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Faculty of Furniture Design and Wood Engineering

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Study on jointing chairs elements using 3D printing technology

SUMMARY

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CONTENT

INTRODUCTION

Nowadays, additive manufacturing (AM) technology is used in many fields, such as prosthetics in medicine, components for the automotive and aeronautics industry, in the food industry and in construction.

In the furniture industry there are attempts to replace components made of wood or wood-based materials, as well as assemblies between components with three-dimensional (3D) printed parts, in particular for wood-based panel joints, giving them the possibility of easy assembly and disassembly. Replacing wood-based joints with 3D printed connectors is an opportunity, as the technology of making wood-based joints requires specialized machinery and assembly operations are time-consuming and labor-intensive.

In design, the concept of hybrid furniture has been introduced, which is a combination of wooden and 3D-printed component elements with aesthetic, ornamental and strength functions, unlimited color and shape potential. Designers, planners and engineers in the furniture industry can therefore take advantage of 3D printing technologies, simplifying structures and realizing product concepts that require minimal consumption of wood material, time and machinery.

3D printed connectors have many advantages in chair construction: the possibility to enhance the design by using colored materials and new concepts, without shape and size constraints, avoiding the use of adhesives and complicated technologies. Defects in classic chair joints (bowing, cracking and breaking) irreparably compromise the furniture. This raises the timely question of whether traditional chair joints can be replaced with 3D printed connectors, which give the furniture the same strength as traditional joints, with the added advantage of simple processing of wooden elements and their dimensional reduction, the removable structure of the chair and the transfer of assembly operations to the customer. This can also extend the service life of the seat by replacing the connectors in the event of the joints weakening over time in certain areas. From the bibliographical research on 3D printed connectors for furniture, it was found that this is an explorable field in terms of material selection and additive manufacturing method, especially for the construction of chairs, in the context of ensuring sufficient strength of the chairs, comparable to those achieved by classical wood joints.

The present research aims to verify the possibility of using 3D printed connectors in the assembly of the elements of the strength structure of a seat model, going through several stages of selection of the 3D printing method and material, the position of the part in the printer and the shape of the connector, based on the investigation of the strength of the "L-type" joint in tension and compression on the diagonal in the connector version, compared to the classic one of the "mortise-tenon" type. Thus, the thesis covers all phases of the design and development of a new product, based on the results of theoretical and experimental research obtained from the applied selections.

Starting from the 3D modeling of the connector in a first version, a preliminary step in this study is the selection of a material, an additive manufacturing method and a 3D printing position of the connector that satisfy the mechanical strength requirements of a seat. In this experimental research, two additive manufacturing methods, four materials for 3D printing of the connector and two positions for placing the model on the printer platform, horizontal and vertical, respectively, were proposed. For the solid wood parts in this preliminary research, a solid wood species with moderate mechanical performance, but to be used in seat construction, was chosen in this preliminary research: larch wood (Larix Decidua Mill.), from which a classical reference assembly mortise-tenon type, commonly used in seat construction, was built.

The selection criteria for the material, method and position of 3D-printed connector were the mechanical tensile and compressive diagonal mechanical performance of the "L-type" corner joints between solid wood elements and 3D-printed connectors in the above-mentioned variants. This testing method is not standardized, but is applied by many researchers in the literature (Derikvand and Eckelman, 2015; Podlena *et al.*, 2015; Smardzewski *et al.*, 2016; Magrisso *et al.*, 2018; Top *et al.*, 2019; Ayrilmis *et al.*, 2020; Krzyzaniak *et al.*, 2021) to compare the mechanical performance of different corner joints.

The next step in the experimental research of the thesis was to test the mechanical performance of the selected connector in assembly with a stronger wood species, commonly used in the construction of chairs and beech wood was chosen.

The next stage in the research was product development, i.e. modification of the shape and dimensions of the connector in order to adapt/align it to the mechanical strengths required by the new wood species used. The two new variants of the proposed connector were investigated in a similar way to the initial one, and the connector finally selected following the application of the mechanical performance criterion was used in the construction of a beech wood chair, and for comparison a reference chair was also made, identical in dimensions and sections of the component parts, but joined in the classic version, mortise-tenon joint.

The last stage of the research presented in the thesis concerns the verification of the designed connector in the final product, i.e. in the chair chosen as a model. For this purpose, the research was conducted in two directions:

- Testing of the two seats (the one with connectors and the reference one) using the system for analyzing the behavior of structures in fatigue tests and the system for optical analysis of 3D deformations for materials and components, by DIC (Digital Image Correlation) method at ICDT Brasov, Research Center "Numerical Simulation, Testing and Mechanics of Composite Materials".
- Testing of the two chairs according to SR EN 1728:2012 on the approved test stand of the Design, Prototyping and Testing Laboratory (Cluj Innovation Park, Regional Center of Excellence for Creative Industries, Cluj-Napoca) - RENAR accredited, for:
    1. Strength of the seat and backrest (SR EN1728:2012 item 6.4)
    2. Strength of the legs towards the front (SR EN 1728:2012 p. 6.15)
    3. Strength of the legs towards the side (SR EN 1728:2012 clause 6.16)

The thesis is structured in seven chapters as follows:

Chapter 1 entitled "THE CURRENT STATE OF RESEARCH ON THE USE OF ADDITIVE MANUFACTURING FOR FURNITURE" is bibliographical research, which provides an in-depth knowledge of additive manufacturing (AM), advantages and disadvantages of using AM, 3D printing methods, printers and materials used for 3D printing, materials with potential use in furniture manufacturing, Voronoi structures in additive manufacturing, testing of L-type fasteners. This chapter is also a summary of the research topics in this direction and emphasizes the results obtained by other researchers in the realization and testing of furniture assemblies and especially those using additive manufacturing methods. Through this theoretical study the research direction addressed in the PhD thesis is structured, starting from establishing the category of materials and 3D printing techniques with potential for use in additive manufacturing of furniture connectors and their testing methods.

Chapter 2 entitled "THE PURPOSE AND OBJECTIVES OF THE PhD THESIS" presents the general objective of the thesis and the specific objectives, setting out the research strategy to achieve these objectives. The main research objective of this PhD thesis is to design, develop and investigate a connecting element obtained by modern additive manufacturing technologies, which replaces the classical mortise-tenon joints of the seat construction and which provides at least the same mechanical strength as the original ones, under the conditions of simplification of the technological manufacturing process and the seat construction system.

Chapter 3 entitled "PRELIMINARY EXPERIMENTAL RESEARCH FOR SELECTION OF METHOD, MATERIAL AND POSITION FOR 3D PRINTING OF CONNECTOR" represents an important section in the experimental research of the thesis, in which two additive manufacturing methods used by other researchers in the furniture field are proposed, namely filament extrusion manufacturing (FFF) and selective laser sintering (SLS), accompanied by four materials corresponding to these 3D printing techniques, namely three types of PLA filaments and polyamide powder, in order to obtain a connector designed for the assembly of the component parts of the strength structure of a chair. The objective of the experimental research undertaken in this chapter is to select the material that gives sufficient strength to the connector, and for this purpose, the diagonal tensile and compressive strength of an "L-type" corner assembly between the solid wood elements associated with the seat components (leg-frame elements/links) using the 3D printed connector is used as the selection method. For comparison, the reference specimen was established as the one made with the classical mortise-tenon joint commonly used in chair construction. In this preliminary study, larch wood (Larix Decidua Mill.), a moderately strong species used in seat construction, was used for the joints.

The reason for this choice is that a gradation of the research is desired, in order to correlate the dimensions of the connector with the strength of the wood species, avoiding oversizing the connector in the early phase of the study, in case it would use a higher strength wood species. A new variable introduced in this research is also the impression position of the piece (horizontal and vertical), which is found to have an important influence on the strength of the connector.

Chapter 4 entitled "TESTING THE MECHANICAL PERFORMANCE OF THE "L-TYPE" CORNER JOINT WITH BLACK PLA CONNECTOR AND BEECH WOOD ELEMENTS" utilizes the results and conclusions of the preliminary research in the previous chapter and tests the mechanical performance of the previously selected connector for joining larch wood elements to similar beech wood elements. It turns out that this connector, with the shape and dimensions designed in the first variant, does not reach the strength performance of the reference sample made in this study in beech wood, which is why a new stage, that of redesigning the connector, is carried out to meet this requirement. The experimental study in this chapter is accompanied by a theoretical study using Finite Element Analysis (FEA), in which the displacement of the system is followed by simulating the two mechanical stresses of the "L-type" connector assembly, thus visualizing the areas of the connector with maximum stresses and strains, valuable information for the connector redesign phase.

Chapter 5 entitled "RESEARCHES ON THE INFLUENCE OF CONNECTOR MODIFICATION ON THE MECHANICAL PERFORMANCE OF BEECH WOOD ELEMENTS IN CORNER JOINING" continues the experimental investigations of the previous chapter, using two other connector variants, modified in shape and dimensions, to fulfill the strength condition of the "L-type" corner joint at the level of the classical mortise-tenon "L-joint". A new finite element analysis on the connector resulting from the modification of the dimensions of the initial variant in the areas of maximum stresses, indicates a reduction of stresses and deformations in the critical areas, but not their disappearance. Following the mechanical tests carried out on the joint with this type of connector, these critical areas yielded, causing the part to break, but the maximum breaking forces were at the values recorded by the reference sample, which is why further research was carried out using this connector.

Chapter 6 entitled "TESTING A SEAT MADE WITH 3D PRINTED CONNECTORS" presents the research carried out on the final product, the chair, using as connection elements the connectors validated in the previous chapter and having as a term of comparison a similar chair built with the classical joints tested previously. The experimental research in this section of the thesis followed two directions: testing the two chairs according to SR EN 1728: 2012 on the approved test stand of the Design, Prototyping and Testing Laboratory (Cluj Innovation Park, Regional Center of Excellence for Creative Industries, Cluj-Napoca) - RENAR accredited, for the resistance of the seat and backrest, the resistance of the legs towards the front and side and, second direction, testing using the system for the optical analysis of 3D deformations for materials and components, using the DIC (Digital Image Correlation) method at ICDT Brasov, Research Centre "Numerical Simulation, Testing and Mechanics of Composite Materials", for visualization of the deformations at the joints, under the application of forces higher than those physically applied on the approved test stand, 1300 N. None of the tests carried out destroyed the two seats, both withstanding forces in excess of 15 000 N without affecting their strength structure.

Chapter 7 entitled "GENERAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. FUTURE DIRECTIONS OF RESEARCH" concludes the PhD thesis, summarizing the results obtained from the research carried out, as well as the possibilities of exploiting them in practice, while indicating some future research directions opened by this theme.

Regarding the dissemination of the results of this PhD thesis, a total of 4 scientific papers have been published (two ISI indexed articles and one article indexed in international databases). The ISI indexed papers have been presented in two international conferences. The fourth paper is accepted for publication in the Bulletin of Transilvania University of Brasov, indexed in international databases.

CHAPTER 1. CURRENT STATE OF THE RESEARCH ON THE USE OF ADDITIVE MANUFACTURING FOR FURNITURE PURPOSE

There are studies in the literature about the possibility of realization of connectors by additive manufacturing (AM) technology, mainly used for joining panels in storage furniture, and less for seating furniture components, and the research on the strength of the joints is not sufficiently investigated.

For right-angle (L-type) joints for furniture parts, tensile and compressive strength is generally tested. There are also a number of researches investigating the strength and stiffness of 3D printed joints for demountable storage furniture (modular furniture) and customizing it in terms of design.

The present study presents current research in the literature on AM technology applied to furniture manufacturing, providing a starting point for the research in the PhD thesis.

1.1 Additive Manufacturing (AM) or 3D printing technology

Additive manufacturing (AM) or 3D printing technology is the technology by which an object is obtained by successively depositing layers of material (Groth *et al.*, 2014).

1.1.1 Advantages and disadvantages of AM

3D printing technology has the potential to revolutionize industries and change the concept of traditional production lines. Adopting 3D printing technology will increase production speed while reducing costs (Shahrubudina *et al.*, 2019).

1.2 Additive manufacturing methods

There is a wide range of additive manufacturing methods. Each of these built the object in successive layers (Lancea *et al.*, 2018).

By type of material used (Ramya and Vanapalli, 2016), 3D printing technologies can be categorized into processes:

- using liquid material;

- powder-based;

- solid-based;

- based on lamination.

Manufacture by filament extrusion (FFF) or thermoplastic extrusion molding (FDM) technology

The FFF method (FDM as its commercial acronym), is the method of depositing layers of a certain thickness by melting thermoplastic filament and is the most widely used in additive manufacturing, due to the affordable equipment and ease of printing. It is used for prototyping but also in production. It consists of applying the material under constant pressure through a nozzle, at a constant speed and complete solidification after exiting the nozzle, adhering to the previous layer of material (Popescu *et al.*, 2018). To support the part, in the case of complex geometries, it is necessary to add additional material (Aydin, 2015). The support structure is subsequently removed, in some cases with some difficulty.

Thermoplastic materials used in FFF include:

- acrylonitrile butadiene styrene (ABS);
- acrylonitrile styrene acrylate (ASA);
- nylon 12 (PA12);
- polycarbonate (PC);
- polyetherimide (PEI or ULTEM);
- polylactic acid (PLA);
- thermoplastic polyurethane (TPU).

Material properties such as ultraviolet (UV) resistance, bio-compatibility, transparency or hardness make them perfect for industries producing special purpose components (Saad, 2016).

Selective Laser Sintering (SLS)

SLS technology uses a high-powered laser beam to sinter the powdered material in successive layers to create the desired object. The 3D modeled virtual part is converted into cross-sectional planes, which are transmitted to the printer software. Based on the received information, the 3D printing equipment controls the path of the laser beam, which sinters the powder layer inside the cup, respecting the cross-sectional shape of the virtual model. After the sintering of the powder layer is completed, the printer platform is lowered into the interior of the vat one layer thick. Then the next powder layer is applied, which is also sintered. The process is repeated until the entire model is built according to the CAD modeling file. Throughout the printing process, the part is permanently embedded in the no sintered powder, resulting in parts with complex shapes without the need for backing material. The advantage of this method is that the residual powder in the bowl can be used in subsequent constructions (Finaa *et al.*, 2017).

Materials used can be: thermoplastic powders (nylon, polyamide, polystyrene, elastomers, composites), metal powders (steel, titanium, alloys), ceramic powders, glass powders (Saad, 2016).

