm for the stretchers, at a moisture content of 8.5%. The calculated density of beech wood, as ratio between the masses and the volumes of the samples at the moisture content of 8.5%, was 698 kg/m$^3$.



**a** **b**

***Fig. 1.***
***Sizes and shape of the 3D printed connector used in the research: a. drawing of the connector; b. the 3D printed connector with black PLA.***

When the 3D printed connector was used, the wooden parts were introduced with a forced adjustment into the connector, and no adhesive was used. The wooden part corresponding to the leg has been introduced 50 mm along the square section (35mmx35mm) of the connector at a length of 50mm, and the two wooden stretchers have been introduced at 30mm depth into the rectangular sections of the connector. The sizes of the connector are presented in Fig. 1a, and the 3D model of the connector made using the software SolidWorks 3D CAD, version 2016 developed by Dassault Systèmes, France is presented in Fig. 1b. For the 3D printing, the 3D model was exported to the printer software as a ".sldprt" file. For the reference, commercial Novobond D2 polyvinyl acetate was used for mortise and tenon jointing.

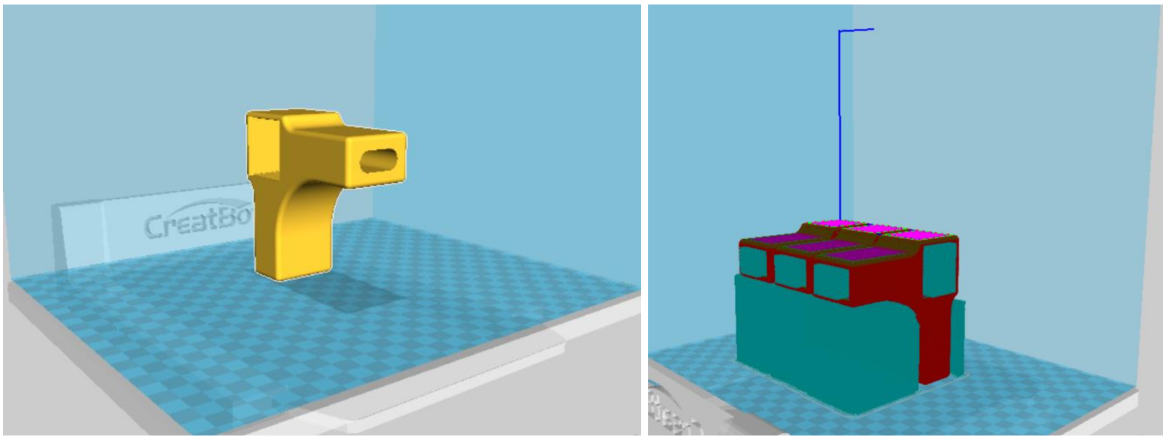
Black PLA filament with a diameter of 2.85 mm was used as material for 3D printing the connectors, using the CreatBot DX Plus-3D printer (manufacturer Henan Creatbot Technology Limited, Zhengzhou City, Henan Province, China). This printer has the following characteristics: filament diameter of 2.85 mm, nozzle temperature up to 260ºC, open filament system, maximum print speed of 200 mm/s, build area of 250mmx300mmx520mm, layer height between 0.05 mm and 0.5 mm, resolution 0.05 mm. In Table 1 the characteristics of the black PLA filament is presented, as provided by the manufacturer Formfutura VOF, Nijmegen (The Netherlands). The filament contains polylactic acid and additional colorant, which can imprint certain properties to the filament. The properties provided by the manufacturer are presented in Table 1.

*Table 1*

***Characteristics of the black PLA filaments used for 3D printing the designed connector***

| **Characteristics** | **Value** |
|---|---|
| Density | 1.24 g/cm$^3$ |
| Melting temperature | 210 ± 10 °C |
| Print temperature | 190 – 225 °C |
| Impact strength | 6 kJ/m$^2$ |
| Tensile strength (ASTM D882) | 105 MPa |
| Tensile modulus (ASTM D882) | 3145 MPa |
| Elongation at break (ASTM D882) | 175% |
| Flexural modulus | 2364.3 MPa |

FFF technology was employed for the 3D printing process. The main printing parameters were, as follows: printing speed of 50 mm/s; extrusion width 0.8 mm, flow 115%, fills density 100%, printing temperature 260°C, bed temperature 60°C, and layer height of 0.2 mm. For the support an overhang angle of 40°C and a fill amount of 40% were used. First, the filament deposition creates the base of the next layers as a closed contour, named perimeter. The infill deposition was selected to be done at an inclination angle of 45º relative to the direction of the perimeter and perpendicular to the previous layer. This pattern, alternating in the X and Y direction is considered appropriate to obtain resistant structures under mechanical loads, according to the studies from the literature (Kadhum *et al.* 2023, Sandanamsamy *et al.* 2023).



