Seid Hajdarevic*[1], Murco Obucina[1], Muhamed Jusufagic[2], Ibrahim Busuladzic[1], Alen Ibrisevic[3], Sandra Martinovic[4]

Withdrawal Capacity of Double-Threaded Nuts Mounted in 3D-Printed Wood-Plastic Composites

Izvlačni kapacitet dvonavojnih matica montiranih u 3D printane drvno-plastične kompozite

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ABSTRACT • *This paper investigated the withdrawal capacity of the double-threaded nuts mounted in 3D-printed materials. The basic technical properties and the withdrawal force of the double-threaded nuts for the specimens made of PLA, WPLA, and layered WPLA+PLA configuration (with and without STP adhesive) were investigated. The results are compared with the literature data of withdrawal force for beech wood, MDF, and particleboard with and without the adhesive. The research has determined the effects of the properties of 3D printed materials (density, compressive and tensile strength), the infill and printing patterns, and adhesive on withdrawal capacity of double-threaded nuts. Double-threaded nuts mounted with adhesive had higher withdrawal forces (about 25 % for PLA and WPLA specimens, and 15 % for layered WPLA+PLA specimens) than those mounted without adhesive. The highest values of withdrawal forces, regardless of the adhesive, were obtained for layered WPLA+PLA configuration, followed by WPLA, and the lowest for PLA. No significant difference was found between the withdrawal forces for WPLA and layered WPLA+PLA specimens for both cases – with and without an adhesive. The withdrawal forces of double-threaded nuts for the PLA specimens were higher than the withdrawal forces for the beech (16.7 % mounted without adhesive and 11.6 % mounted with an adhesive), and other combinations showed a difference higher than 35 % in favor of 3D printed materials. The present analysis, which determines and compares used traditional dismountable connectors in 3D-printed furniture elements, is applicable for research and practice.*

KEYWORDS: *3D printing; wood; wood-plastic composites (WPC); double-threaded nut; withdrawal force*

* Corresponding author
[1] Authors are full professors at University of Sarajevo, Mechanical Engineering Faculty, Department of Wood Technology, Bosnia and Herzegovina. https://orcid.org/0000-0002-3636-010X, https://orcid.org/0000-0001-9906-6306, https://orcid.org/0009-0004-8322-9683
[2] Author is PhD student at University of Sarajevo, Mechanical Engineering Faculty, Bosnia and Herzegovina.
[3] Author is senior assistant at University of Sarajevo, Mechanical Engineering Faculty, Department of Wood Technology, Bosnia and Herzegovina. https://orcid.org/0009-0000-5323-5418
[4] Author is associate professor at University of Sarajevo, Mechanical Engineering Faculty, Department of Wood Technology, Bosnia and Herzegovina. https://orcid.org/0000-0001-7105-1743

SAŽETAK • *U ovom je radu istraživan izvlačni kapacitet dvonavojnih matica montiranih u 3D printane materijale. Ispitivana su osnovna tehnička svojstva i izvlačna sila dvonavojnih matica za uzorke izrađene od PLA, WPLA i slojevite WPLA + PLA konfiguracije (bez STP ljepila i s njim). Rezultati su uspoređeni s podatcima iz literature o izvlačnoj sili za bukovinu, MDF i ivericu bez ljepila i s njim. Istraživanjem je utvrđen utjecaj svojstava 3D printanih materijala (gustoće, tlačne i vlačne čvrstoće), ispune i šablone printanja te ljepila na izvlačni kapacitet dvonavojnih matica. Dvonavojne matice montirane uz upotrebu ljepila imale su veće izvlačne sile (oko 25 % za PLA i WPLA uzorke i 15 % za slojevite WPLA + PLA uzorke) od onih montiranih bez ljepila. Najveće vrijednosti izvlačne sile, neovisno o ljepilu, dobivene su za slojevitu WPLA + PLA konfiguraciju, zatim slijedi WPLA, a najniže su za PLA. Nije pronađena značajna razlika između izvlačne sile WPLA i slojevitih WPLA + PLA uzoraka pripremljenih bez ljepila i s njim. Izvlačne sile dvonavojnih matica za PLA uzorke bile su veće od izvlačnih sila za bukovinu (16,7 % uzoraka montiranih bez ljepila i 11,6 % montiranih s ljepilom), a ostale kombinacije pokazale su razliku veću od 35 % u korist 3D printanih materijala. Prikazana analiza, koja određuje i uspoređuje korištene tradicionalne rastavljive spojnice u 3D printanim elementima namještaja, primjenjiva je za istraživanje i praksu.*

KLJUČNE RIJEČI: *3D printanje; drvo; drvno-plastični kompoziti (WPC); dvonavojna matica*

1 INTRODUCTION
1. UVOD

Global awareness of environmental protection and sustainable resource management is rising, therefore the development and adoption of new technologies to enhance production efficiency and environmental responsibility in furniture industry is becoming essential. Consumers are demanding products made from sustainable resources that are biodegradable, have low environmental impact and pose no health risk for humans (Krapez Tomec and Kariz, 2022). In this context, traditional wood industry is facing several challenges, such as high wood resource consumption, waste generation and environmental pollution. 3D printing technology has revolutionized both innovation and environmental sustainability in traditional woodworking. Compared to subtractive manufacturing technologies, such as CNC milling and turning, which are characterized by the removal of excess material to obtain the desired shape, 3D printing, as an additive manufacturing process, only adds material where it is needed, fusing the material layer-by-layer, which contributes to significantly reducing waste generation. Also, recycled wood and plastic can be extruded into wood-plastic filaments, that are suitable for 3D printing, therefore promoting circular economy and leading to low or zero waste (Wimmer *et al*., 2015). Case studies show that 3D printing technology demonstrates up to 40 % reduction of manufacturing related material waste compared to traditional woodworking furniture production. Also, 95-98 % of non-melted raw material can be reused (Krapez Tomec *et al*., 2024). Despite the potential in increasing plastic recycling rates, consumers are demanding more environmentally friendly products that are not petroleum based. Recycled wood and wood residues generated from primary and secondary wood processing can be combined with biopolymer polylactic acid (PLA), a compostable synthetic polymer made from a monomer feedstock derived from corn starch, into additive manufacturing. Use of wood-PLA composites (WPLA) in additive manufacturing has garnered considerable attention, primarily due to the favorable ecological footprint and enhanced material attributes (Krapez Tomec *et al*., 2024). According to Jarza *et al*. (2023), small-and medium-sized companies can benefit the most from adopting the additive manufacturing. Machines can do jobs instead of workers, the use of resources is reduced and anybody with lower manual skills can produce demanding, complicated and unique products. For large companies, the major benefit from adopting the additive manufacturing is fast development of prototypes, testing, finishing and market presentation, which makes them more competitive, because they can launch a new product on the market faster than the competition.