1.3 Materials used for 3D printing technology

The most widespread materials used in 3D printing are polymers, due to their wide availability, excellent mechanical properties, low cost and simplicity of adaptation to different 3D printing techniques (Ranjan *et al.*, 2022). Polymers are used in powder, filament and sheet form. AM technologies also use active polymerization of photosensitive resins (Stansbury and Idacavage, 2016). Thermoplastic polymers such as nylon, acrylonitrile-butadiene-styrene (ABS), polyethylene terephthalate (PET), polycarbonate (PC), polylactic acid (PLA) and thermoplastic polyester (TPC) are used in 3D printing using FFF technology to produce complex geometries (Shahrubudina *et al.*, 2019).

1.4 Materials with potential use in 3D printing technology for the furniture

PLA and PLA matrix composites

PLA is a bio-plastic, formed from a repeated chain of lactic acid and is recyclable using conventional methods. Specifically, PLA is an aliphatic thermoplastic polyester derived from corn and can even be composted like other organic materials. PLA is versatile, and PLA-based composites have been investigated in the literature, including composites with natural fibers, micro fibrillated cellulose, man-made cellulose and abaca fibers, carbon nanotubes, and even metal reinforcement elements (Pringle *et al.*, 2022).

PLA reinforced with glass staple fiber has been studied as a material solution for the filament used in FDM 3D printing technology (Li *et al.*, 2018).

1.5 Voronoi structures in additive manufacturing

The Voronoi diagram is a partition into regions approximated by a set of points distributed in the plane called seeds or sites. For each seed there is a corresponding region consisting of all points in the plane closer to that seed than to any other. These regions are called Voronoi cells. The repetition of several cells constitutes the Voronoi diagram (Fig.1) (Aurenhammer, 1991; Martínez *et al.*, 2018; Merland *et al.*, 2014; Gan *et al.*, 2005).

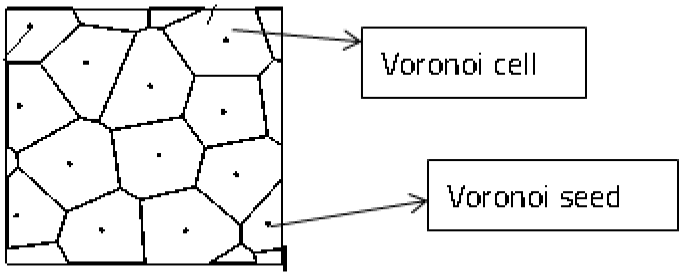


Fig. 1. Shape of the Voronoi diagram (Gan *et al.*, 2005)

1.6 Applications of additive manufacturing technology in the furniture industry

In the furniture industry, mass production is still carried out using traditional methods. However, today's level of technology in additive manufacturing makes it possible to produce joints, components or entire pieces of furniture using AM technology. Although mainly used in the production of prototypes, there are clear trends that AM is also being used for mass production. Compared to traditional technologies, 3D printing technology offers design freedom and makes it possible to produce complex geometries (Aydin, 2015).

1.7 Testing of “L type” corner joints

Mortise-tenon joints are still widely used in timber construction. Despite the increasing use of applied tenon joints, but mortise-tenon joints are irreplaceable for some types of furniture construction, particularly seating.

Seats are exposed to various direct and indirect loads during their lifetime. In general, different types of mechanical loading, such as tensile, compressive, bending, shearing and torsion, affect the joints of the elements that make up the seat structure. As a result of these loads, adverse effects such as bending, cracking and tearing may occur in the connecting elements of the seat structure.

Diagonal compression and tensile tests of 'L-type' joints between seat elements, made with mortise-tenon joints and with round tenon, in order to determine the comparative mechanical performance of the two types of joints were presented in the study (Ayrilmis *et al.*, 2020). According to the results of the tests, the mortise-tenon joint gave better results than the one with applied tenons.

1.8 Conclusions

- Furniture prototypes 3D printed and made demonstratively to showcase the capability of the printer are not tested for mechanical strength.

- To verify the mechanical strength of a joint, the literature recommends testing a corner (L-type) assembly under diagonal tensile and compressive loads and calculating the bending moment (Derikvand and Eckelman, 2015; Smardzewski *et al.*, 2016; Magrisso *et al.*, 2018; Top *et al.*, 2019; Ayrilmis *et al.*, 2020; Krzyzaniak *et al.*, 2021). This method is a model to compare the mechanical strengths of corner joints and was applied to select the connector according to the applied variables (3D printing material, seating position in the printer, shape and dimensions) for the construction of the final product, the chair.
- In the literature there are studies on the possibility of realization of connectors by additive manufacturing (AM) technology, mainly used for joining panels in storage furniture, and less for seating furniture components, and the research on the strength of the joints is not sufficiently investigated.
- The field of 3D printed connectors for seating is under-explored in terms of material and additive manufacturing method in the context of providing strengths comparable to those of traditional chairs.
- 3D printed connectors can bring advantages in chair construction: free design, avoidance of adhesives and complicated technologies, disassembly and transfer of assembly operations to the user, extension of the life of the chair by replacing connectors in case of weak joints, saving of massive wood by reducing the size of the chair components and last but not least, reduction of transportation costs due to reduced packaging.

CHAPTER 2. AIMS AND OBJECTIVS OF THE DOCTORAL THESIS

The general objective of the PhD thesis is to investigate the possibility of replacing the classical seat construction connecting elements, mortise-tenon joints, with 3D printed connecting elements, which provide at least the same mechanical strength as the original ones, while simplifying the seat construction system.

Starting from the objective of the thesis, the experimental and theoretical research strategy involves the following specific objectives:

OS1. Determination of the dimensions for the components of the seat joined in the classic version (mortise-tenon).

OS2. 3D modeling of a connector to replace the cep proprio-shell joint between the leg and the two seat links.

OS3. Experimental investigation of the mechanical strengths of the 3D printed connector joint using different materials and 3D printing techniques.

OS4. To simulate the behavior of the 3D printed connector joint in compression and tension using finite element analysis (FEM) in order to optimize the shape and dimensions of the connector.

OS5. To test the mechanical strengths of the classical mortise-tenon assembly between the seat components considered in the experimental research, using two different wood species: larch (Larix decidua Mill) and beech (Fagus sylvatica L.).

OS6. Comparison of results and selection of wood species, method and 3D printing material for the construction of a chair with connectors obtained with AM technology.

OS7. Testing the strength of the chair made in the classical version and with 3D printed connectors in a specialized laboratory and comparing the results.

Steps towards achieving the objectives:

- Literature survey on the current state of development of AM technology, specific printing methods and materials, areas of use, application results in furniture manufacturing and testing possibilities.
- 3D modeling of the connector to replace the mortise-tenon joint.
- Experimental research on the mechanical strengths of seat element assembly using 3D printed connector by applying different 3D printing methods, materials and positions:

- 3D printing of the connector with the FFF method in the seating position without support layer, using three types of materials: white PLA, black PLA, glass fiber reinforced PLA;

- realization of the L-type assembly and its diagonal tensile and compression testing, data processing and comparison of results;

- selecting the material that obtained the best mechanical results and changing the printing position;

- 3D printing the connector with the SLS method and using the PA12 material;

- making the L-type assembly and testing it in tension and compression, processing the data and comparing the results with those obtained using the connector 3D printed using FFF additive manufacturing technology;

- selecting the optimal 3D printing method and the material with the best mechanical test results;

- ◘ Experimental research on the influence of the wood species used in the assembly on its mechanical tensile and compressive strength:

- 3D printing the connector with the method and material selected above;

- realization of the L-type assembly and its tensile and compression testing on the diagonal using two wood species: larch and beech;

- data processing and comparison of results;

- selection of the wood species with the best mechanical results for final testing in the construction of a chair.

- ◘ Experimental investigation of the influence of connector shape and size on the mechanical tensile and compressive strength of the L-type assembly:

- Simulating the behavior of the 3D printed connector assembly in compression and tension using finite element analysis (FEA);

- modification of the connector shape to improve mechanical strengths;

- 3D printing and mechanical testing in the 'L-type' assembly of the new connector;

- data processing and comparison of results, selection of the connector with the final shape and dimensions for the seat construction for final testing.

- ◘ Experimental investigation on the strength of a chair built with 3D printed connectors:

- designing a chair with the previously tested component parts (keeping the same dimensions for the leg and leg links, seat frame rails and cross members;

- manufacturing the seat in classical design (with its own cep-shell jointing elements);

- manufacture of the seat with the same components in the proposed construction system with connectors;

- testing the seats in a specialized test laboratory and comparing the results.

The strategy to solve the PhD thesis objective is schematically represented in Fig. 2.

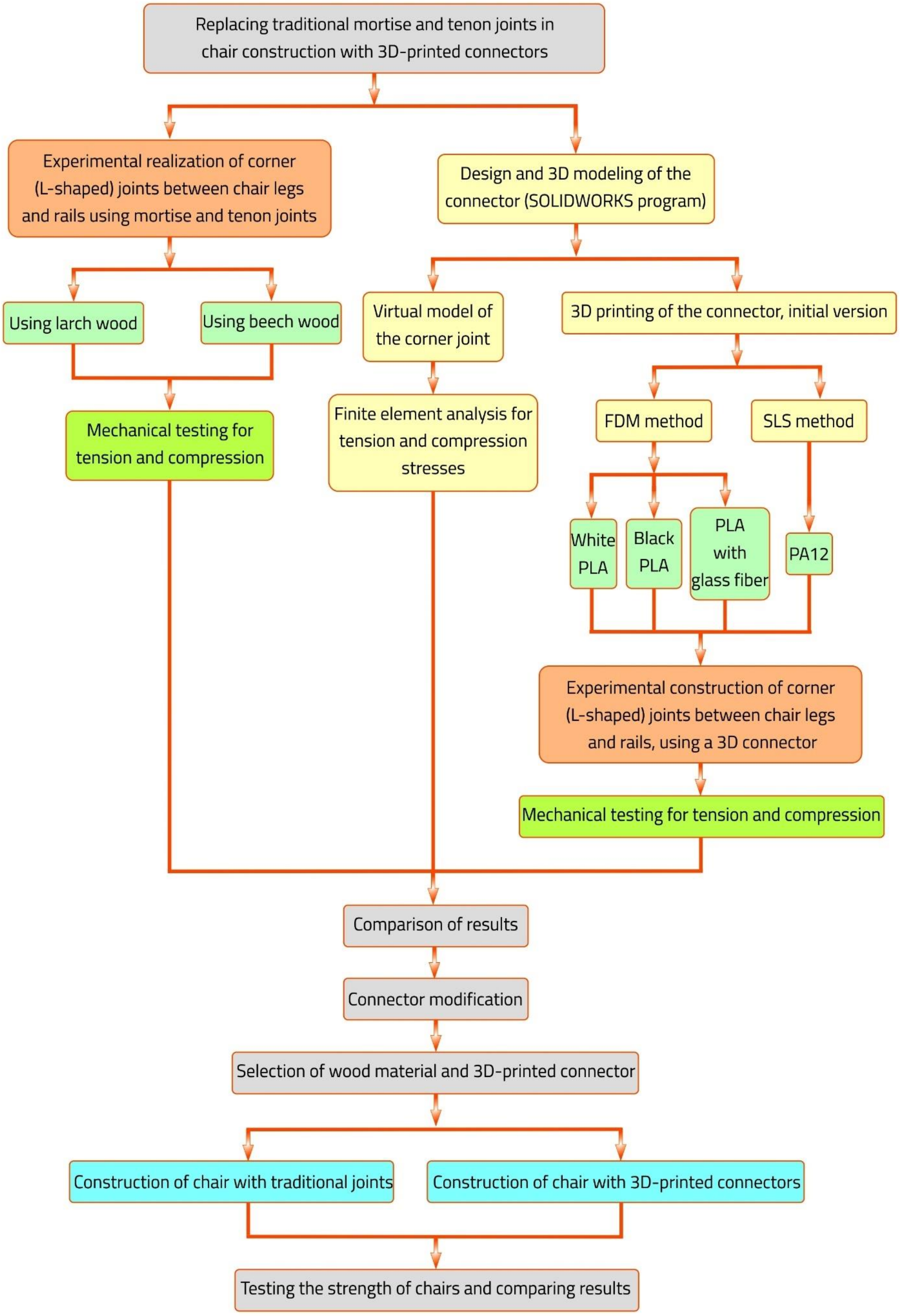


Fig. 2. Strategy for solving the objective of the PhD thesis

CHAPTER 3. PRELIMINARY EXPERIMENTAL INVESTIGATIONS FOR THE SELECTION OF METHOD, MATERIAL AND POSITION OF THE CONNECTOR DURING 3D PRINTING

In the preliminary experimental research presented in this chapter of the thesis, the starting point was the modeling of a connector intended to join the elements of a chair (the frame elements, i.e. the lower links joined to the chair legs).

The criteria for the selection of material, method and 3D printing position was the mechanical performance of the connectors in an "L-type" corner joint subjected to diagonal tensile and compressive stresses, with the idea of satisfying the mechanical strength requirements necessary for the construction of a chair.

In this experimental research, two additive manufacturing methods, four materials for 3D printing of the connector and two positions for placing the model on the printer platform were proposed, respectively:

- FFF method of additive manufacturing with the following materials:
    - White PLA;
    - black PLA;
    - Composite PLA with glass insert.
- SLS additive manufacturing method using the following material:
    - White PLA;
    - Black PLA;
    - DuraForm PA Plastic polyamide powder.

The two positions for placing the model on the printer platform:

- Horizontal, without support.
- Vertical, with support bracket.

For the solid wood parts, larch (Larix Decidua Mill.), a wood species with moderate mechanical performance but used in chair construction, was chosen in this preliminary research. The classical 'own log-plank' assembly commonly used in chair construction served as a reference sample.

3.1 Experimental design

The experimental model envisages the realization of an "L-type" corner assembly, including the seat leg and its links, as can be seen in the detail in Fig. 3. The same construction system is applied for the seat frame, consisting of the four seat legs and the stringers and cross members connecting them.