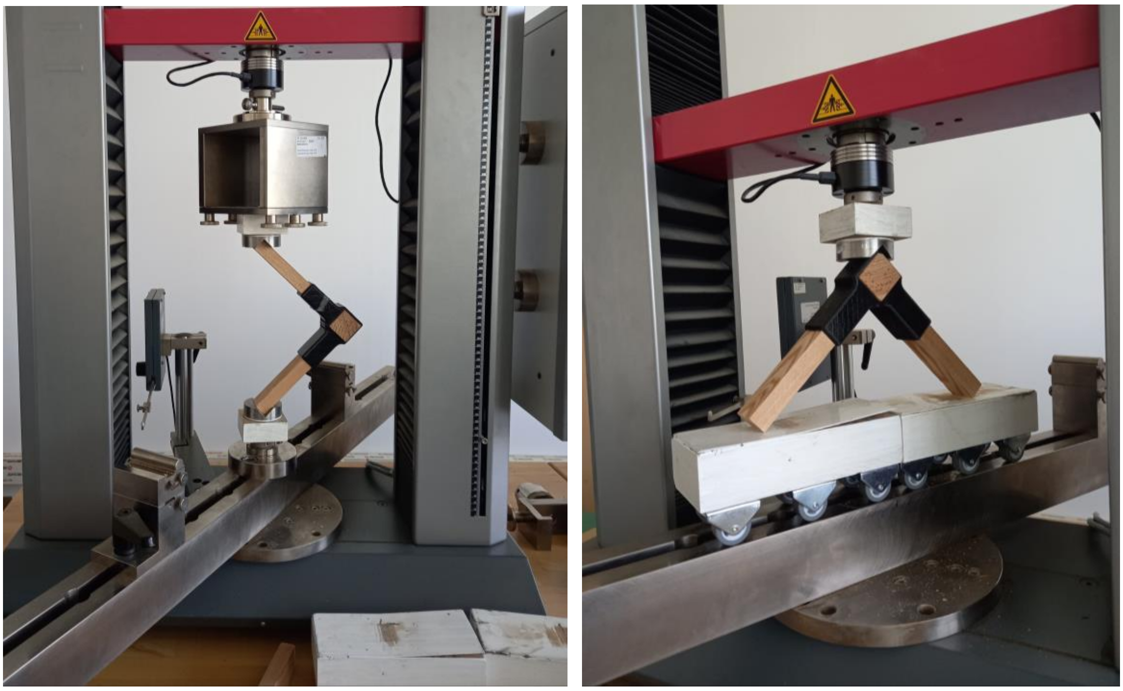
**a** **b**

***Fig. 2.***

***The printing position of the connector (a) and the placement of the support for 3 parts during the 3D printing process.***

The printing position of the connector is shown in Fig. 2a. As seen in Fig. 2b, three connectors were printed in the same time, but the deposition of the printed layers was possible only with the help of a support material, which is removed after printing.

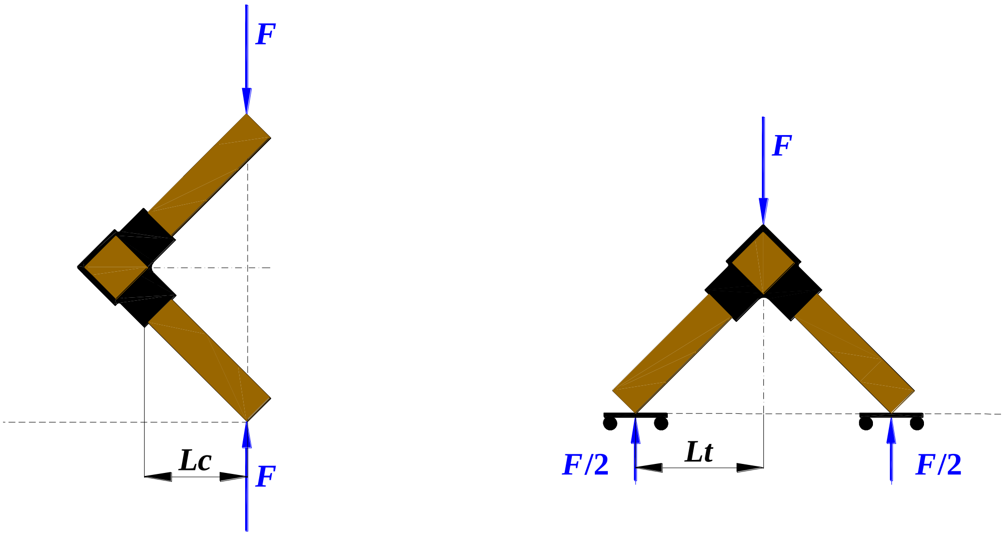
Both the classical mortise-tenon L-type joint between the wooden parts (reference), and the L-type joint with connector were subjected to diagonal compression and diagonal tensile testing in the same conditions. The tests were conducted on the Zwick/Roell Z010 universal testing machine (Ulm, Germany) for six samples of each L-type corner joint. The position of the L-type corner joint for the diagonal compression test is presented in Fig. 3a, and for the diagonal tensile test in Fig. 3b.