Traditionally, mass produced furniture, based on its function, can have panel or frame structure, or a combination of both. Integrity and durability of these structures depend on the quality of the connections between the constituent elements. Various factors influence strength and durability of these connections, such as materials used, the quality of the assembly process, the type of connection between the structural elements, and the type of forces the furniture is expected to be exposed to during exploitation (Bas *et al*., 2024).

Constructive connections in furniture can be dismountable and glued. If glued connection between structural elements is used, then disassembly is not possible without breaking or damaging the connection. Dismountable connections, on the other hand, enable construction disassembly, which can be beneficial for reducing the costs of transportation, assembly and storage. Lower costs of production increase the competitiveness of the product on the market. The most widespread dismountable connections are the cam fittings and the bolt and barrel nut connectors (Bas *et al*., 2024).

The strength and stiffness of furniture constructions primarily depend on the physical and mechanical properties of the necessary connections between the structural elements. Bolt fasteners cannot endure cyclic stress without loosening, which can lead to serious accidents, even if anti-loosening bolts are used (Shinbutsu *et al*., 2017). In contrast, the double-threaded nuts and thread bolts connectors, quite common in the production of tables and beds, have an excellent anti-loosening ability. The production of this type of connection elements is very cheap, from the point of production technology, and also, such elements do not impose great requirements during assembly (Mihulja *et al*., 2012).

During exploitation, furniture is exposed to different forces that cause tension or pressure in the joints, which has an influence on their strength and durability. It has been proven that the connections with double-threaded nuts, exposed to withdrawal forces, tend to extract from the material, thus considerably weakening the structures (Ibrisevic *et al*., 2023). Mihulja *et al*. (2012) established that the proper drilling and the diameter of the hole have a large effect on the extraction of nuts. Considering different types of material that can be used in furniture production, an additional strengthening factor might be needed in order to increase the strength of the joint. The only possible solution for strengthening constructive connections with double-threaded nuts and thread bolts is to impose adhesive. The type of adhesive, distribution, adhesive line thickness and moisture content have a significant influence on the strength of the connection (Bas *et al*., 2024). Ibrisevic *et al*. (2023) examined the influence of the adhesive type and different types of wooden materials (beech, medium-density fiberboard, and particleboard) on the withdrawal capacity of double-threaded nuts. They concluded that the best withdrawal capacity was obtained for samples with beech wood glued with Silan terminated polymers (STP), while the lowest withdrawal capacity was obtained for samples with particleboard glued with polyvinyl acetate mounting D2 adhesive.

In recent years, there has been increased interest in the use of 3D printing technology for prototyping and manufacturing furniture joints, chair connectors and threaded fasteners. Smardzewski *et al*. (2016) investigated mechanical properties of externally invisible 3D printed cabinet furniture joints made of wood-based composites. The results showed that the designed joints were characterized by high stiffness and strength. Nikolau *et al*. (2022) used reinforced polylactic acid (PLA) with fiberglass (20 wt. %) to design a 3D printed connector for joining the leg and two stretchers of a chair made from larch. The authors concluded that the direction of filament layer deposition correlates with the joint's strength. Petrova and Jivkov (2024) investigated bending moments and stiffness of joints of thin structural elements connected by 3D printed connectors made of polylactic acid (PLA). The results showed high strength under arm compression bending load. The stiffness coefficients of 3D-printed joints were higher than of conventional detachable mitre joints, but lower than the glued ones. Hajdarevic *et al*. (2018) investigated stress and strain in frontal parallel joints connected with two different 3D printed connectors made of PLA and bonded to spruce wooden parts with one component polyurethane adhesive. The results showed that the values of normal stress at the point of failure of the joints and at the proportional limit of frontal parallel joints with PLA connectors were significantly lower compared to clear spruce wood beam. Also, the values of the effective modulus of elasticity of the joint with PLA connectors were lower than the modulus of elasticity of spruce wood. Krzyżaniak and Smardzewski (2019) analyzed the effect of assembly forces on stiffness and strength of 3D printed, externally invisible and demountable, furniture joints made of polyamide. They concluded that designed 3D printed joints can be used as an alternative to replace metal joints to assemble furniture, while providing external invisibility and the possibility not to use tools during assembly. Hajdarevic *at al*. (2023) investigated if 3D-printed connectors could replace the typical L-shaped joints in the construction of a chair. Different connectors were designed and manufactured using acrylonitrile butadiene styrene (ABS). The results showed that joints with 3D-printed connectors had 42–51 % lower strength than traditional wooden mortise-and-tenon joints. The authors concluded that with the proper design, optimization and materials selection, 3D-printed connectors could have similar mechanical characteristics as connectors made from plywood or aluminum. Eraliev *et al*. (2022) investigated if 3D printed threaded fasteners could lower their self-loosening. They used three types of 3D printing materials: acrylonitrile butadiene styrene (ABS-2), poly lactic acid (PLA), and glass. The results showed that ABS-2 bolt has good anti-loosening performance under cyclical temperature changes. The PLA bolt did not show good performance in low temperature changes, and the glass bolt showed the lowest performance in high temperature changes. Krapez Tomec *et al*. (2024) evaluated the environmental aspect of PLA and wood – PLA products and compared them to traditional metal parts used as connectors in traditional wood furniture industry. They concluded that metal parts manufactured using conventional subtractive processes have higher environmental impact compared to 3D-printed parts obtained from PLA and wood-PLA. They also concluded that the mechanical and physical properties of the printed parts are not significantly lower, compared to conventional wood composites (particleboard and fiberboard). In order to improve the mechanical and physical properties of 3D-printed alternatives from renewable materials, wood fibers and nanocellulose can be added.

This paper aims to determine how different types of 3D printed materials affect the withdrawal force of double-threaded nuts in constructions made of PLA and wood-PLA composites. Withdrawing force of double threaded nuts mounted with and without adhesive will be tested. The obtained results will be compared with the results of withdrawal force of double-threaded nuts in different types of wooden materials in order to determine if double-threaded nuts can be used in dismountable connections in 3D printed furniture made of polylactic acid (PLA) and wood-PLA.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The idea for this research was to examine whether traditional dismountable connectors, mostly used in wooden furniture, could also be used in 3D-printed furniture. Two different kinds of materials: Creality Hyper PLA (CR-Hyper PLA) and Creality Wood (CR-Wood) in three different configurations were used to determine their technical properties and withdrawal capacity of double-threaded nuts. One set of samples was made of CR-Hyper PLA, another set of samples was made of CR-Wood, and a third set of samples was made of layered CR-Hyper PLA and CR-Wood (samples with CR-Wood faces and CR-Hyper PLA core). Hyper fast white PLA (CR-Hyper PLA) was used because of its good adhesion properties. WPLA (CR-Wood) was made of white pine wood flour and biodegradable PLA.