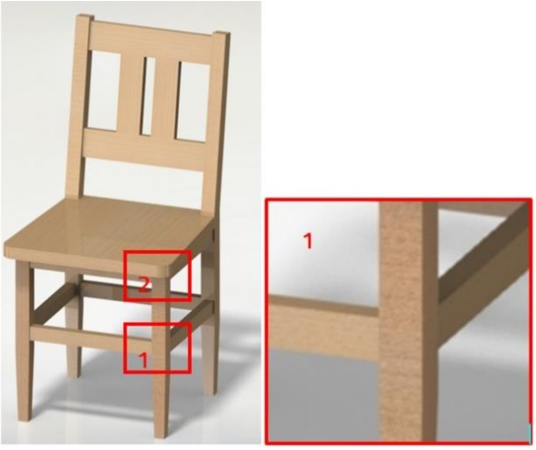
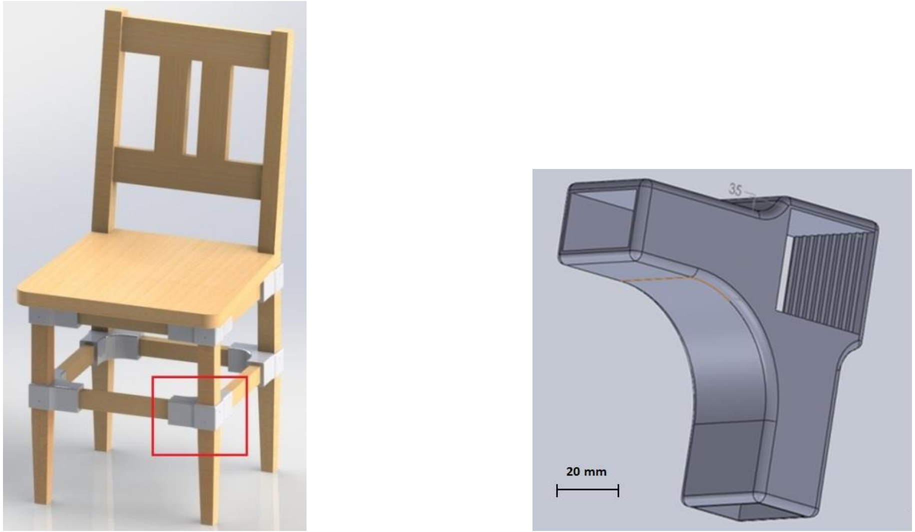


Fig. 3. The seat model considered for the connector design, i.e. for the "L-type" joint between the legs and the links (detail 1) and between the cross-member and the seat leg-leg cross-member (assembly 2).

For this 90° joint, the design of a connector is envisaged to make the joint in such a way that the woodworking processes are as simple as possible, without requiring large amounts of labor and processing time. In the classic machining method, the joints for wooden structures of this type are made with mortise and tenon joint

The 3D designed chair model for this research, which uses connectors printed with additive manufacturing technology for the 90° joint of the chair leg with the rest of the elements, is shown in Fig. 4a, and the designed connector model is shown in Fig. 4b.



a. b.

Fig. 4. The designed connector construction system: a. 3D modeling of the seat with connector; b. 3D model designed for the connector.

The software used in the 3D modeling of the seat and the joint for the seat frame and leg link components is SolidWorks 3D CAD, version 2016 developed by Dassault Systèmes, France.

3.2 Materials used in the experimental research

3.2.1 Wood species and materials used in additive manufacturing. Characteristics

For the experimental research in this PhD thesis, two species of wood used in the construction of chairs were considered: a resinous species, namely larch wood (*Larix Decidua* Mill.) and a deciduous species, namely beech wood (*Fagus sylvatica* L.).

The density of larch wood, calculated at a moisture content of 9.2%, was 607 kg/m^3, and that of beech wood, as the ratio between the masses and volumes of the samples at a moisture content of 8.5%, was 698 kg/m^3. The commercial polyvinyl adhesive *Novobond D2* was used for the classic mortise and tenon joining.

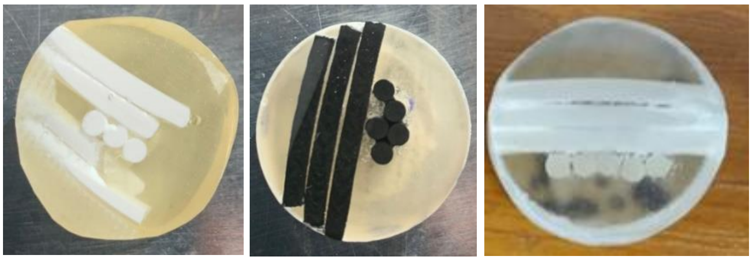
White PLA filament, black PLA filament and a glass fiber reinforced white PLA composite (PLA-Glass 041-285-750) were used as materials for the FFF technology connector in order to have the possibility to compare the mechanical performance of the 3D printed connector made of different materials.

DuraForm PA Plastic powder manufactured by 3D Systems (Hertfordshire, United Kingdom) was chosen as the material for the SLS 3D printing method of the connector.

3.2.2 Micrographic analysis of the materials used in the 3D printing of the connector

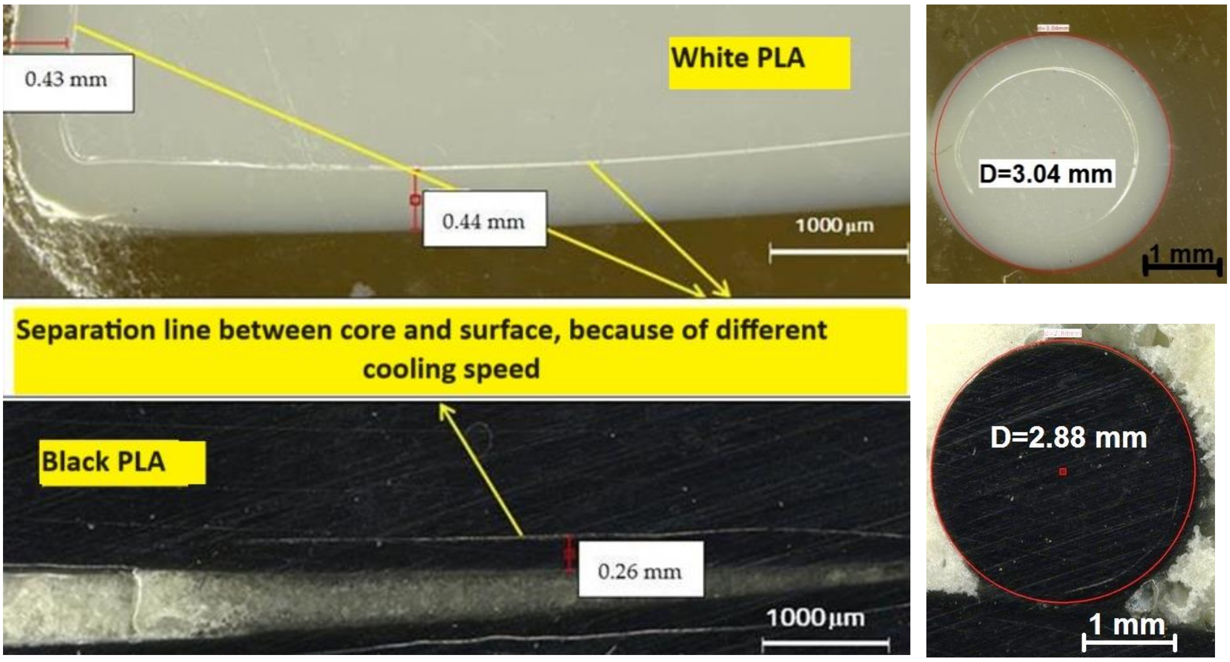
The microscopic investigation of the filament samples aimed to reveal manufacturing defects that would predict the 3D printing quality and mechanical strengths of the resulting parts.

An *Emspira 3* digital microscope (Leica Microsystems, Danaher Corporation, Washington DC, USA) with 86× magnification for black and white PLA filaments and Nikon OMNIMET-BUEHLER optical microscope (Tokyo, Japan) with 50×, 100× and 200× magnification for glass fiber PLA filaments were used. The *Emspira 3* digital microscope with *PlanApo* 1.0x objective has an 8:1 zoom ratio with 26×-206× magnification ranges, and the *Nikon OMNIMET-BUEHLER* is equipped with up to 1000× resolution and software suitable for finer quantitative structural quantitative structural analysis. Five focuses (86×, 50×, 100×, and 200×) were used for micrographs of longitudinal and cross-sections of white PLA, black PLA, and glass-fiber-reinforced PLA filaments, longitudinally and transversely cut and embedded in *Dentacryl Technicky* technical resin (Prolep vos, České Budějovice, Czech Republic) (Fig. 5)



a. b. c.

Fig. 5. Samples of filaments used in 3D printing of connectors, embedded in technical resin: a. white PLA; b. black PLA; c. white PLA reinforced with glass fibers. (Nicolau *et al.* 2022).



a. b.

Fig. 6. Magnified 86× images of black and white PLA filaments: a. in longitudinal section; b. in cross-section. (Nicolau *et al.* 2022).

Microscopic analysis of the white PLA and black PLA filaments (Fig. 6) shows that the filament material is homogeneous in both longitudinal and cross-section and no defects in the filament structure such as voids, cracks, material agglomerations are observed.

a. b.

Fig.7. Longitudinal section micrograph of glass fiber reinforced PLA filament; a. 50× magnification; b. 100× magnification (Nicolau *et al.* 2022).

Microscopic analysis of sections of the white glass fiber reinforced PLA white filament revealed a number of manufacturing defects such as uneven distribution of glass fiber with areas of fiber clumping and portions of the filament where glass fiber is missing. Also, fiberglass reinforcement voids in the matrix were evident.

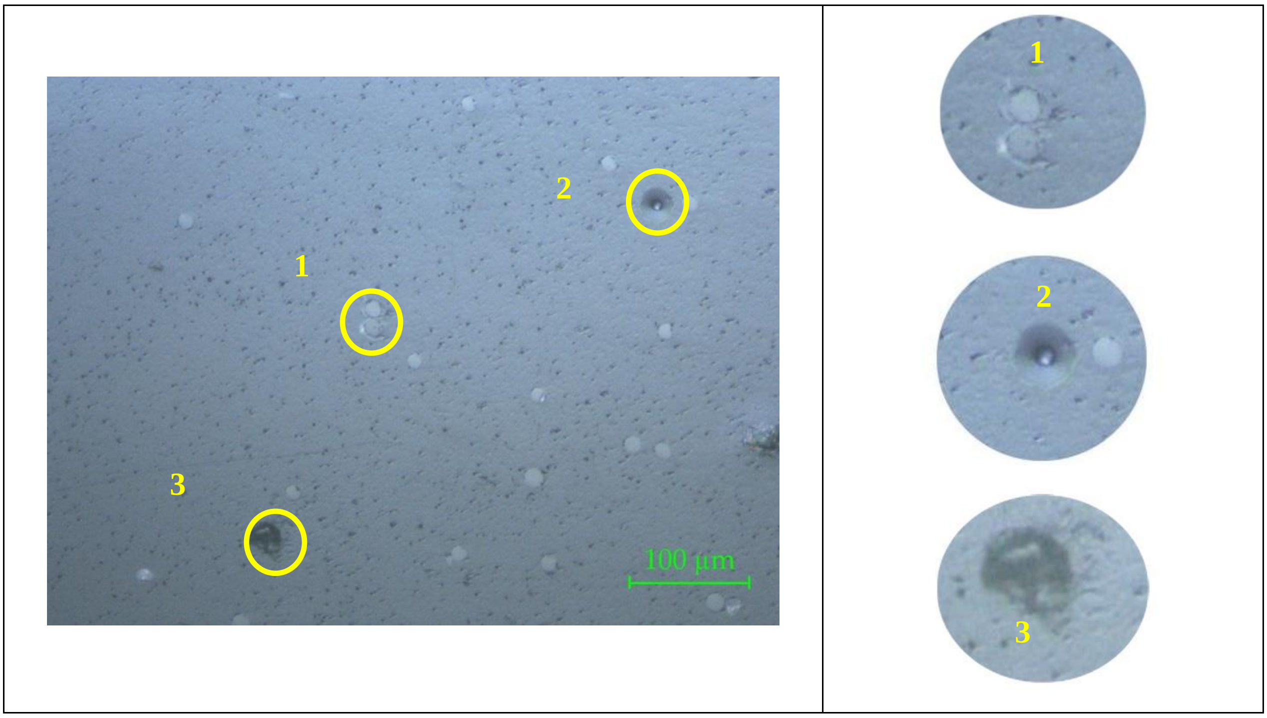


Fig. 8. Cross-section micrograph of the glass fiber PLA filament at 200× magnification (Nicolau *et al.* 2022).

3.3 3D printed connectors used in the experimental research

3.3.1 3D printed connectors using FFF additive manufacturing method

The FFF filament extrusion manufacturing method was used to 3D print connectors with white PLA, black PLA and glass fiber reinforced PLA filaments.

The initial filament deposition is intended to create the basis for the deposition of subsequent layers and to define a closed contour. This will be referred to as the perimeter (P) of the 3D printed connector. The layer-by-layer deposition recommended for good mechanical performance of the resulting part is at an inclination angle of 45° with respect to the perimeter direction and perpendicular to the previous layer (Fig. 9).

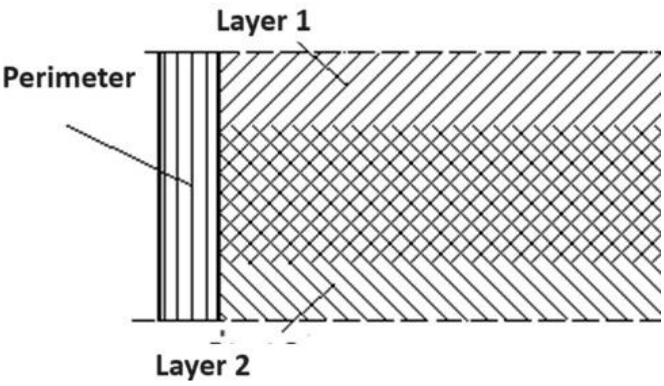


Fig.9. Perimeter and layered filament deposition in FFF technology (Nicolau *et al.,* 2022).

3.3.2 3D printed connectors using SLS additive manufacturing method

The SLS technology used to 3D print the connectors in this experimental research uses a high-power laser beam, which, by melting (sintering) the powder in alternating layers of 100 μm, results in the 3D printed part.

The layers were sintered alternately in X and Y direction to achieve high density as recommended in the literature (Simchi and Pohl, 2003).

3.3.3 Connector positions on the printer platform

In the first part of the research, for the manufacturing of the connectors by the FFF method from the filaments selected for the experimental research, namely white PLA, black PLA and white PLA reinforced with short glass fibers, the horizontal position of the model on the printer platform, called "position 1", was chosen (Fig.10)

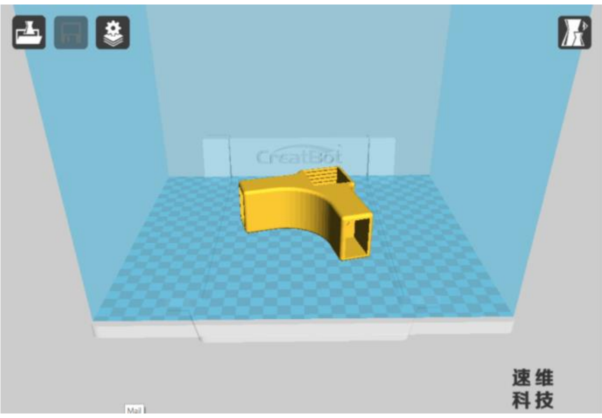


Fig.10. Position 1 (horizontal) of 3D printing of the connector.