a b

*Fig. 3.*
***Testing the L-type corner joint where the 3D printed connector is included, under compression load (a) and tensile load (b).***

The theoretical models for calculating the bending moments under compression load (Mc) and under tensile load (Mt) respectively are presented in Fig. 4a and Fig. 4b.



a b

*Fig. 4.*
***The scheme of testing the L-type corner joint under compression load (a) and tensile load (b)***

The bending moments under the tensile (Mt) and compression (Mc) loads were calculated with equations (1) and (2), respectively:

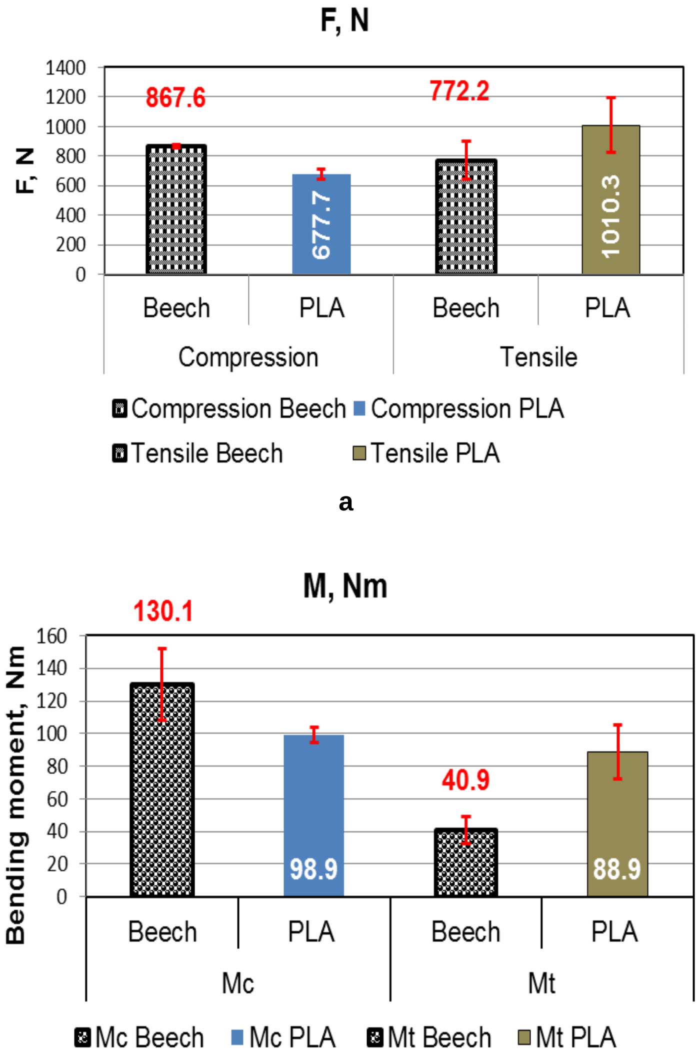
$$M_t = \frac{F}{2} \cdot L_t\,, [N \cdot m] \qquad (1)$$

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

where: Lt and Lc are the moment arms under tensile and compression loads, in m, and F is the maximum failure load, in N.

## RESULTS AND DISCUSSION

The average values of the maximum breaking forces recorded for the L-corner joints with connector (named as PLA) and for the reference (named as Beech) subjected to diagonal compression and diagonal tensile loads are presented in Fig. 5a and the mean values of the moments calculated with equations (1) for tensile and (2) for compression, are presented in Fig. 5b.



a

b

*Fig. 5.*

***Variation of the mechanical properties: Maximum force F, in N (a) and bending moments under compression load (Mc) and tensile load (Mt) (b).***

In the case of mortise and tenon beech wood joints, for both types of tests, it was observed that the more affected part of the assembly was the tenon, which have deformed and then broken, followed by deep cracks along the stretchers and rarely along the leg (Fig. 6). In Fig. 6, the chair leg fracture is marked with 1, the tenon break areas are marked with 2 and the deep crack of the stretcher with 3.