2.1 3D printing sample setup
2.1. Izrada 3D printanih uzoraka

Bambu Lab X1 carbon with AMS was used for printing testing specimens. Bambu Lab X1C was calibrated out of the box. For dimensional accuracy test specimens were printed and measured with Holex digital caliper. They passed dimensional accuracy of ±2 %. Filament was stored in AMS (Automatic Material System) enclosure during printing, conditions of environment were consistent (enclosed). The AMS enclosure helped maintaining a dry environment during printing, which prevents moisture absorption and filament degradation. Filament settings used were configured according to manufacturers' (Creality) recommendations for speed and temperature. The 3D printer had a nozzle diameter of 0.4 mm. The infill density was set to 100 %, the layer height was 0.2 mm, the print speed was 50 mm/s. The printing temperature was set to 220 °C. The printing bed temperature was 60 °C. All samples were printed in the 0° orientation to the build plate. Brim was used for better adhesion to build-plate in all printed specimens. Hot adhesive has been used periodically only on 15 printed specimens for tensile strength testing (Figure 2a), since printing orientation caused adhesion problems and tool head had collision with the last layers of printed specimens and moved them from a build-plate.

2.2 Methods for examining properties of PLA and WPLA materials and WPLA+PLA layered configuration
2.2. Metode ispitivanja svojstava PLA i WPLA materijala te WPLA + PLA uslojene konfiguracije

Density, tensile strength and compressive strength of the 3D printed materials were tested. Determination of selected mechanical properties was done according to the ISO 527-2 and ASTM D695 standards for tensile strength and compressive strength, respectively. Test specimen geometry and dimensions are shown in Figure 1.

For tensile strength testing, five specimens were 100 % infill PLA, five specimens were 100 % infill WPLA and five specimens were 100 % infill with PLA, in combination with WPLA. The testing area of 80 mm length for WPLA / PLA / WPLA testing specimens was divided into three parts. The length of PLA in the middle was 26.5 mm. The rest of the length was WPLA (Figure 2.a.). For compressive strength testing, a total of 15 test specimens were printed. Five specimens were 100

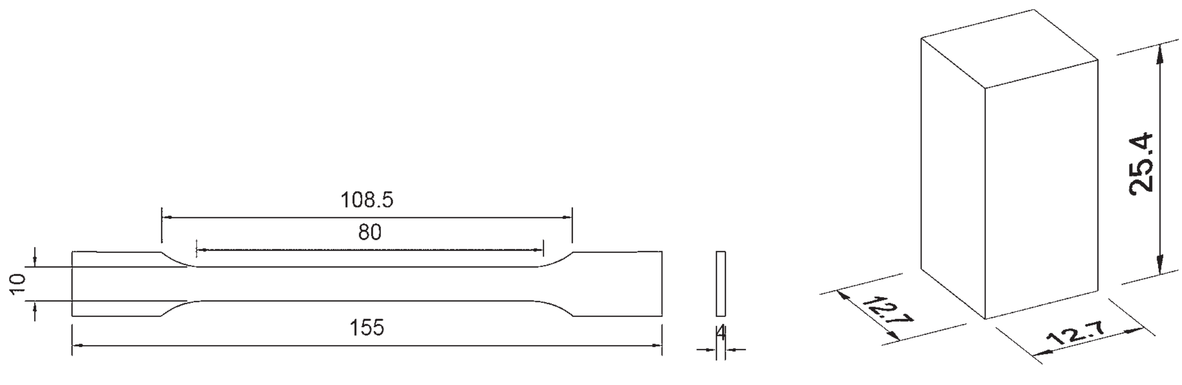
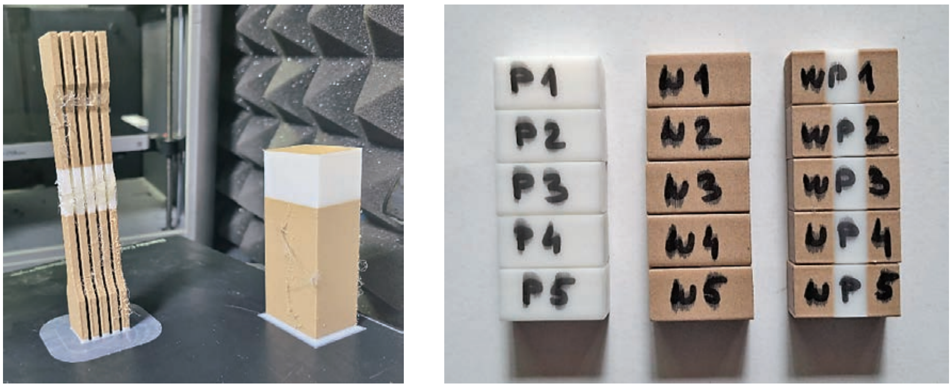
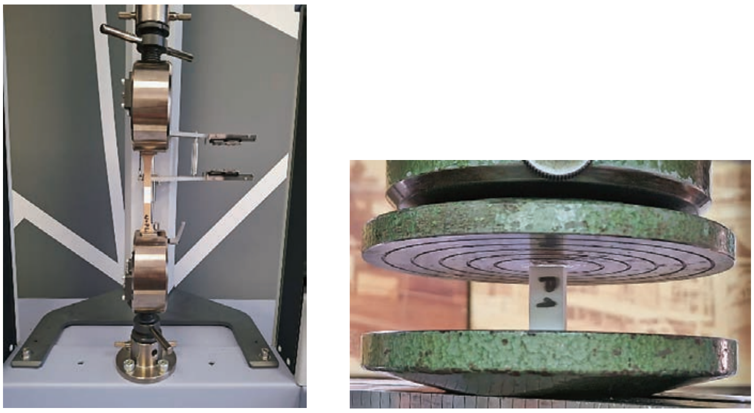


Figure 1 Test specimens: a) tensile strength testing, b) compressive strength testing
Slika 1. Ispitni uzorci: a) za ispitivanje čvrstoće na vlak, b) za ispitivanje čvrstoće na tlak



a) b)

Figure 2 Test specimens for testing mechanical properties of material: a) tensile strength testing, b) compression strength testing
Slika 2. Uzorci za ispitivanje mehaničkih svojstava materijala: a) za ispitivanje čvrstoće na vlak, b) za ispitivanje čvrstoće na tlak



a) b)

Figure 3 Strength testing: a) tensile strength, b) compressive strength
Slika 3. Ispitivanje: a) čvrstoće na vlak, b) čvrstoće na tlak

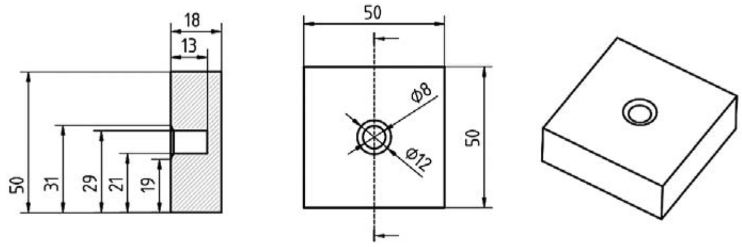
% infill PLA, five specimens were 100 % infill WPLA and five specimens were 100 % infill with 8.46 mm, or 1/3 of specimen thickness in the middle (core), with PLA, in combination with WPLA (faces) (Figure 2b).