Fig. 11. Position 2 of 3D printing of the connector

The 3D printed connectors in this position were used in the construction of the "L" type corner joints, together with the larch wood elements. These joints were subjected to diagonal tension and compression tests to evaluate their mechanical performance.

The aim of the mechanical tests is to select the filament, or filaments, with which the best mechanical performance of the connector 3D printed by the FFF additive manufacturing method is obtained, and these filaments will be further used to obtain 3D printed connectors in the vertical position, referred to as "position 2" (Fig. 11), which will be a new variable in the experimental investigation of the mechanical strength of connectors in an "L-type" joint.

For 3D printing using SLS technology, DuraForm PA Plastic polyamide powder was chosen as the material, and the connectors fabricated with this material were printed in both positions 1 and 2.

3.3.4 Microscopic investigation of the quality of the 3D printed surfaces with glass fiber reinforced PLA using FFF additive manufacturing method

Microscopic investigation of the samples extracted from two 3D printed connectors was carried out under a NIKON OMNIMET-BUEHLER optical microscope (Tokyo, Japan). Three focus settings (50×, 100× and 200×) were used, and microscopic analysis was performed on both their longitudinal and cross-sections. Longitudinal and transverse sections of the specimens were embedded in Dentacryl Technicky technical resin (Fig. 12).

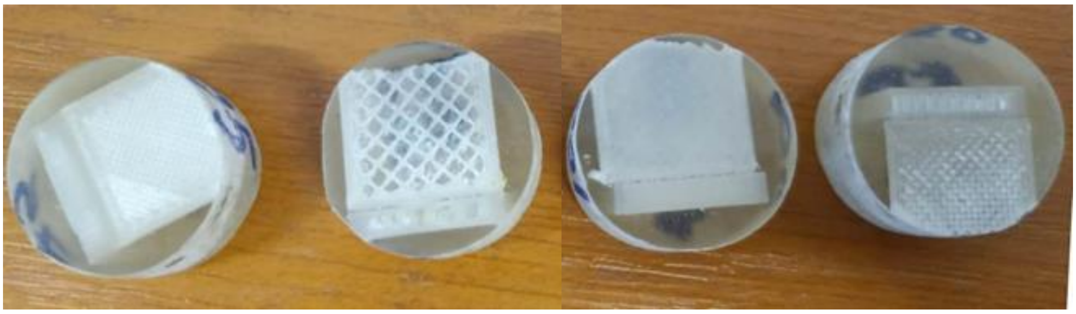


Fig. 12. Samples prepared for quality evaluation of 3D FFF-printed surfaces with glass fiber composite filament (Nicolau *et al.*, 2022)

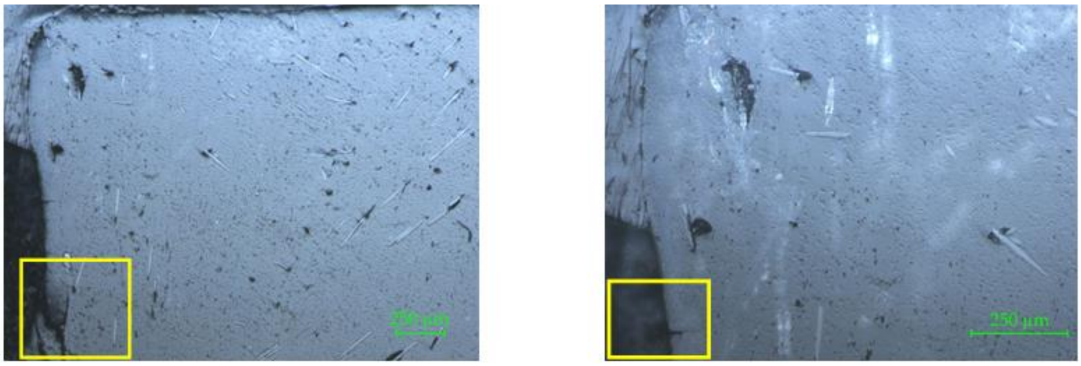


Fig. 13. Microscopic investigation of the longitudinal section of the PLA 3D printed connector with glass fiber inserts.

Several defects are visible in Fig. 13, i.e. cracks in the perimeter area and tearing of the reinforcement elements where they were agglomerated.

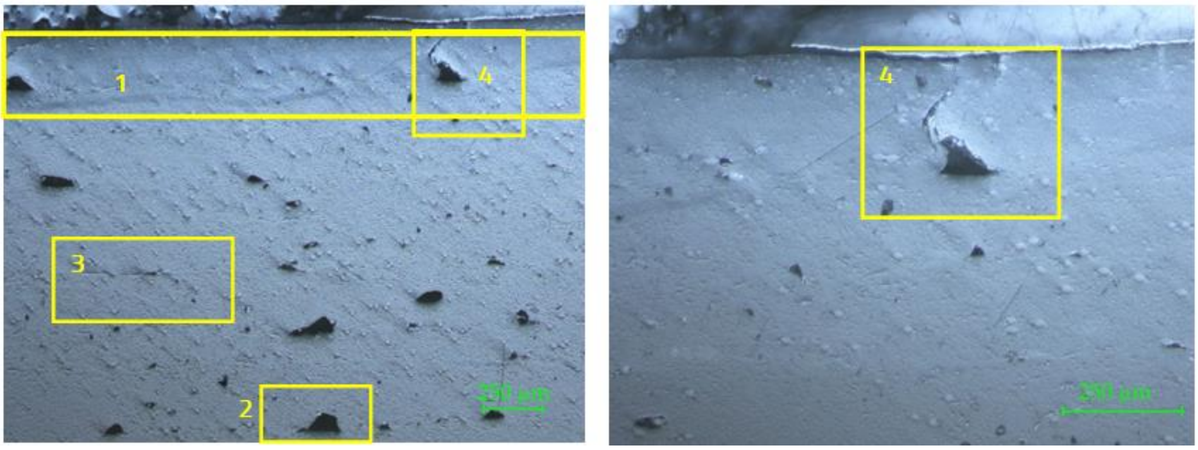


Fig. 14. Microscopic investigation of the cross-section of PLA 3D printed connector with glass fiber inserts

Cross-sectional microscopy of the 3D printed PLA connector with fiberglass inserts shows a number of printing defects such as micro-cracks, fiber reinforcement fiber breaks, end defects and uneven distribution of reinforcement material in the matrix.

3.4 Testing the mechanical strength of the „L-type” corner joint

In the first stage of the experimental investigations related to the mechanical strengths of "L-type" corner joints, 3D printed connectors were tested in "position 1" with the two additive manufacturing methods, namely FFF and SLS, using all the 3D printing materials proposed in the experimental investigation. For comparison, a classical "L-type" joint with its own ball and socket is also tested in parallel. The species used for joint construction is larch wood.

The comparative results of these mechanical tests form the basis for the selection of 3D printing materials that fulfill the mechanical strength condition and with which further experimental research is continued.

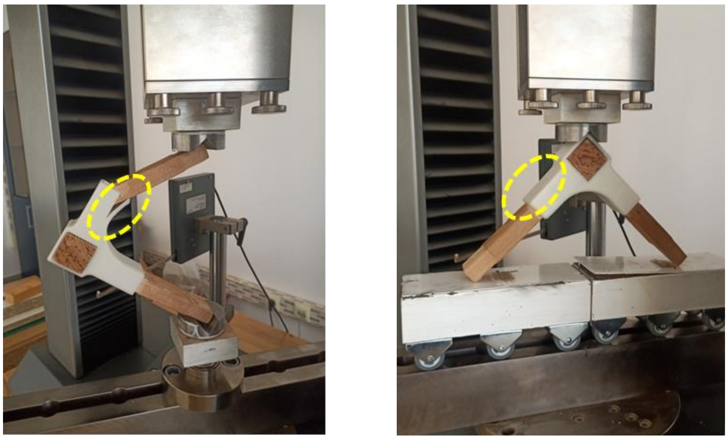
3.4.1 Theoretical considerations

The corner assembly (L-type) specimens were tested in both compressive and tensile tests using models described in the literature (Yerlikaya, 2013; Ayrilmis *et al.*, 2020; *Kasal et al., 2023)*.

The tests were carried out on the Zwick/Roell Z010 universal testing machine (Ulm, Germany) for five specimens of each category at a speed of 7 mm/min.

3.4.2 Mechanical testing of 3D printed connectors in position 1 (horizontal) of laying on the platform

The behavior of connector specimens, illustrated in Fig. 15.a for tensile stress and Fig. 15.b for compressive stress, is common to these types of specimens. In general, cracks and fracture flaws occurred in the connector along the edge at which the thrust force exerted by the wood piece from the inside to the outside is maximum.



a. b.

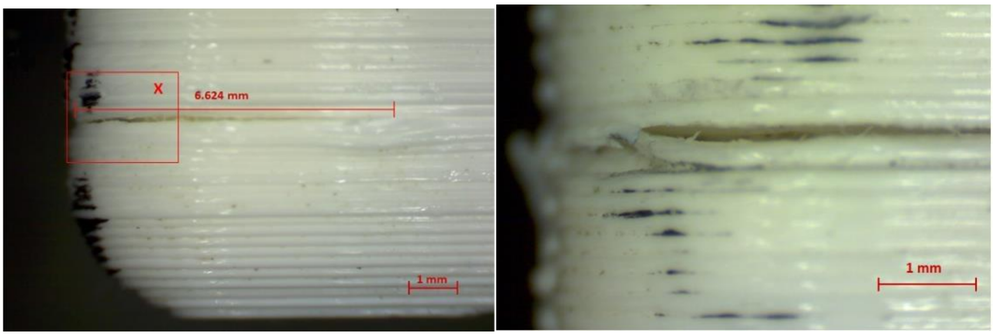
Fig. 15. The specific rupture defects of the connector at the "L-type" corner joint under the load of: a. tensile; b. compression (Nicolau *et al.,* 2022).

3.4.3 Microscopic investigation of the failure defects of the 3D printed connectors in position 1 (horizontal)

For the microscopic investigation, representative defects were selected for each type of material used in 3D printing, except for PLA composite with glass fiber inserts, which was excluded from further experimental investigations due to the poor results obtained in the tensile and compressive mechanical strength tests in the diagonal direction. Two magnification powers (50×, 100×) were used and microscopic analysis was performed on both longitudinal and cross-sections of the parts.

White PLA connector - 3D printing position 1

In Fig. 16.a it can be seen that the rupture of the material under compressive stress occurred exclusively in the form of delamination between two adjacent layers.



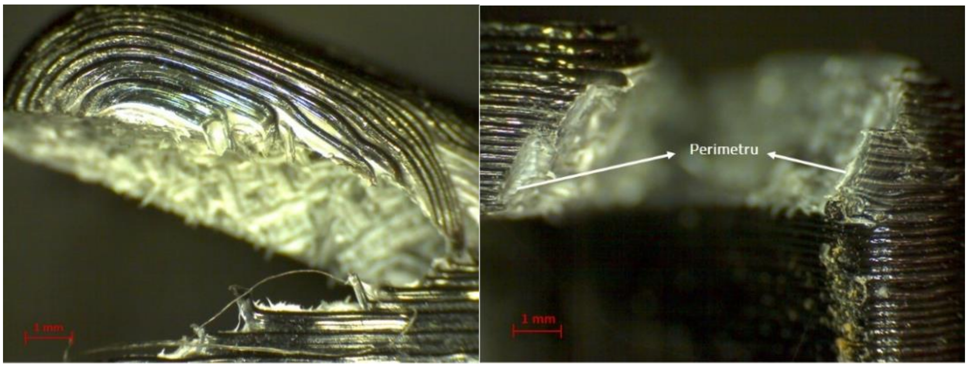
a. b.

Fig. 16. Delamination of white PLA 3D printed connector (position 1) under: a. compression; b. tensile stress.

Fig. 16.b shows the defects occurring after tensile stress in position 1, characterized by delamination between two adjacent layers.

Black PLA connector - 3D printing position 1

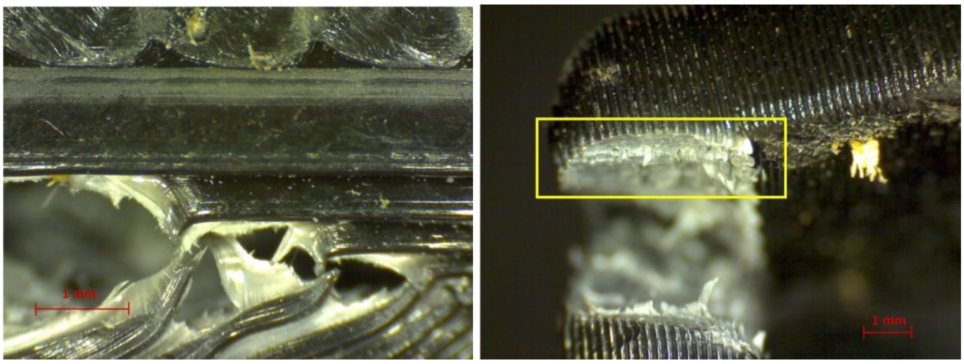
Fig. 17 shows the breakage defects occurring after compressive stressing of the black PLA connector. The fracture extended over several deposition layers. The explanation could be that the adhesion of the layers in this case is better than in white PLA fabrication. The same type of breakage defect is also observed in the cross-section, this time in the perimeter of the 3D printed part (Fig. 17 b), with the exception that the filament deposition on the part was not affected.



a. b.

Fig. 17. Delaminations of the 3D printed black PLA connector (position 1) under compressive stress longitudinal section (a), cross section (b)

Fig. 18.a shows the perimeter and the deposition layer of the material, as well as the 90° arrangement of the two successive layers. Very frequently, in parts 3D printed with black PLA, breakage defects appeared in the perimeter area. In Fig. 18.b, the actual sectioning of the deposition layers up to the gap into which the wooden part was inserted (the bond) was evident, the material practically yielding under the force exerted by the edge of the wooden part.