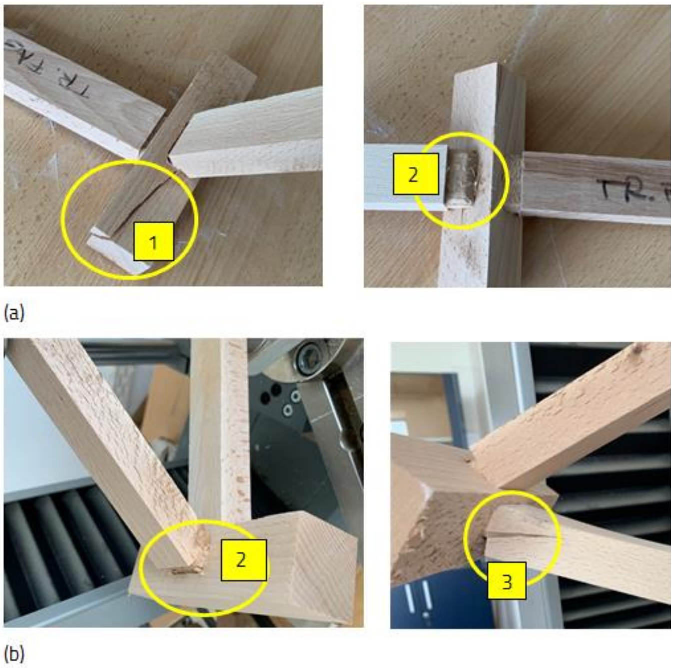


*Fig. 6.*
***The L-type corner joint of beech wood elements and the way of breaking them after applying the tensile (a) and compression loads (b).***

In the case of mortise and tenon joints subjected to compression and tensile loads, the predominant break (Fig. 6) occurred transversely on the tenon section, which demonstrates a better adhesion between the beech wood fibers, a property that is characteristic of high-density wood. Also from studying the graphs contained in Fig. 5 we note that the maximum force (F) under compression load has higher values than the one resulted under tensile load, and the bending moment (Mc) is greater than the tensile bending moment (Mt) in case of reference sample.

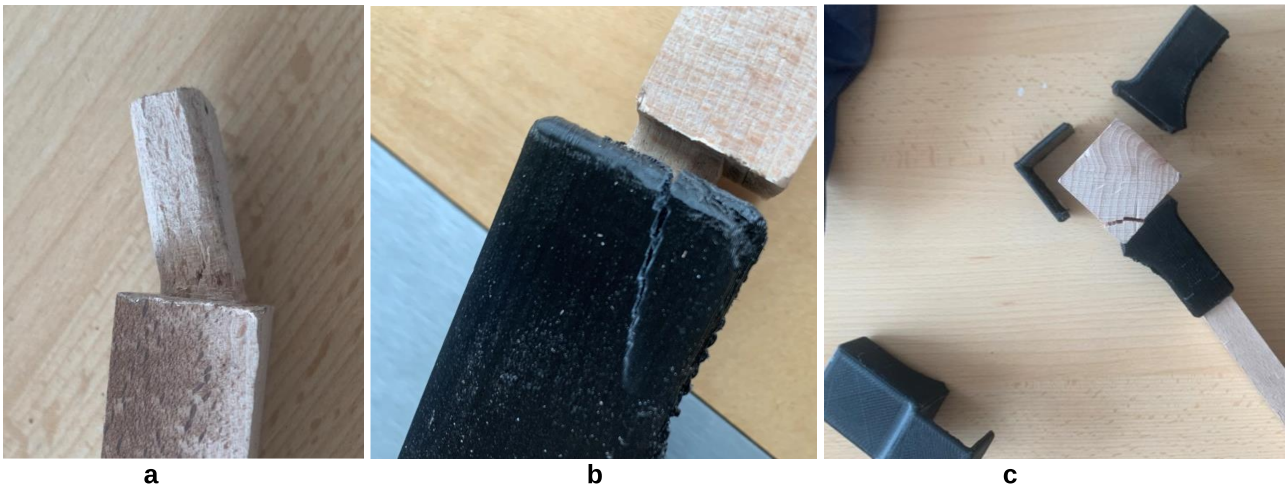


*Fig. 7.*
***The L-type corner joint where the 3D printed connector was used, and the way of breaking them after applying the tensile and compression loads; fracture of tenon (a), fracture of connector in the area of stretcher insertion into the connector (b) and partial fracture of leg combined with total fracture of connector (c).***