The tensile strength tests were carried out on a universal testing machine, Shimadzu, 10kN (Figure 3a.). The displacement velocity during tests was maintained at 5 mm/min. The compressive strength tests were carried out on a universal testing machine, ZWICK, 50kN (Figure 3b.). The tensile/compressive strength (σ_t; σ_c) of the tested material was determined using the following equation: $\sigma = F_{max}/A_0$ MPa, where F_{max} is maximal force (N) and A_0 cross-sectional area (mm^2).

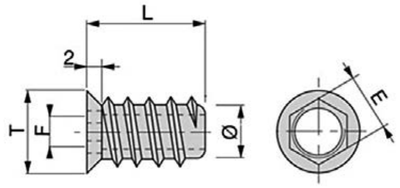
2.3 Method of examining the withdrawal capacity of double-threaded nuts for PLA and WPLA materials and WPLA+PLA layered configuration
2.3. Metoda ispitivanja izvlačnog kapaciteta dvonavojnih matica za PLA i WPLA materijale te WPLA + PLA uslojene konfiguracije

The geometry and dimensions of the samples for examining the withdrawal capacity of double-threaded nuts were 50 × 50 × 18 mm (Figure 4a). These dimensions were chosen because of the better positioning of the work piece in the process of fastening the nuts. The diameter and depth of the hole in the middle of each sample was 8 mm and 13 mm, respectively. Dimensions of double-threaded nuts used to test the withdrawal capacity are shown in Figure 4b.

Three types of 3D printed materials were used to test the withdrawal capacity of double-threaded nuts. A total of 30 test specimens were printed. Ten specimens were 100 % infill PLA, ten specimens were 100 % infill WPLA, and ten layered specimens were 100 % infill with WPLA faces and PLA core with identical thickness of each layer (6 mm, or 1/3 of specimen thickness), as shown in Figure 5a. Before testing, specimens were divided into two groups. In the first group, there were 15 specimens with double threaded nuts mounted without adhesive. In the second group, there were 15 specimens with double threaded nuts mounted with adhesive. Before mounting the double-threaded nuts, the adhesive (cca 0.35 cm^3) was put in the holes to further strengthen the nuts, using a syringe. Silane terminated polymers – STP adhesive (Kleiberit STP 605.1) was used. Double-threaded nuts were mounted into the specimens with an electric screwdriver. The



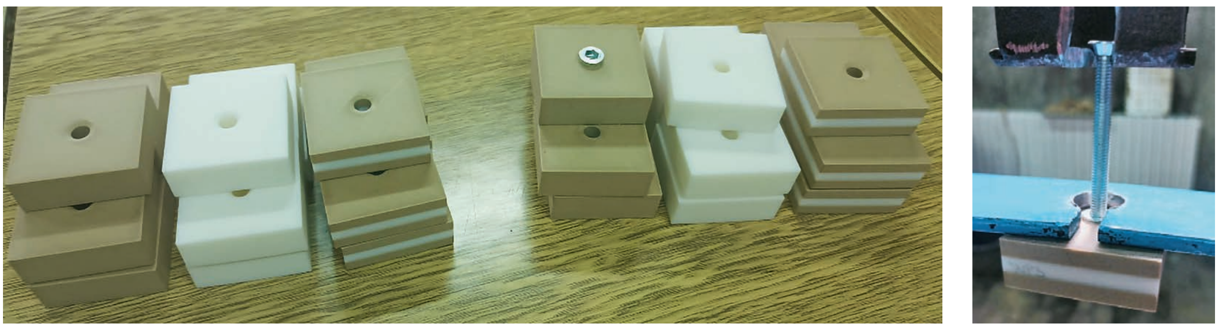
a)



L	13 mm
F	M6
T	11 mm
E	6 mm
Ø	7 mm

b)

Figure 4 Geometry and dimensions: a) specimens for withdrawal capacity of double-threaded nuts testing, b) double-threaded nuts M6×13 (https://www.lccshop.hr; SKU: 008005)
Slika 4. Geometrija i dimenzije: a) uzorci za ispitivanje izvlačne sile dvonavojnih matica, b) dvonavojne matice M6 × 13 (https://www.lccshop.hr; SKU: 008005)



a) b)

Figure 5 Withdrawal capacity testing: a) 3D printed specimens, b) testing device
Slika 5. Ispitivanje izvlačne sile: a) 3D printani uzorci, b) pristroj za ispitivanje

tests were carried out on a universal testing machine (ZWICK, 50 kN), as shown in Figure 5b. The withdrawal force of the double-threaded nuts was read on the force indicator.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Properties of PLA and WPLA materials and WPLA+PLA layered configuration
3.1. Svojstva PLA i WPLA materijala i WPLA + PLA uslojene konfiguracije

Table 1 gives the results of density, compression strength, and tensile strength of the specimens made of PLA, WPLA, and layered WPLA + PLA filament. The mean density of the WPLA specimens was 6 % lower than those of the PLA specimens, and 5 % lower than the layered composite WPLA + PLA specimens. All groups of specimens had a low and similar coefficient of density variations. Additionally, the t-test was used to determine if the means of two sets of experimental results were significantly different from each other. No significant difference (p = 0.135) was observed with a 95 % confidence level (α=0.05) between density of the PLA samples and layered WPLA + PLA samples.

Compressive strength was higher than tension strength for all three groups of printed specimens. The mean compression strength of the PLA specimens was 79.3 %, and of the layered WPLA+PLA 10.9 % higher than that of the WPLA specimens. A significant difference was observed between compression strength for all three groups of samples. The differences are dominantly the result of different responses of the material to the compression load shown in the force-displacement diagrams of the tested specimens (Figure 6a). The PLA specimens had a wide defined elastic region, i.e. proportional zones with high failure points as brittle material. The diagram and deformed WPLA and layered WPLA+PLA specimens show the ductile characteristics (Figure 6b). Forces at the yield points are taken to calculate compression strength.