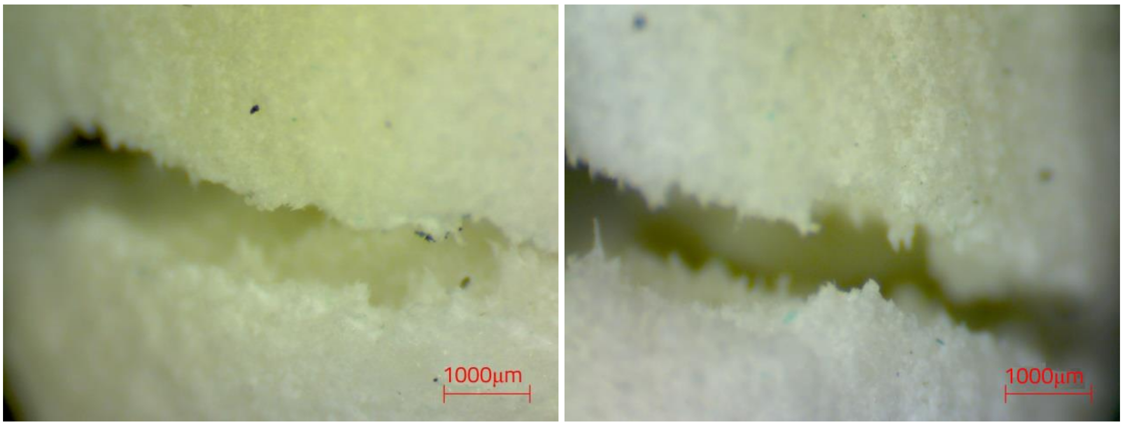


a. b.

Fig. 18. 3D-printed black PLA connector (position 1) under tensile stress, longitudinal section (a), cross section (b)

Connector made of DuraForm PA Plastic - 3D printed in position 1

The images in Fig. 19.a and Fig. 19.b illustrate the general mode of breakage of the pieces in longitudinal and transverse direction, respectively, very similar on both sections.



a. b.

Fig. 19. Defects of SLS-printed connector with DuraForm PA Plastic in position 1 compression test, longitudinal section (a), compression test, cross section (b)

3.4.4 Mechanical testing of the 3D printed connectors in position 2 (vertical) on the printer platform

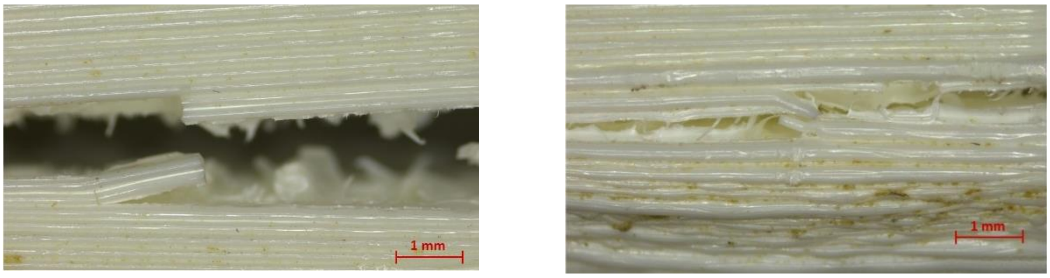
Five connectors 3D printed in position 2 (upright position, with backing material), made of white PLA and black PLA filaments, obtained by the FFF additive manufacturing method and DuraForm PA Plastic powder with the SLS additive manufacturing method, were used to make "L-type" corner joints for solid larch wood elements.

Following the tests, the average values of the maximum tensile and compressive shear forces of the investigated joints were recorded and the average values of the bending moments for the two tests were calculated with relations (1) and (2).

3.4.5 Microscopic investigation of failure defects of the 3D printed connectors in position 2 (vertical)

White PLA connector – 3D printed in position 2

In Fig. 20, microscopic images of representative fracture flaws for white PLA connectors subjected to the diagonal tensile test in the 'L-type' corner joint are shown at 86× magnification.

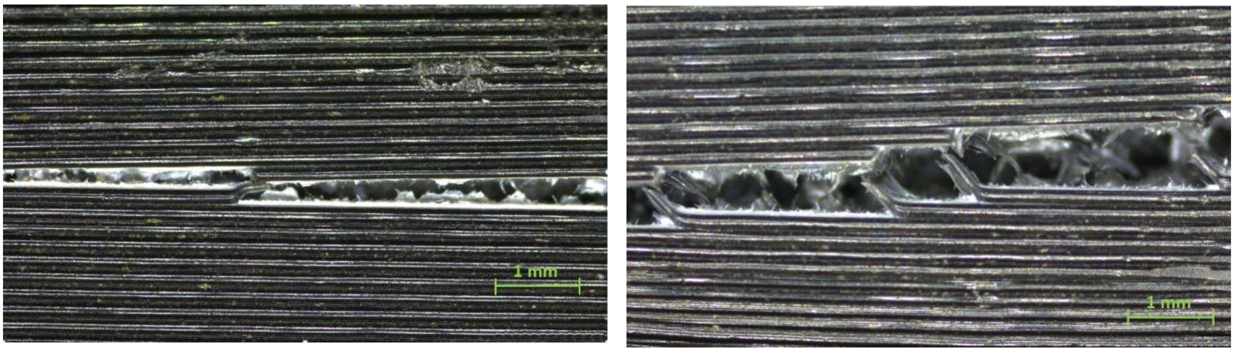


a. b.

Fig. 20. Fracture failures of white PLA connectors (position 2) following mechanical stresses in: a. tensile; b. compression

Black PLA connector - 3D printed in position 2

The microscopic representation of the partial breakage defects that occurred in the black PLA connectors after mechanical testing is shown in Fig. 21.a and Fig. 21.b for the tensile and compression test. These images were obtained at 86× magnification power.



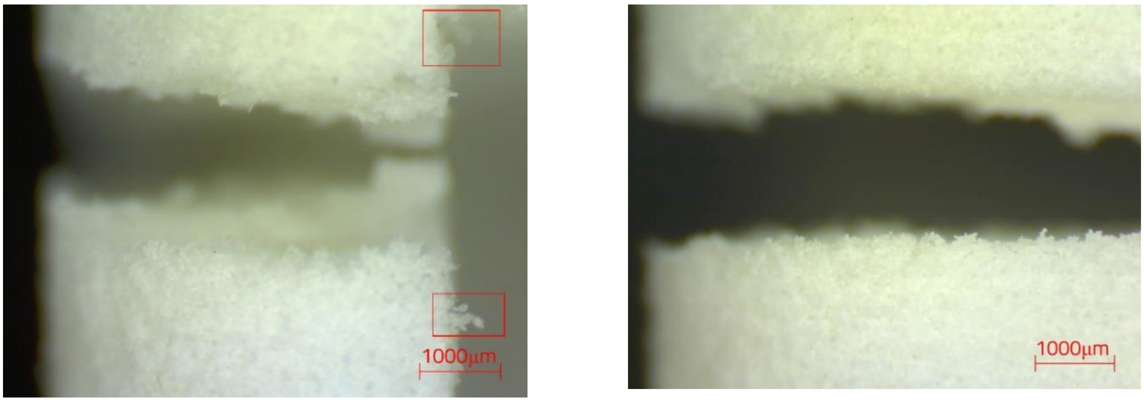
a. b.

Fig.21. Microscopic investigation of partial breakage defects in the 3D printed connector under mechanical stress: a. tensile test; b. detail X; c. compression test; d. detail Y.

The analysis of the partial material breakage defects in the microscopic images reveals an interesting behavior of the black PLA, namely that although the parts showed delamination between several adjacent layers, some material bonds were preserved between them, which maintained the strength of the part, allowing higher values of the maximum breaking forces than in the other cases studied so far.

Connector made of DuraForm PA Plastic - 3D printed in position 2

The images in Fig. 22.a,b show micrographs of connector fracture defects, considered to be generic, regardless of stress.



a. b.

Fig.22.Defects of SLS-printed connector with DuraForm PA Plastic in position 2: a. tensile test, longitudinal section; b. tensile test, cross section

The connectors 3D printed by the SLS additive manufacturing method showed a brittle character. The breakage of the connectors occurred at low forces compared to when white PLA and black PLA were used as materials.

The poor performance of this material under the printing conditions used in this study does not recommend it for further research in this direction, but is a future research direction.

3.4.6 Selection of the additive manufacturing method, material and print position of the designed connector based on the results of the experimental research

The criterion for material and 3D printing method selection was to compare the mechanical performance of the connectors in an "L-type" corner joint subjected to tensile and compressive stresses.

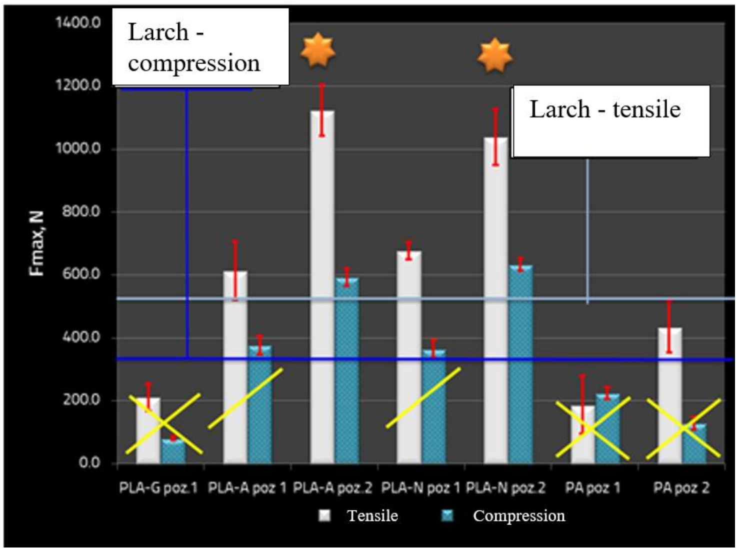


Fig. 23. Comparative diagram of maximum shear forces at diagonal tensile and compressive stresses for "L-type" corner joints with 3D printed connectors.

For this purpose, two additive manufacturing methods and four connector 3D printing materials, two 3D printing positions and a single wood species for the spliced wooden parts, namely larch wood, were used.

From the analysis of the graph presented in Fig. 23, it can be seen that the following 3D printing materials were eliminated on the criterion of mechanical performance in terms of Fmax force: PLA-G (used as filament with FFF method) and PA (3D printing position 1 and 2.

The two PLA filaments (white and black), whose mechanical performance is favored by 3D printing position 2, were left for final selection for further experimental research.

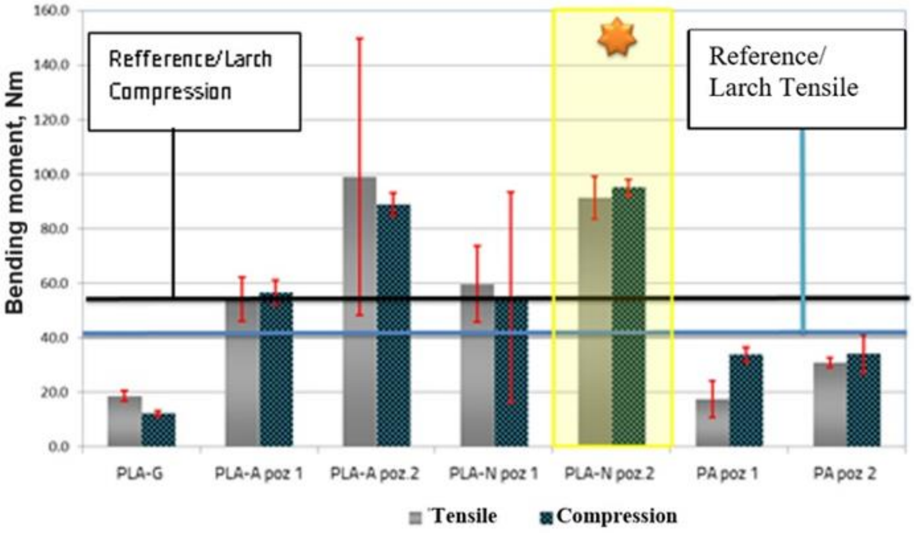


Fig. 24. Comparative diagram of bending moments at diagonal tensile and compressive stresses for "L-type" corner joints with 3D printed connectors.

Analyzing also the comparative plot in Fig. 24 for the tensile and compressive bending moments on the diagonal, it can be seen that white PLA performs better in tensile tests, while black PLA performs better in compressive tests, and the values of the bending moments are quite close.

The black PLA filament was finally selected for further investigation as it showed better adhesion to the deposition of layers in the additive manufacturing process.

3.5 Conclusions on selection of method, material and position for the 3D printing of the connector

- The material in the composition of the white PLA and black PLA filaments is homogeneous, both in longitudinal and cross-section, and no defects in the filament structure such as voids, cracks, agglomerations of material are observed.
- Microscopic investigation of the glass fiber reinforced white PLA filament showed the random distribution of glass fibers in the matrix, with areas where the presence of the reinforcement was not detected and areas where glass fiber bundles crowded the matrix, especially in the core, where the adhesion between these fibers and the matrix were poor.

- The *DuraForm PA Plastic* polyamide DuraForm PA Plastic powder used to 3D print the connector by the SLS method did not give the connector the mechanical strength required for further experimental investigations. Microscopic investigations showed that the sintering of the particles in certain areas was insufficient and the adhesion of the layers deposited by the additive manufacturing process was poor, which is why the maximum forces at which the connectors failed were very low. A solution to improve the mechanical strengths could be to optimize the printing parameters, but this topic requires a series of tests and trials and may be a future research direction.

- The predominant fracture in the black PLA connector is characteristic of brittle materials and does not show a continuous delamination between two adjacent layers, but rather a breaking (fracturing) of the material, but at high breaking forces, indicating that the strength of the material is under stress and not the adhesion between the layers deposited during 3D printing.
- Compared to the results of the tests carried out on the classical own cep and scoop joints between solid larch wood elements, the average values of the maximum forces and bending moments for the joints with PLA with fiberglass and polyamide (PA) connectors are much lower, so that these materials are not a viable alternative for replacing the classical seat element joints at this time.
- Printing the connectors vertically has proven to be the best solution for manufacturing connectors with better resistance to mechanical tests of the joints.

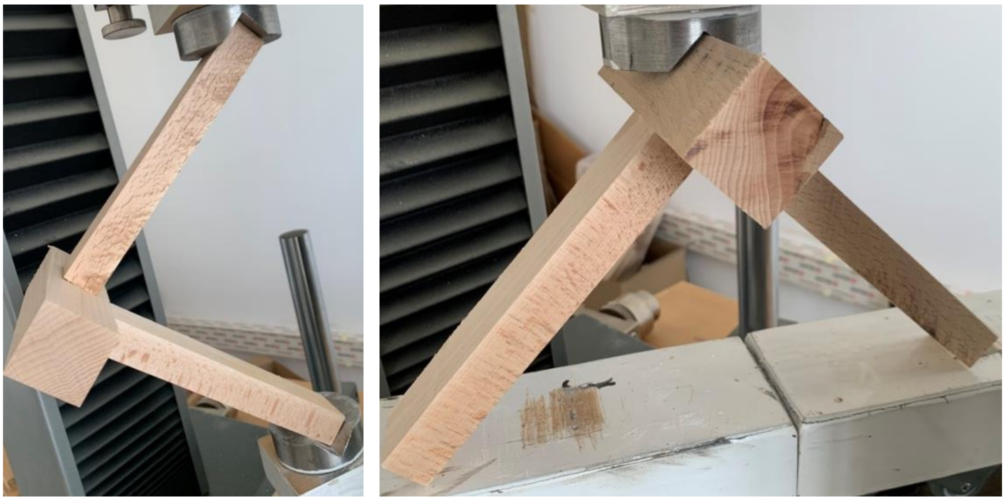
CHAPTER 4. TESTING OF THE MECHANICAL PERFORMANCE OF THE „L-TYPE” CORNER JOINT WITH BLACK PLA CONNECTOR AND BEECH WOOD ELEMENTS

4.1 Mechanical testing of beech-wood classic mortise and tenon joint

The assembly with the mortise and tenon joint is considered as reference in the experimental research at this stage, for comparison with the performance of the assembly with the 3D printed connector made of black PLA filament, using the FFF additive manufacturing method, in the 2nd printing position, selected for further experimental research.