When testing the joints with the 3D printed connector, as seen in the graphs from Fig. 5, the maximum force (F) under tensile load is higher than the one obtained after the compression load was applied, and still the bending moment Mc remained higher than Mt. The conclusion is that the connector contributes to the strength of the L-type corner joint when it is subjected to tensile loads, but this assembly is not as resistant as the classical mortise and tenon joint in case of applying diagonal compression forces on the joint.

Analysing the images in Fig. 7, it can be seen the most frequent transversal fracture occurred at the tenon after applying the compression load (Fig. 7a). In Fig. 7b the cracks occurred at the connector in the stretcher insertion area (Fig. 7b) and rarely to the leg connection (Fig. 7c), when the corner joint was subjected to tensile load. The cracks in Fig. 7b caused the stretcher to slip out of the joint, faster in case of larger delamination or rupture, but the recorded maximum forces (F) were anyhow higher under tensile load for the assembly with connector than for the reference assembly. The same effect of sliding out the 3D printed connector of the socket on the joint damage was noticed for L-type joints of particleboard (Krzyżaniak *et al.* 2021). In this case, a great importance has the size accuracy of the wooden components and of the connector. When the adjustment between the connector and the stretcher is too wide, it is easier for the stretcher to slip out of the connector, causing the fractures of the connector. As noticed by several researchers (Chacón *et al.* 2017, Popescu *et al.* 2018), the accuracy of the printed specimen depends on the printing parameters and have influence on the mechanical properties of the final object.

The way the connectors were broken after subjected them to mechanical loads indicated that black PLA is a hard and breakable material. This feature can be influenced by the addition of colorant into the PLA natural material, which changes the tensile and yield strengths, the maximum strain and crystallinity in relation to the PLA as a natural state material (Wittbrodt and Pearce 2015).

Being made from a hard and breakable material, the 3D printed connector practically fractured on several layers after mechanical testing (Fig. 7), so the propagation of the cracks is not influenced by the interlayer adhesion, which can be considered a good one. In case of L-type corner joints with 3D printed connectors subjected to diagonal tensile and diagonal compression, the major failures occured in the connectors. Instead, the wooden elements were partially or totally broken during the tests for the wooden mortise and tenon L-type corner joints. This can be considered as an advantage for the assemblies with 3D printed connectors, because the wooden parts can remain unaffected during the use of the chair, and damaged connectors can be replaced, thus allowing the reuse of the damaged chair.

More than that, the assembly with 3D printed connectors allows the dismountable construction of the chair, so any damaged wooden components can be replaced, prolonging the life cicle of the chair. Black PLA proved to be a brittle material, so further research can be conducted on the increasing of the mechanical performance of the printed connector to the diagonal compression load, by applying tools like finite element method (FEM) to study the stresses occured in the connector, followed by an optimization of the shape and of the size of the connector, and by the construction of a chair with these optimized connectors and test the chair for strength and durability.

## CONCLUSIONS

- The analysis of the defects occurred in the connectors after mechanical testing revealed a good interlayer adhesion, but fractures in the structure of the PLA material, specific to hard and breakable materials.
- The wooden elements were very much affected in case of mortise and tenon jointed elements and less affected in case of using the 3D connectors for the assembly. It can be said that the 3D printed connector protects the wooden components from breaking in case of applying diagonal tensile and diagonal compression loads on the L-type corner joints with these connectors.
- The assembly with 3D printed connectors can be used in the construction of the chairs, allowing their dismountable construction and prolonging their life by replacing the damaged connectors or wooden components in case of damages occurred during their use.
- Black PLA filament used for the 3D printed connector behaves like a brittle material, and the mechanical testing of L-type corner joints that use this connector usually fracture several layers of the part with partial interlayer delamination, but have the tendency to maintain the strength in the affected area, as proved by the high values recorded for the maximum forces at break in case of diagonal tensile loads.
- The strength of the L-type corner joint with connector under the compression load is lower than for the mortise and tenon assembly, so further research is needed to improve this property, by optimizing the shape and sizes of the connector, and improve the adherence between the connector and wooden parts.
- A chair with the optimized connectors has to be constructed as a further step in research and strength and durability tests have to be conducted in order to see if the connector ensure enough strength to the assembly.

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