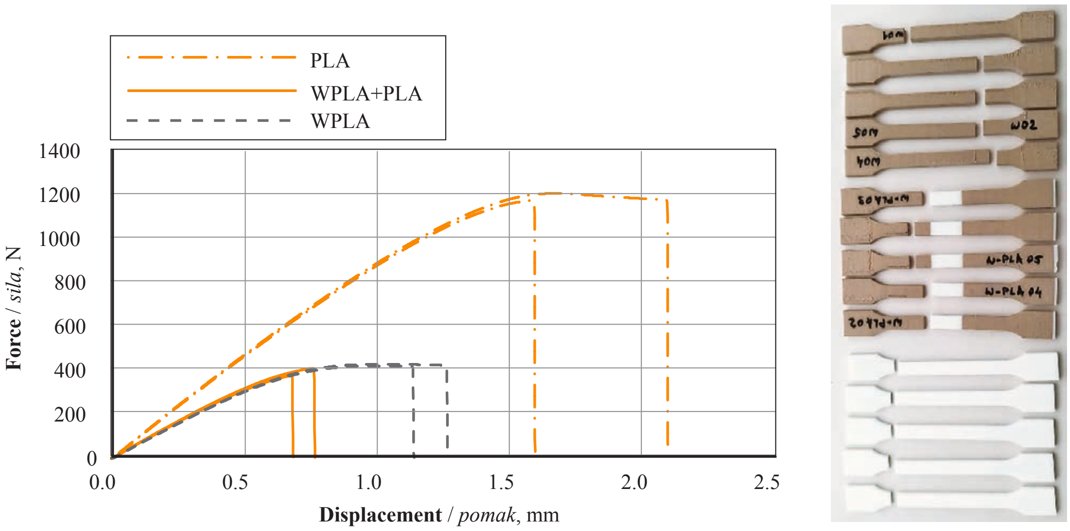
Table 1 Density, compression strength, and tensile strength of printed material
Tablica 1. Gustoća, čvrstoća na tlak i čvrstoća na vlak printanog materijala

Properties *Svojstvo*	**PLA**			**WPLA+PLA**			**WPLA**		
	Mean	Std. Dev.	Coef.of var. %	Mean	Std. Dev.	Coef.of var. %	Mean	Std. Dev.	Coef.of var. %
ρ, g/cm^3	1.17	0.01	0.85	1.16	0.01	0.86	1.10	0.01	0.91
σ_c, MPa	73.49	2.35	3.19	45.47	0.28	0.61	40.99	1.27	3.09
σ_t, MPa	28.82	0.54	1.86	10.12	0.51	5.01	10.10	0.47	4.64

ρ – density, σ_c – compression strength, σ_t – tensile strength / ρ – *gustoća,* σ_c – *čvrstoća na tlak,* σ_t – *čvrstoća na vlak*

a) b)

Figure 6 Compression strength: a) sketch of deformation – force diagram, b) characteristic failures (specimens from left to right: PLA, WPLA+PLA, and WPLA)
Slika 6. Čvrstoća na tlak: a) skica dijagrama deformacija – sila, b) karakteristični lomovi (uzorci slijeva nadesno: PLA, WPLA + PLA i WPLA)



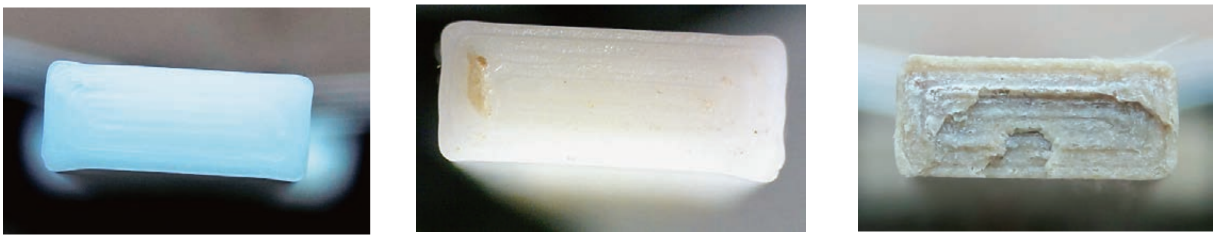
a) b)

Figure 7 Tensile strength: a) deformation – force diagram of randomly selected samples, b) characteristic failures (specimens from top to bottom: WPLA, WPLA+PLA, and PLA)
Slika 7. Čvrstoća na vlak: a) dijagram deformacija silâ za slučajno izabrane uzorke, b) karakteristični lomovi (uzorci od vrha prema dnu: WPLA, WPLA + PLA i PLA)

The deformation – force diagrams obtained by testing the tensile strength of six randomly selected samples are shown in Figure 7a. The mean tensile strength of the PLA specimens was 2.85x, and a layered WPLA+PLA 0.2 % higher than the WPLA specimens. No significant difference was observed between tensile strength for the layered WPLA+PLA and WPLA (p = 0.9606). The angle between printed orientation and the tensile force line (90°), and the adhesion properties of printed materials had a dominant influence on tensile strength value. The results showed no differences in adhesion between the WPLA layers and adhesion in the contact surface of the WPLA and PLA layers (Figure 7b).

Figure 8 shows a 20x magnified view of the characteristic deformations and fracture zones of PLA, layered WPLA+PLA, and WPLA materials after strength testing. After the compression strength test, the PLA material showed no significant deformation and noticeable failure, in contrast to the WPLA material, which

a)



b)

Figure 8 Specimens failures (from left to right: PLA, WPLA+PLA, and WPLA): a) compression strength, b) tensile strength
Slika 8. Lomovi uzoraka (slijeva nadesno: PLA, WPLA + PLA i WPLA): a) čvrstoća na tlak, b) čvrstoća na vlak

Table 2 Withdrawal force of double-threaded nuts (F_{max})
Tablica 2. Izvlačna sila dvonavojnih matica (F_{max})

Specimens *Uzorci*	**PLA**		**WPLA+PLA**		**WPLA**	
	No adhesive *Bez ljepila*	Adhesive *S ljepilom*	No adhesive *Bez ljepila*	Adhesive *S ljepilom*	No adhesive *Bez ljepila*	Adhesive *S ljepilom*
1.	3433.50	3963.24	4689.18	5248.35	3659.13	4836.33
2.	3109.77	3953.43	4542.03	4924.62	4208.49	5052.15
3.	2962.62	4208.49	4973.67	5356.26	3796.47	5248.35
4.	3149.01	4355.64	4179.06	5317.02	4394.88	4767.66
5.	3796.47	4071.15	4247.73	5297.40	3865.14	5071.77
Mean, N	3290.27	4110.39	4526.33	5228.73	3984.82	4995.25
Std.Dev., N	330.39	171.46	326.00	174.39	305.80	193.78
Coef.of var., %	10.04	4.17	7.20	3.34	7.67	3.88

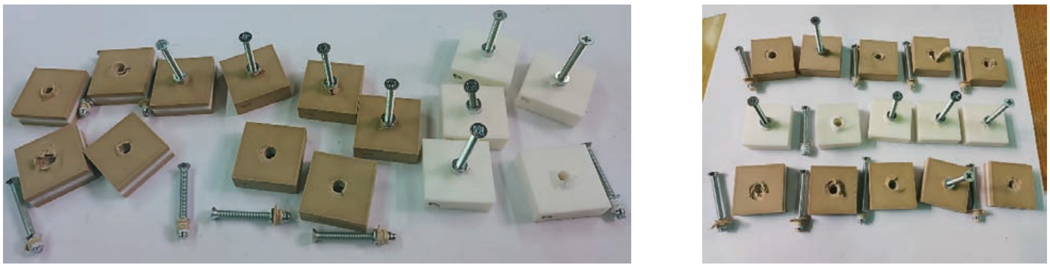
exhibited yielding and large plastic deformation with a rough surface. Delamination of the layer was a typical fracture of PLA and WPLA material under tension.