The wooden components (assimilated to the leg and seat frame links/elements) were made of beech wood (*Fagus sylvatica* L.), with a moisture content of 8.5% and a density, determined by calculation, of 698 kg/m3. The "L-type" corner joint followed the dimensions and construction of the classical larch wood joint used in the preliminary research.

Diagonal tensile and compression tests for the corner joints were carried out on the universal testing machine *Zwick/Roell Z010* (Ulm, Germany) for six specimens of each category (Fig. 25).



a. b.

Fig. 25. Testing of beech wood mortise and tenon joints under diagonal: a. compression test; b. tensile test.

Predominant failure by longitudinal fiber separation is characteristic of larch wood. Both in the case of the parts subjected to the compression test and in the case of those subjected to the tensile test, in larch wood the crack propagated longitudinally along the leg segment, which proves that, as expected, beech wood is more resistant to the two stresses, and the breaks mainly occurred in the cross section of the tenon.

4.2 Testing the joints of beech wood elements with black PLA connectors – version 1 (initial)

Compared to the results obtained by the reference samples of larch wood and beech wood (Fig. 26), the connector designed in the first variant yielded much faster to tensile and compressive stresses.

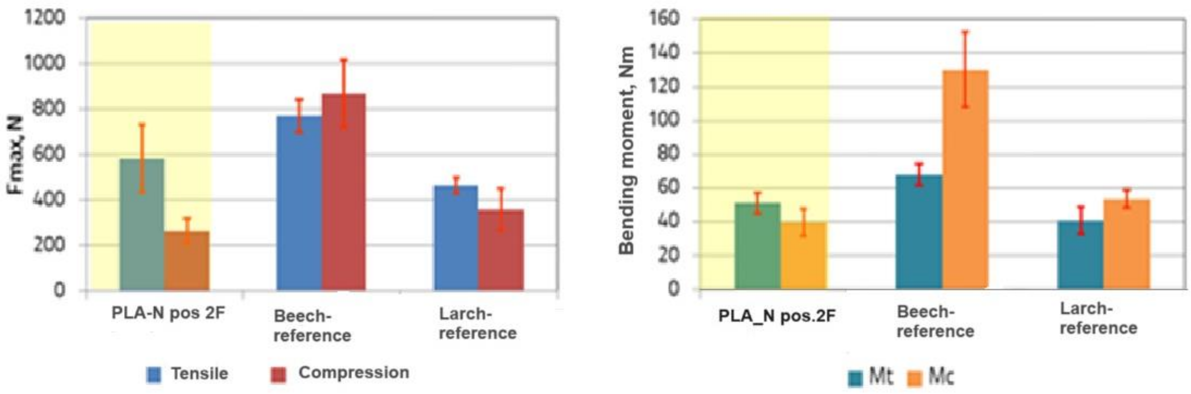


Fig. 26. Comparative results of mechanical performance between the black PLA connector samples in position 2 of 3D printing with beech wood (PLA-N poz2F) and the reference samples of beech wood and larch wood.

Considering the poor results obtained by the connector designed in version 1 for mechanical stresses, it was considered necessary to continue the research with the modification of the connector, with the thickening of the walls in the areas of contact with the links, where the maximum stress of the connectors and their breakage was observed, especially at compression stress (Fig. 26.b).

4.3 Finite element analysis (FEA) of black and beech wood connector joint (initial version) under compression test

The finite element analysis, developed with the software developed by Siemens Software, aimed to study the field of displacements during compressive stress (with the weakest results of the joint with the black PLA connector), the specific stresses and strains in the connector.

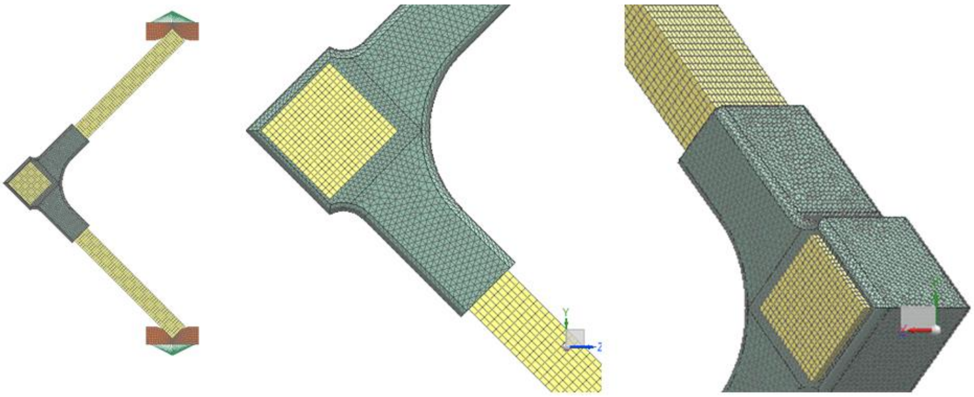
4.3.1 Finite element analysis under compression stress for joints of beech wood elements with black PLA connectors – version 1 (initial)

The FEA analysis model involved several stages:

- Transfer of the CAD model made in *SolidWorks* software to Simcenter simulation software (from the Siemens PLM Software suite) for the CAE model and discretization (Fig 27. a);
- Defining the connections between the connector and the three solid wood elements involved establishing rigid connections between the leg segment and the connector.
- Determination of elasticity indices for beech wood and black PLA as follows:

For beech wood, elasticity indices from specialized literature were used (Curtu and Ghelmeziu 1984), and for black PLA, those in the technical sheet.

In the FEA, the refinement of the discretization of the areas of the connector model considered critical was applied, where a higher accuracy was sought, while a somewhat coarser discretization was kept in the areas considered to be less critical (Fig. 27, Fig. 28).



a. b. c.

Fig. 27. Building the FEA model for compression stress and discretization: a. the model transferred to Simcenter simulation software; b. discretization on the components of the assembly and establishing the axes OX and OZ; c. more complex discretization of the connector and establishment of the OX axis.

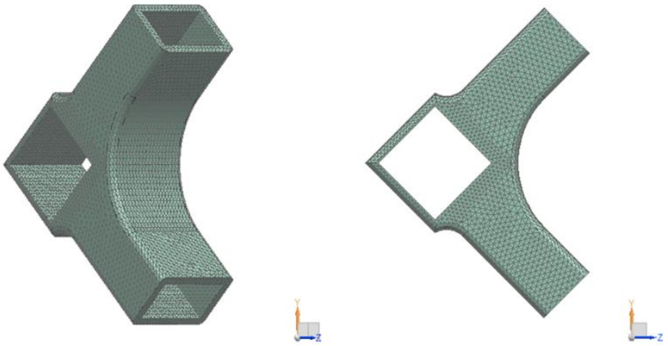


Fig. 28. The mode of differential discretization of the connector, according to the areas considered to be critical.

The results of the finite element analysis are shown in Fig. 29, Fig. 30 and Fig. 31 for viewing the displacements in the assembly between the connector and the solid beech wood elements, for the magnitude of the stresses and respectively the deformations in the connector.

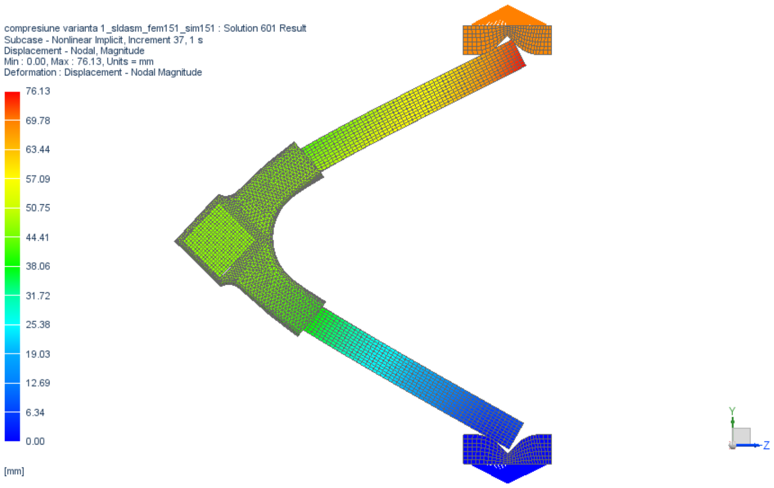

compresiune varianta 1_sldasm_fem151_sim151 : Solution 601 Result
Subcase - Nonlinear Implicit, Increment 37, 1 s
Displacement - Nodal, Magnitude
Min : 0.00, Max : 76.13, Units = mm
Deformation : Displacement - Nodal Magnitude

Fig. 29. The result of the displacement field determined with FEA for the compression stress.

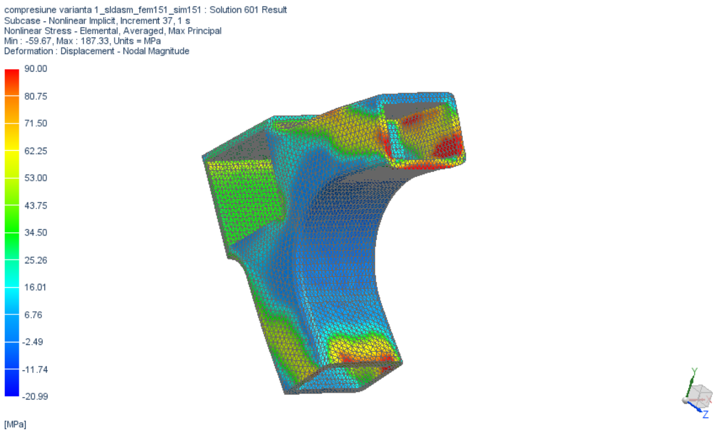


Fig. 30. Result of stresses in the connector determined with FEA for compression stress.

The deformations resulting from the finite element analysis and illustrated in Fig. 31 indicates the corner areas on the curved side of the connector.

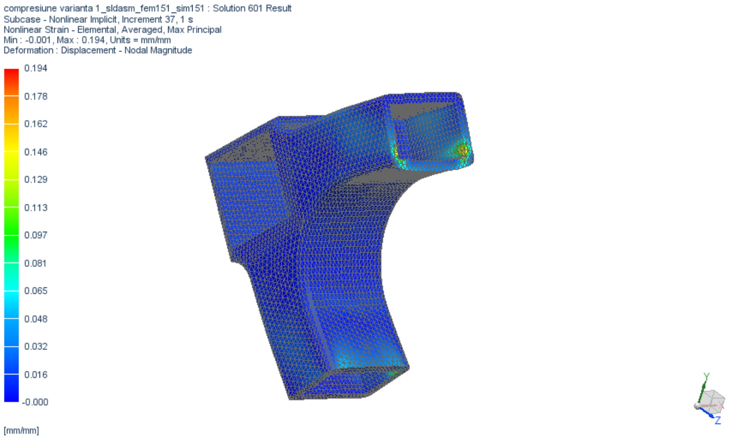


Fig. 31. Result of specific deformations in the connector, according to FEA, for compression stress

4.3.2 *Finite element analysis under tensile stress for joints of beech wood elements with black PLA connectors – version 1 (initial)*

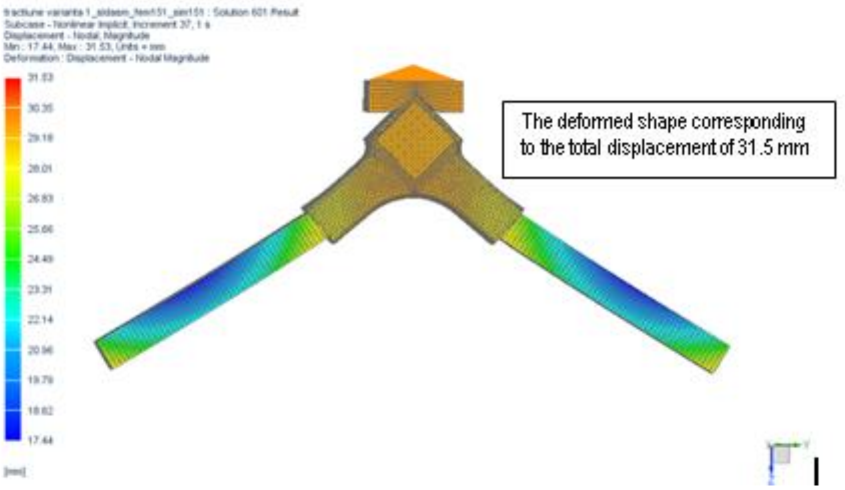
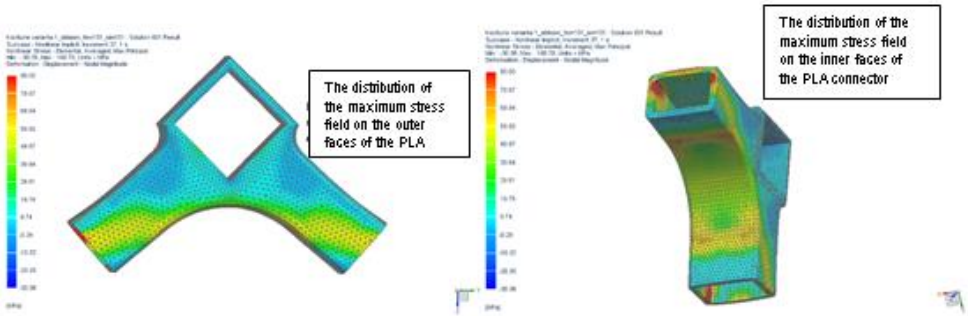


Fig. 32. The result of the displacement field determined with FEA for the tensile stress.

The displacement field in the assembly between the connector and the solid beech wood elements can be seen in the image in Fig. 32. The maximum displacements, corresponding to the area where the force acts, reach the approximate value of 30 mm. Also note the displacements of the links in the connection area with the connector, estimated at approx. 28 mm, which simulates the tendency of the link to come out of the connector, as it happened in the real experimental test.