3.2 Withdrawal capacity of double-threaded nuts mounted into PLA and WPLA materials and WPLA+PLA layered configuration
3.2. Izvlačni kapacitet dvonavojnih matica montiranih u PLA i WPLA materijale te u WPLA + PLA uslojenu konfiguraciju

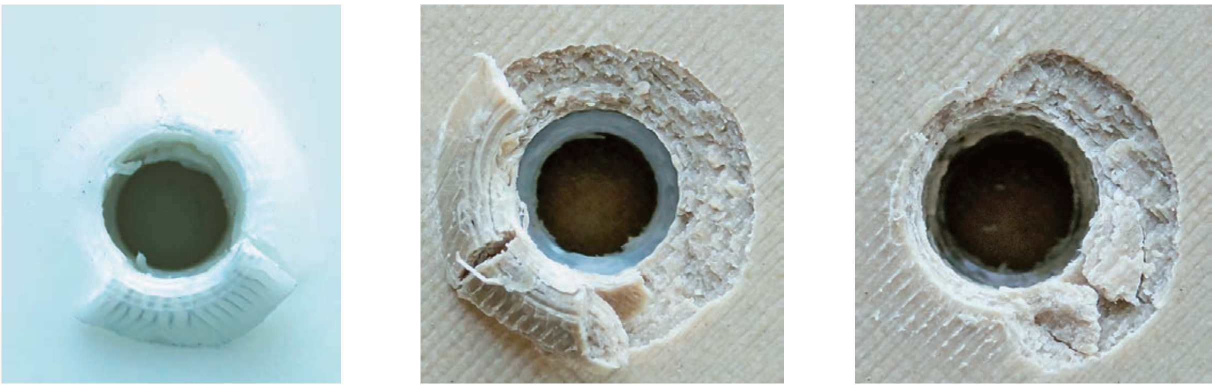
The results of the maximum withdrawal forces (F_{max}) of the double-threaded nuts (mounted with and without STP adhesive) are given in Table 2. Mean values of withdrawal forces of the double-threaded nuts mounted with adhesive were higher than those mounted without adhesive for all three groups of printed specimens. The withdrawal forces of specimens without adhesive exhibit approximately twice as high variability as those with the adhesive.

The PLA specimens with adhesive had 24.9 %, the layered WPLA+PLA specimens with adhesive 15.5 %, and the WPLA specimens with adhesive 25.4 % higher mean withdrawal forces of the double-threaded nuts for the same group of specimens without adhesive. Withdrawal forces of double-threaded nuts for the layered WPLA+PLA specimens were 13.6 % and 37.6 % higher for specimens without adhesive, and 4.7 % and 27.2 % higher for the specimens with adhesive, than the withdrawal forces of the WPLA and PLA specimens, respectively. For WPLA specimens, the withdrawal force was approximately 21 % higher than for the PLA specimens, regardless of the adhesive application. The minimal percentage difference in withdrawal force was 3.1 %, between WPLA without adhesive and PLA with adhesive, and the maximal percentage difference in withdrawal force was 45.5 %, between PLA without adhesive and WPLA+PLA with adhesive.

The characteristic patterns of the fractures of the double-threaded nuts caused by the withdrawal forces are shown in Figure 9. The fracture modes of the double-threaded nuts are similar to common fractures in wood, or other fiber materials. The nut started to pull out after the material around the thread failed. The material remains partially attached to the thread while the



a)



b)

Figure 9 Failures caused by withdrawal force of double-threaded nuts: a) specimens without adhesive (left), specimens with adhesive (right), b) failures of PLA, WPLA+PLA, and WPLA material
Slika 9. Lomovi uzrokovani izvlačenjem dvonavojnih matica: a) uzorci bez ljepila (lijevo) i uzorci s ljepilom (desno), b) lomovi PLA, WPLA + PLA i WPLA materijala

outer layers delaminate and/or the fibers break. The amount of the pulled-out material and size of the degraded zone of material in the outer layers and/or the amount of the material that remains attached to the double-threaded nuts after fractures are generally higher for double-threaded nut samples mounted with adhesive, particularly so for WPLA and WPLA+PLA samples.

Comparative distributions of results of maximum withdrawal forces (F_{max}) of the double-threaded nuts of the three groups of samples mounted with and without adhesive are shown in Figure 10. The samples with adhesives from the same group of materials, e.g. PLA group, have higher withdrawal forces (F_{max}) of the double-threaded nuts than those without adhesive. Results of the T-test showed a significant difference between the withdrawal forces of the double-threaded nuts between samples without adhesive and the samples with adhesive for the same group of printed materials used.

No significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts

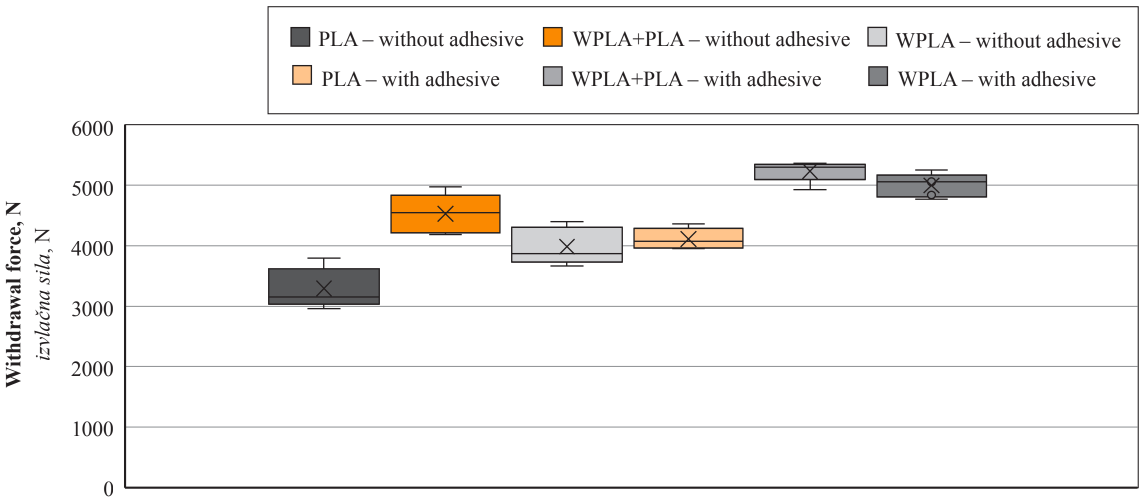


Figure 10 Distribution of results of withdrawal forces of double-thread nuts mounted into PLA, WPLA+PLA, and WPLA printed material
Slika 10. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih u PLA, WPLA + PLA i WPLA printani materijal

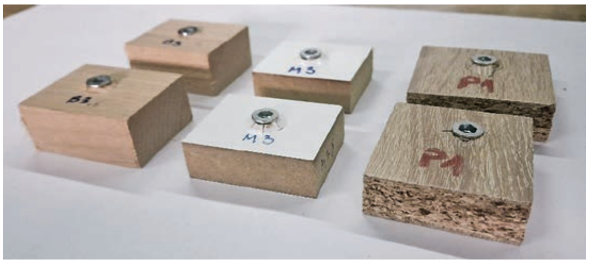


Figure 11 Failures caused by withdrawal force of double-threaded nuts mounted into beech wood, MDF, and particleboard
Slika 11. Lomovi uzrokovani izvlačenjem dvonavojnih matica montiranih u bukovo drvo, MDF i ivericu

for WPLA specimens and layered WPLA+PLA specimens without adhesive (p = 0.0998), or for the same groups of specimens with adhesive (p = 0.1186). Also, no significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts for PLA specimens with adhesive and WPLA specimens without adhesive (p = 0.3577), or for PLA specimens with adhesive and layered WPLA+PLA specimens without adhesive (p = 0.0832).

3.3 Comparison of withdrawal capacity of double-threaded nuts mounted into PLA and WPLA materials and wooden materials

3.3. Usporedba izvlačnog kapaciteta dvonavojne matice montirane u PLA i WPLA materijale i drvne materijale

The withdrawal forces (F_{max}) of the double-threaded nuts mounted into PLA, layered WPLA+PLA, and WPLA specimens were compared with the results of withdrawal forces for wood (beech) and coated wood composites (medium-density fiberboard (MDF) and particleboard), as shown in Figure 11. The data used is from the paper that analyzed the effect of wooden material types and adhesive types on the withdrawal capacity of double-threaded nuts (Ibrisevic *et al*., 2023).

The results of the withdrawal force (F_{max}) of double-threaded nuts (without adhesive and with STP adhesive; 15 specimens for each combination) given in Table 3 are comparable because they were obtained using the same type of double-threaded nuts, the same amount of STP adhesive and the same methodology described in this paper.

Withdrawal forces of the double-threaded nuts mounted with adhesive were higher than those mounted

Table 3 Descriptive statistics of withdrawal force (F_{max}) of double-threaded nuts for beech wood, MDF, and particleboard (Ibrisevic *et al.,* 2023)
Tablica 3. Deskriptivna statistika izvlačne sile (F_{max}) dvonavojnih matica za bukovo drvo, MDF i ivericu (Ibrisevic *et al*., 2023.)

Withdrawal force F_{max}, N *Izvlačna sila F_{max},* N	**Beech** / *Bukovina*			**MDF**			**Particleboard** / *Iverica*		
	Mean	Std. dev.	Coef. of var.	Mean	Std. dev.	Coef. of var.	Mean	Std. dev.	Coef. of var.
No adhesive *Bez ljepila*	2820.2	384.8	0.1	1296.2	182.3	0.1	977.0	188.7	0.2
STP adhesive *Sa STP ljepilom*	3684.0	399.5	0.1	1881.0	194.0	0.1	1337.3	140.8	0.1

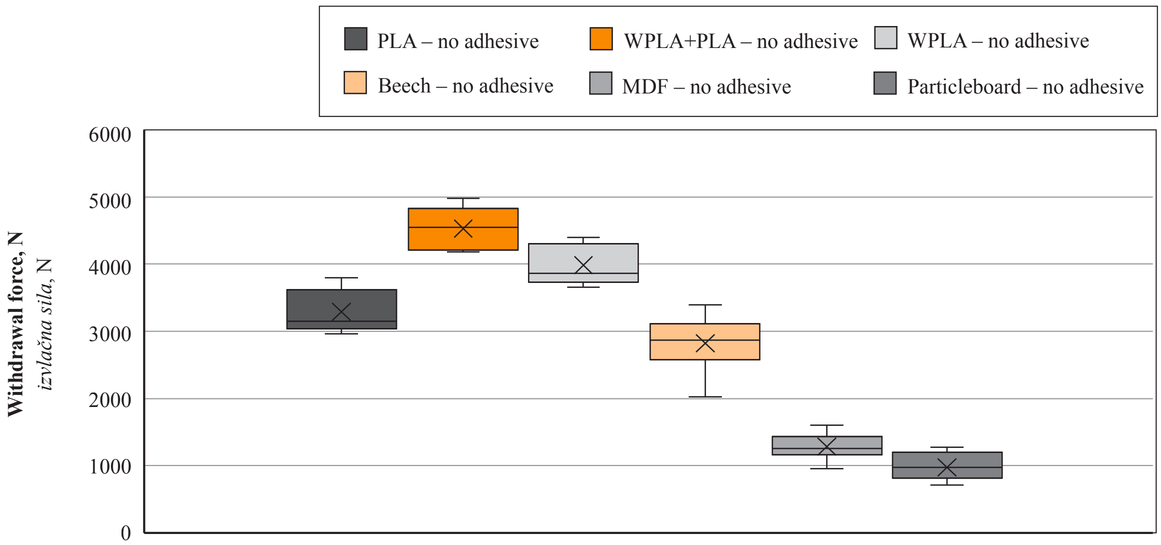


Figure 12 Distribution of withdrawal force results of double-threaded nuts mounted without adhesive into PLA, WPLA+PLA, WPLA, beech wood, MDF, and particleboard
Slika 12. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih bez ljepila u PLA, WPLA + PLA, WPLA, bukovo drvo, MDF i ivericu