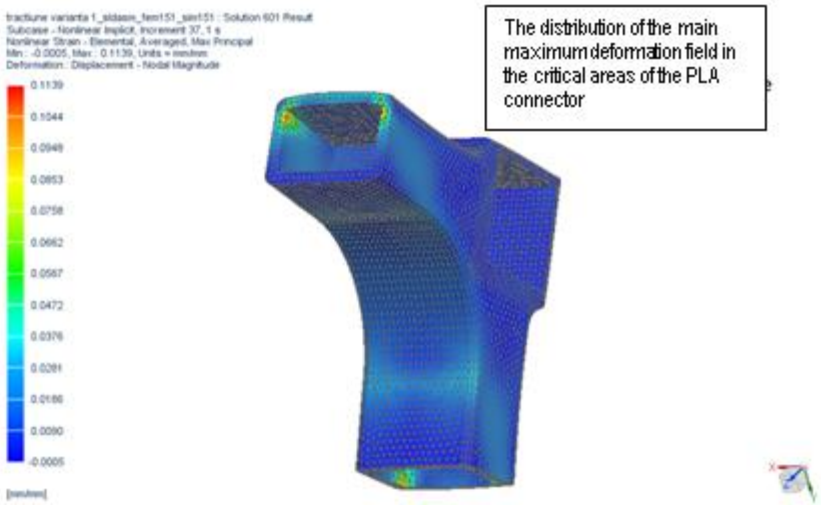


The distribution of the maximum stress field on the outer faces of the PLA

The distribution of the maximum stress field on the inner faces of the PLA connector

Fig. 33. Result of the stresses in the connector determined with FEA, for the tensile stress.

The result of the voltages in the connector, shown in Fig. 33, indicates the maximum values on the edge of the edge of the connector, at the top, where the pieces of wood tend to come out of the joint. In that area the stresses reach the maximum value of 90 MPa.



The distribution of the main maximum deformation field in the critical areas of the PLA connector

Fig. 34. The result of specific strains in the connector, according to FEA, for tensile stress

The deformations resulting from the finite element analysis and illustrated in Fig. 34 indicates the corner areas of the connector.

4.4 Conclusions on testing the L-type corner joint between the beech wood elements and the black PLA connector, version 1 (initial)

- The 3D printed black PLA connector in position 2 (vertical) recorded lower values of maximum breaking forces and bending moments, both in tension and compression, compared to the reference beech wood samples, placing se at the moment e compression just below the threshold touching the larch wood reference assembly.

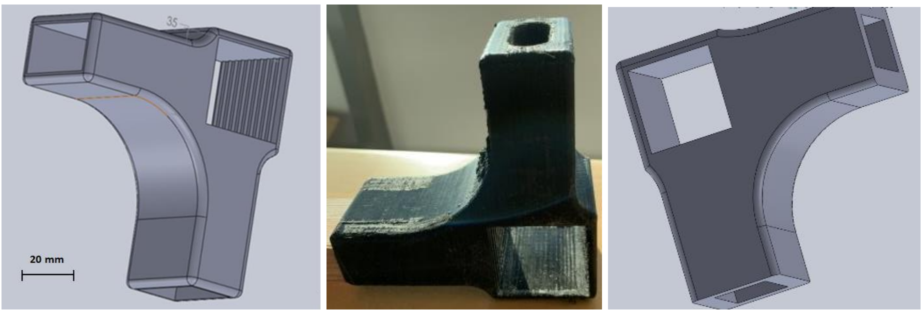
- The poor performance of the joint can be explained by the fact that beech wood, being a wood with a higher density, acts more strongly on the connector walls than larch wood, producing the breaking of the bonds between the deposition layers with a higher force and more serious damage of the 3D printed part.
- Finite element analysis (FEA) confirmed the areas of maximum stress, which failed by breaking in the mechanical tests performed.
- The results obtained by the FEA simulation overlap quite well with the results of the real model. The values of the displacements in compression and traction overlap those obtained in the tests carried out experimentally.
- Due to the poor performance of the originally designed connector, it was considered necessary to continue research with modification of the connector. It was chosen to thicken the connector walls in the areas of contact with the links, where the FEA showed that the stresses were maximum (up to 90 MPa) and where their breakage occurred.

CHAPTER 5. RESEARCH ON THE INFLUENCE OF THE MODIFIED CONNECTOR ON THE MECHANICAL PERFORMANCE OF THE CORNER JOINT WITH BEECH WOOD ELEMENTS

Considering the fact that in the tensile and diagonal compression tests the connector proved to be the weakest part of the tested assembly, in order to improve the mechanical properties of the "L-type" corner joint, the decision was made to remodel the connector with a change in the thickness of the zone of connecting the connector with the wooden ties, where the maximum stresses and breakage defects were found following the performance of the mechanical tests.

5.1 Presentation of new designed experimental models of connectors

Starting from the initial variant, hereafter named in the experimental research "Variant 1", two other different constructive variants for the connector were developed (Fig. 35). The 3D printing material still remains the one selected following the preliminary research, namely the black PLA filament, positioned vertically in the printer (in position 2).



a. b. c.

Fig. 35. Variants of the connector: a. Variant 1; b. Variant 2; c. Variant 3

The assembly depth of the connector in the 2nd variant (Fig. 35.b) remains equal to that of the original connector (variant 1). Instead, the rounding of the cavity contour aims to eliminate stress concentrators from the sharp edges of the cavity. The connections will require additional processing compared to option 1, namely the processing of the dowel.

In variant 3 from Fig. 35.c the same solid wood elements are used as in option 1, without any additional processing of the wood being necessary. Connector model 3 changes compared to variant 1 by the thickness of the walls in the area of connection with the links, but also with the leg, so that the thickness of the wall at the connection with the links increases from 3 mm to 8 mm, and in the area of connection with the leg to 3 mm to 5 mm.

5.2 Finite element analysis (FEA) for the connector (variant 3) jointed elements under diagonal compression stress

The 3rd design version of the connector kept the original shape of the connector, but thickened the walls of the connector, meaning that those stress concentrators at the edges of the connector can still produce rupture failures in those areas. To investigate the magnitude of these stresses, the FEA analysis was repeated for the new model. A reduction in peak stress areas and deformations was observed, which should result in a better behavior of this connector under joint compression stress.

5.3 Finite element analysis (FEA) for the connector (variant 3) jointed elements under diagonal tensile stress

Following the tensile finite element analysis for the connection with the connector in the 3rd design variant, it was found that the areas with maximum stresses, as well as the deformations in the connector, were reduced, so that a better behavior of it is expected under tensile stress of the joint.

5.4 Mechanical testing of "L-type" joints between beech wood elements and connectors in variants 2 and 3

Diagonal tensile and compressive tests for the assemblies with the new connectors were performed on the same Zwick/Roell Z010 universal testing machine (Ulm, Germany) for six samples of each connector type.

The comparison of the mechanical performances between the assemblies of beech wood elements with printed connectors in the three design variants and the beech wood reference sample, is presented in the diagrams in Fig. 36.a for maximum forces and Fig. 36.b for bending moments.

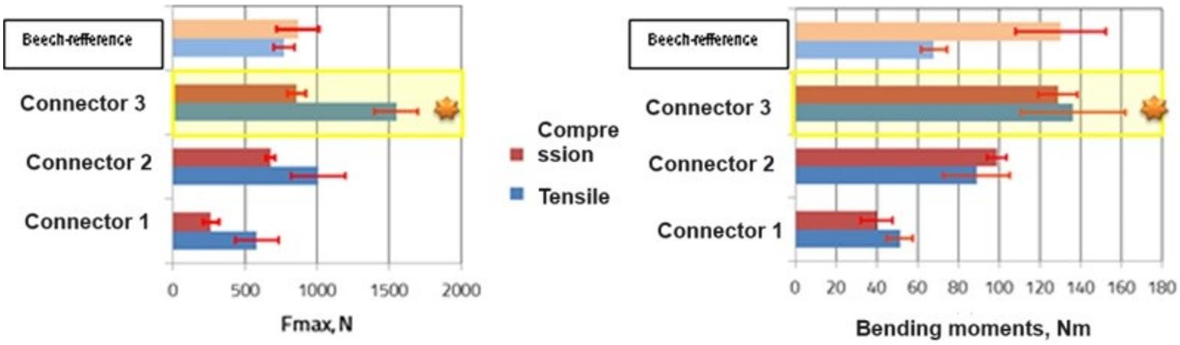


Fig. 36. Comparison of the mechanical performances between the assemblies of beech wood elements with printed connectors in the three variants: a. maximum forces; b. bending moments.

As can be seen in the comparative graphs in Fig. 36, the connector designed in the 3rd variant met the performance of the reference beech wood assembly. In traction, the assembly with this type of connector achieved even higher values.

5.5 Conclusions regarding the results of joint tests with variants 2 and 3 of the connectors

- Following the compression and tensile tests of the joints for which the 2nd version of the connector was used, a single specimen broke in the area of maximum stress (the area where the connector joins the seat). The vulnerable area turned out to be at the junction of the connector with the leg segment.
- The variant that met the mechanical performance of the classic beech wood reference joint is the one with the printed connector in the 3rd variant. As a result of mechanical stress, this type of connector suffered less severe damage than the 2nd, for which total breaks were recorded.

CHAPTER 6. MECHANICAL TESTING OF THE CHAIR WITH 3D PRINTED CONNECTORS.

6.1 Presentation and creation of final products intended for testing

In Fig. 37.a shows the 3D model of the chairs with connectors, designed in the SolidWorks 3D CAD Design program, and in Fig. 37.b, the 3D model of the same chair in the classic design variant.

a. b

Fig. 37. The 3D models of the chairs made in the design program SolidWorks 3D CAD Design Software: a. the chair with 3D printed connectors; b. the chair with classic joints.

The prototypes of the two chairs were made in the Multifunctional Workshop of the Faculty of Furniture Design and Wood Engineering, in two copies each, to be tested as follows:

- Optical analysis of 3D deformations using the DIC (Digital Image Correlation) method at ICDT Brașov, Research Center "Numerical simulation, testing and mechanics of composite materials".
- Testing according to SR EN 1728:2012 on the test stand, for:

1. Strength of the seat and backrest (SR EN1728:2012 point 6.4)

2. Resistance of the legs towards the front (SR EN 1728:2012 point 6.15)

3. Resistance of the legs to the side (SR EN 1728:2012 point 6.16)

6.2 Optical analysis of 3D deformations using DIC (Digital Image Correlation) method

In order to optically analyze the 3D deformations of the two chairs (the one with connectors and the reference one), two pieces of equipment from the Research Center "Numerical simulation, testing and mechanics of composite materials" of ICDT Brașov were used.

- System for analyzing the behavior of structures in fatigue tests, series 1451, K22305 (manufactured by Walter & Bai – Switzerland).
- The system for the optical analysis of 3D deformations for materials and components, by the DIC (Digital Image Correlation) method - ARAMIS SRX (ZEISS GOM Metrology).

The testing of the chairs to study their deformations in the joint area was carried out with the help of a GTM force transducer and a system for monitoring the displacement of selected points in the area of the joints between the link and the leg of the chair by the image correlation method.

The image of the two combined equipment is shown in Fig. 38.

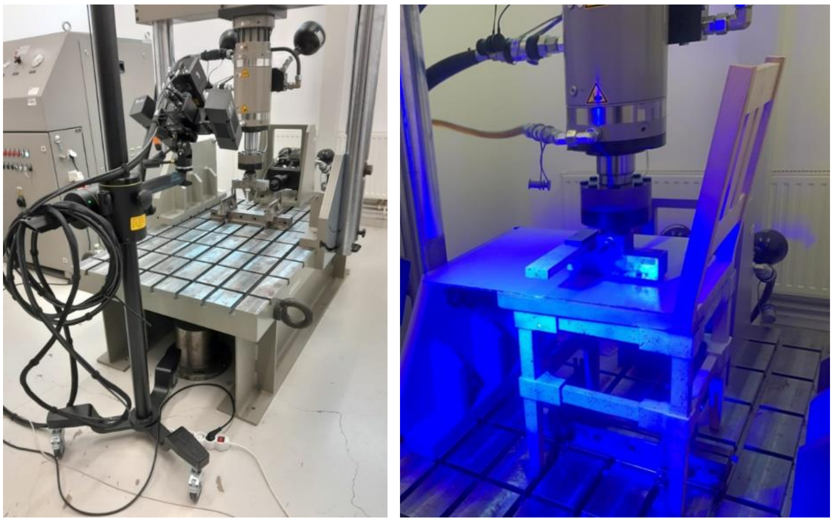


Fig. 38. System for the analysis of the behavior of structures in fatigue tests coupled with the System for the optical analysis of 3D deformations by the DIC method.

To study the displacements occurring in the chairs loaded with a static load, the monitored surfaces were painted, so as to obtain a grid of points (markers), through which the deformations can be visualized (Fig. 39).

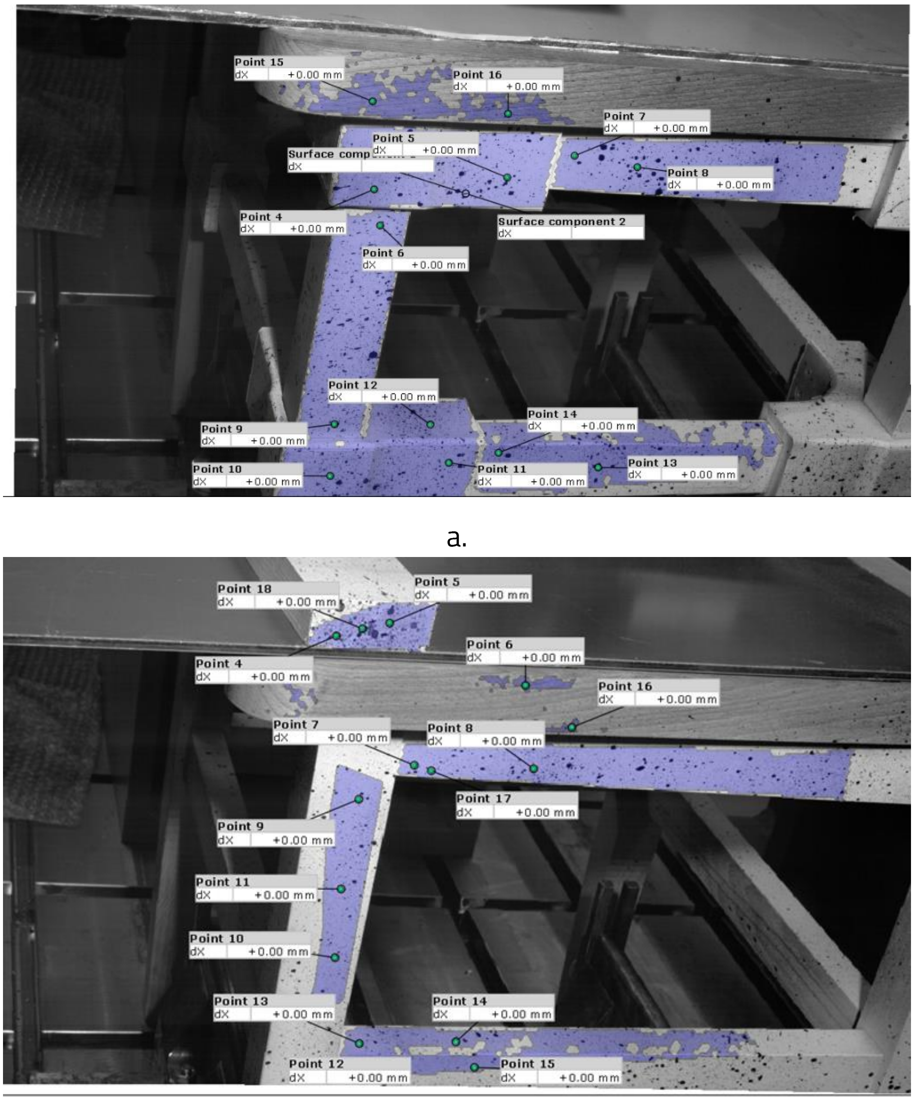
a. b.