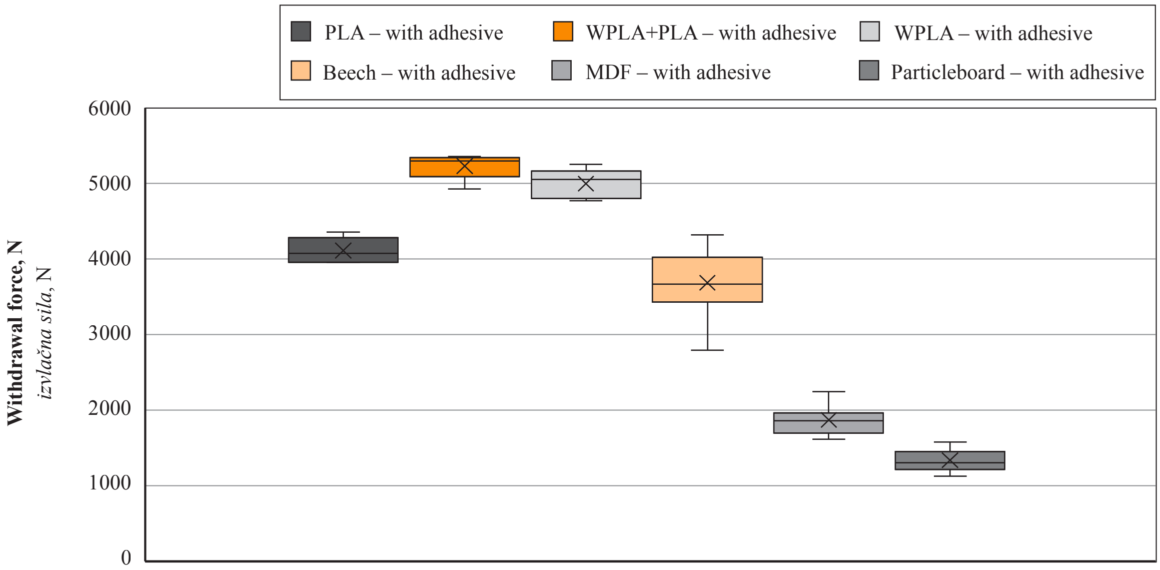


Figure 13 Distribution of withdrawal force results of double-threaded nuts mounted with adhesive into PLA, WPLA+PLA, WPLA, beech wood, MDF, and particleboard
Slika 13. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih uz pomoć ljepila u PLA, WPLA + PLA, WPLA, bukovo drvo, MDF i ivericu

without adhesive for all wooden materials. The beech specimens with adhesive had 30.6 %, the MDF specimens with adhesive 45.1 %, and particleboard specimens with adhesive 36.9 % higher withdrawal forces of the double-threaded nuts for the same group of specimens without adhesive. Namely, gluing creates a solid bond between the surfaces of two different materials (metal and wood, or wood-based materials), and a different distribution of internal forces occurs in the loaded joint, i.e., a stress distribution, which ultimately affects the value of the withdrawal force. Furthermore, the withdrawal force for beech specimens was approximately 2x higher than the mean withdrawal force for MDF specimens, and approximately 3x higher than for particleboard specimens, regardless of whether adhesive was used. The withdrawal forces of the MDF specimens were 32.7 % without adhesive and 40.6 % with adhesive higher than the mean withdrawal force of the particleboard specimens.

Comparative distributions of the maximum withdrawal forces (F_{max}) results of the double-threaded nuts for the 3D printed materials and wooden materials mounted with and without adhesive are shown in Figure 12 and Figure 13. A comparison of the withdrawal forces results between 3D printed materials and wooden materials showed that withdrawal forces of double-threaded nuts for the PLA specimens without adhesive were 16.7 % higher and for specimens with adhesive 11.6 % higher than the withdrawal forces of the beech with and without adhesive, respectively. All other combinations showed a difference higher than 35 % in favor of 3D printed materials.

No significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts for the beech specimens with adhesive and PLA specimens without adhesive (p = 0.0604), for the beech specimens with adhesive and WPLA specimens without adhesive (p = 0.1129), and for the particleboard specimens with adhesive and MDF specimens without adhesive (p = 0.3849). In general, the withdrawal capacity of double-threaded nuts mounted in materials with adhesive can reach the value of the withdrawal capacity for materials that have better physical and mechanical properties, i.e. density and strength.

4 CONCLUSIONS
4. ZAKLJUČAK

This paper analyzed the withdrawal capacity of the double-threaded nuts mounted in 3D-printed materials with and without STP adhesive. The basic technical properties and the withdrawal force of the double-threaded nuts for the specimens made of PLA, WPLA, and layered WPLA+PLA configuration, with 100 % infill, were investigated. The values of the withdrawal force of six specimen groups are compared with the literature data of withdrawal force for beech wood, MDF, and particleboard with and without the same adhesive.

The results showed that the specimens, made with 100 % infill, had a higher density than 1.1 g/cm^3. Compressive strength was higher than tension strength, and, for both strengths, PLA had higher values than WPLA and layered WPLA+PLA. Their values and failure modes resulted from the material used, the combination of materials, and dominantly the printing pattern. No significant difference was observed between tensile strength for the layered WPLA+PLA and WPLA, which is a consequence of adhesion in the contact surface of the layers.

Withdrawal forces of the double-threaded nuts mounted with adhesive were higher (about 25 % for PLA and WPLA specimens, and 15 % for layered WPLA+PLA specimens) and they showed approximately less variability than those mounted without adhesive for all three groups of printed specimens. The highest values of withdrawal forces (for both with and without an adhesive) were obtained for layered WPLA+PLA configuration, followed by WPLA and the lowest for PLA. No significant difference was found between the withdrawal forces for WPLA and layered WPLA+PLA specimen for both cases, with and without an adhesive. Also, no significant difference was found between the withdrawal forces for PLA specimens with adhesive and WPLA or layered WPLA+PLA specimens without adhesive. The test results showed a significant influence of the properties of 3D printed materials (density, brittle, and ductile characteristics), the infill and printing pattern, and adhesive used on the withdrawal capacity of the double-threaded nuts.

Withdrawal forces of double-threaded nuts for the PLA specimens were higher than the withdrawal forces of the beech specimens (16.7 % for specimens mounted without adhesive and 11.6 % for specimens mounted with adhesive), and other combinations showed a difference higher than 35 % in favor of 3D printed materials. No significant difference was found between the withdrawal forces for the beech specimens with adhesive and for PLA or WPLA specimens without adhesive. The results showed that the analyzed configurations of 3D printed materials have a higher withdrawal capacity of the double-threaded nuts than hardwood and wood-based materials.

The results of the present analysis show that common double-threaded nuts can be used in dismountable connections in 3D printed furniture, or furniture parts made of PLA and wood-PLA. It enables manufacturers to create and produce dismountable furniture construction, furniture parts on demand, and repair more easily damaged construction parts made of 3D-printed wood-plastic composites.

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Corresponding address:

SEID HAJDAREVIC

University of Sarajevo, Mechanical Engineering Faculty, Department of Wood Tehnology, Vilsonovo šetalište 9, 71000 Sarajevo, BOSNIA AND HERZEGOVINA, e-mail: hajdarevic@mef.unsa.ba