Fig. 39. Preparing the seats for testing: a. the seat with connectors; b. the chair with classic joints.

The seat testing in this study intends to analyze the displacements of the 16 and 18 selected points respectively (Fig. 40).

The parameters with which the test was carried out were the following:

- The displacement of the punch of the force transducer was set at a fixed value of 5 mm;
- Punch travel speed: 0.02 mm/s;
- Making 400 frames with a fixed frame rate of 2Hz.



b.

Fig. 40. Selected points for measuring displacements: a. seat with connector; b. the chair in classic, reference construction.

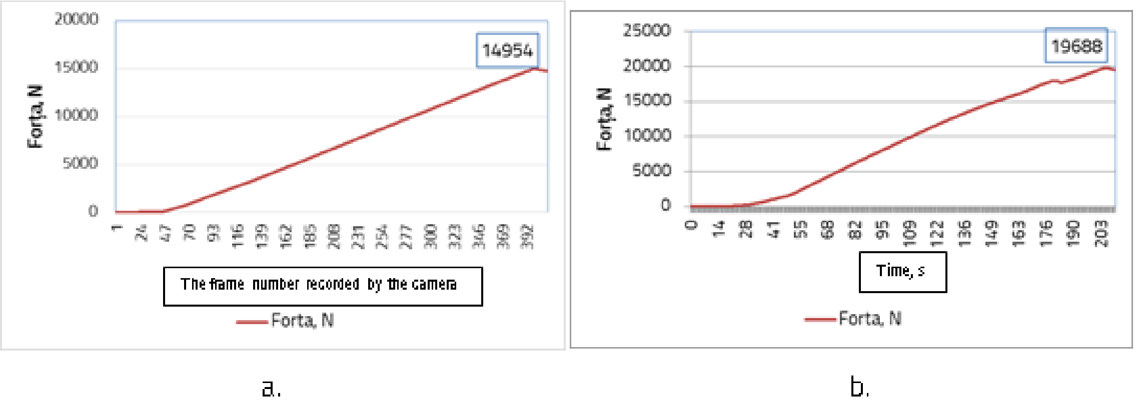


Fig. 41. The magnitude of the maximum forces supported by the two chairs during the optical analysis of 3D deformations by the DIC method: a. the chair with 3D printed connectors; b. the reference seat with classic self-pin and hollow joints.

As it follows from the graph in Fig. 41.a seat with connectors withstood a force of 14 954 N, equivalent to 1495 kgf, much more than required for its functional role. As for the seat with classic joints, the displacement of the punch by 5 mm determined pressure forces of 19 688 N (Fig. 41.b), where displacements of the order of tenths of mm were recorded.

6.3 Chair strength testing

The chairs were tested on the test stand with equipment from *Hegewald & Peschke Meß- und Prüftechnik* GmbH (Nossen, Germany) within the Design, Prototyping and Testing Laboratory (Cluj Innovation Park, Regional Center of Excellence for Creative Industries, Cluj-Napoca).

The tests to which both types of seats (with classic joints and with 3D printed connectors) were subjected on the test stand were aimed at determining the resistances, namely:

- Seat and backrest resistance (SR EN1728:2012 point 6.4) – Fig. 42.a;
- Resistance of the legs towards the front (SR EN 1728:2012 point 6.15) – Fig. 42.b;
- The resistance of the legs to the side (SR EN 1728:2012 point 6.16) – Fig. 42. c.

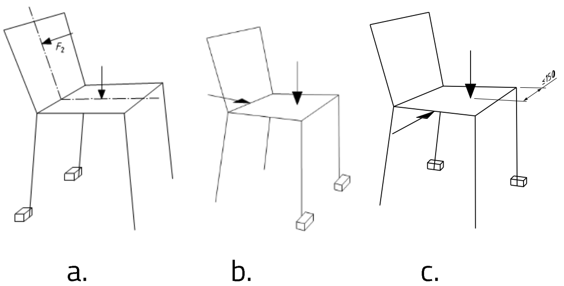


Fig. 42. Testing the strength of the seat and backrest according to: a. SR EN1728:2012 point 6.4; b. SR EN 1728:2012 point 6.15; c. SR EN 1728:2012 point 6.16 (SR EN1728:2012)

Both types of seats withstood these demands, without having, after the completion of the tests, tears, loose joints, or deformations of the structure, according to the test reports received.

The results of the performed tests revealed that the joint with connectors gives the seating furniture the resistance required by the standards in force. No difference was noted during and after the test between the strength of the seat with classic joints and the seat with 3D printed connectors.

6.4 Conclusions regarding the testing of seats with 3D printed connectors

- Following the tests carried out on the approved test stand, it has been proven that the joint with 3D printed connectors can be a viable alternative to the classic self-pin and socket type joint in the construction of seats.
- Both chairs successfully passed the resistance tests according to SR EN1728:2012 points 6.4, 6.15 and 6.16, proven by the test report issued by the RENAR accredited laboratory that performed them.
- Both seats withstood 1300 N seat and 400 N seat back loads without breaking defects after the test was completed.

Chapter 7. GENERAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. DISSEMINATION OF RESULTS. FURTHER DIRECTIONS OF RESEARCH

7.1 General conclusions

- Few scientific works were found in the specialized literature regarding the design and testing of furniture connection elements obtained through additive manufacturing methods, which proves the novelty element of the present research from the doctoral thesis.
- The test methods recommended for checking the mechanical strength of a joint and applied in the specialized literature are the finite element method and the testing of a corner assembly (L-type) to diagonal tensile and compressive loads and the calculation of the bending moment for those two requests.
- Microscopic investigations on the filaments of white PLA, black PLA and white PLA reinforced with glass fiber showed that the first two have a homogeneous structure, without defects such as voids, cracks, or material agglomerations, while the composite filament showed a random distribution of fiberglass in the matrix, with areas where the presence of reinforcement was not detected and areas where the fiberglass bundles crowded the matrix.
- It is possible that the homogeneous structure of the filaments of white PLA and black PLA is an argument for the better mechanical strengths of the 3D printed connector with these materials.
- The DuraForm PA Plastic powder used in the 3D printing of the connector by the SLS method did not give it the mechanical strength necessary to continue the experimental research.
- Mechanical test results and microscopic investigation of tear defects showed that the adhesion of white PLA layers is weaker than that of black PLA filament due to long delamination between layers.
- The predominant break in the case of the black PLA connector is that characteristic of brittle materials and does not show a continuous delamination between two adjacent layers, but rather a breaking (fracturing) of the material.
- The average values of peak forces and bending moments for joints with fiberglass PLA and polyamide (PA) connectors are much lower than the reference, so these materials are not currently a viable alternative for replacement joints classic chair elements.
- Printing connectors in a vertical position has proven to be the best solution for manufacturing connectors with better resistance to mechanical joint tests.
- Finite element analysis (FEA) confirmed the areas of maximum stress, which failed by breaking in the mechanical tests performed.
- The results obtained by the FEA simulation overlap quite well with the results of the real model. The values of the displacements in compression and traction overlap those obtained in the tests carried out experimentally.
- Due to the low performance of the initially designed connector in the beech wood elements assembly version, it was considered necessary to continue the research with the redesign of the connector.

- Dimensional modification of the connector in the areas where the FEA showed that the stresses are maximum (up to 90 MPa) and where their breakage occurred, proved beneficial for the joints of beech wood parts.
- The modification of the connector in the second variant, by eliminating the stress concentrators visualized with the help of FEA (at the corners, in the assembly area with the links), moves the vulnerable area to the connection of the connector with the leg segment, and the maximum breaking forces do not reach benchmark performance.
- At the joints with the 3rd version of the connector (resulted after changing the thickness of the initial connector in the joint areas with the wooden parts), following the mechanical tests of the corner assembly, the connector yielded in the joint area with the ties, but not in the wooden elements.
- The mechanical performance comparable and even better than that of the beech wood reference sample, but also the simplicity of the processing process for the solid wood elements, recommend the connector designed in the 3rd variant in the demountable construction of the seats.
- Following the tests carried out on the approved test stand, it has been proven that the joint with 3D printed connectors can be a viable alternative to the classic self-pin and socket type joint in the construction of seats.
- The seat built in the detachable version with connectors has successfully passed the resistance tests for the seat, backrest, cross bar and frame stringer, according to SR EN1728:2012 points 6.4, 6.15 and 6.16, a fact proven by the test report issued by the accredited laboratory RENAR.
- The seat loading forces that the two chairs withstood, following the measurement of displacements with the 3D optical deformation analysis system using the DIC method, were at least 10 times higher than those stipulated in the SR EN1728:2012 standard.

7.2 Original Contributions

- Solving an innovative theme, which went through all the design and development phases specific to a new product, each phase being the result of a theoretical and experimental research stage, based on a research protocol with as its object of study a connector intended for assembling the elements strength of a chair, respectively the elements of the chair frame and the links, assembled with its legs.
- Design and 3D modeling of a connector for the assembly of resistance elements in the structure of a chair in the program SolidWorks 3D CAD Design Software and generate the file for 3D printing and for FEA.
- Designing and 3D modeling of a chair in the same software, using the dimensions and sections recommended by the existing design standards, in two assembly options: fixed, with its own pin type joints - hollow and removable, with the help of designed connectors.
- Establishing an experimental research protocol for testing the strength of the connector and seat built with this concept.
- 3D printing of a total of 116 connectors, with 4 different materials (PLA black, PLA white, PLA white reinforced with glass fibers), by using two additive manufacturing methods (FFF and SLS) and two different printing positions for parts obtained.

- Manufacture of "L-type" joints for the subassemblies with connectors and for those in the classic variant with mortise and tenon, intended for tensile and compression tests on the diagonal, using two species for the solid wood elements: larch and beech.
- Testing all variants of "L-type" joints in traction and diagonal compression and processing the resulting data.
- Finite element analysis to simulate tensile and compression tests, in order to visualize system displacements, stresses and deformations in the connector.
- Based on the FEM results, the redesign and 3D remodeling of the connector was carried out in two other variants, to increase the resistance in the assembly with beech wood, which became critical.
- Experimental testing of the new connector models in the corner joints of the beech wood elements, by subjecting them to the two stresses: tensile and diagonal compression, and comparing the results with those of the reference model in beech wood.
- Repeating the FEA for the new model considered optimal and interpreting the results.
- Construction of four chair prototypes, two in the classic version with a fixed constructive system and two in the demountable version - assembled with previously validated connectors.
- Verification and validation of the designed connector in the final product by two test methods:
    1. Testing the seat with connectors and the reference seat (classic) using the system for the analysis of the behavior of structures in fatigue tests and the system for the optical analysis of 3D deformations, by the DIC (Digital Image Correlation) method.
    2. Testing of the two chairs according to SR EN 1728:2012 on the approved test stand of the Design, Prototyping and Testing Laboratory (Cluj Innovation Park, Regional Center of Excellence for Creative Industries, ClujNapoca) - RENAR accredited.
- Obtaining for the first time images and values of the displacements that occur at different points of the seat joint area under the action of high seat pressing forces, with the help of the system for the optical analysis of 3D deformations.
- Testing the resistance limits of the seats with the help of the system for the optical analysis of 3D deformations.
- The multidisciplinary approach to the subject treated in the doctoral thesis, starting from the notions of computer design and modeling with a dedicated software, the strength of materials, finite element analysis, the use of modern equipment and software for experimental research, data processing and interpretation.

7.3 Dissemination of Results

1. Nicolau, A.; Pop, M.A.; Coșereanu, C. (2022). 3D Printing Application in Wood Furniture Components Assembling. Materials, 15, 2907. https://doi.org/10.3390/ma15082907. (Article presented at the international conference BRAMAT 2022, Brașov, March 9-12, 2022).

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https://doi.org/10.3390/app132112044. (Article presented at the international conference ICWSE 2023, Brașov, November 2-4, 2023).

3. Nicolau, A.; Coșereanu, C. Mechanical Properties of L-Type Corner Joints Connected with 3D Printed PLA Connectors Using FFF Technology, Pro Ligno 20(2), 2024.

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7.4 Further Research Directions

- Continuing research for the use of DuraForm PA Plastic polyamide powder for 3D printing by the SLS method of similar assembly elements and the pursuit of improving the mechanical resistance of the parts obtained by optimizing the laser actuation parameters.
- Testing other printing materials (filaments and powders) than those tested in this doctoral thesis.
- Continuing the development of the connector concept studied in the present research, by approaching it from an aesthetic point of view for the final product, the chair.
- Elaboration of a Voronoi structure for the proposed connector, using dedicated software, to take into account the stresses highlighted with FEA and to give it an attractive design.
- Investigating the influence of PLA filament color on the strength of the 3D printed part.
- Designing and testing other types of innovative connectors, intended for easy assembly of seating furniture or storage.
- Designing 3D printed connectors that allow different 90° angle assemblies and devising methods to test their joint strength.
- Implementation of innovative solutions based on additive manufacturing, to replace complex wood processing technologies, difficult constructive solutions and to save the resource that is so precious these days, wood.
- Aging testing of the sub-assembly between the wooden parts and the connector, to investigate the behavior of the wood in combination with the connector material at various temperature and humidity variations.
- Fatigue testing of the seat made with 3D printed connectors to study the durability of the joint.
- Continuation of connector strength research using other 3D printing positions (at 45°) and other layer deposition variants.
- Application of other variants of mechanical testing of "L-type" corner joints, in order to anticipate the behavior of the joints in the seat structure.

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