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Investigation of Adhesion and Flexural Behavior of FDM-Based PLA+-Wood Hybrid Joints for Furniture Applications

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ABSTRACT

In this study, the effects of different adhesive systems (isocyanate and polyurethane D4) and surface preparation processes (sanded/unsanded) on the adhesion strength and flexural performance of hybrid joints formed by fused deposition modelling (FDM) printed modified polylactic acid (PLA+) connectors and Scots pine (*Pinus sylvestris* L.) wood were experimentally investigated. Surface roughness (Ra) was measured with a profilometer prior to bonding, tensile tests were performed according to ASTM D3164-03, and three-point bending tests were carried out according to ASTM D790-17. Flexural tests were applied in two different loading configurations, with the PLA+ layer located either in the tensile or compressive region to represent real-world usage conditions, and fracture surfaces were examined using an optical microscope. The obtained data were statistically evaluated using multifactor analysis of variance (ANOVA) followed by Tukey HSD tests. Tensile test results showed that the combination of isocyanate-based adhesive and sanded surface provided the highest adhesion strength (5.99 MPa) and maximum stress (11.99 MPa). PU D4-based adhesive generally exhibited lower performance, and the beneficial effect of sanding on maximum stress in the PU system was not statistically significant. In three-point bending tests, adhesive type emerged as the primary factor, whereas the effect of surface treatment on bending stress was negligible. Fracture mode analyses revealed predominantly substrate failure for isocyanate-bonded joints and mainly cohesive failure within the PU D4 adhesive layer for PU D4-bonded joints. These findings indicate that isocyanate-based adhesives significantly improve the structural performance of FDM-based hybrid joints for furniture and customized production applications.

Keywords: Fused deposition modelling (FDM), Hybrid jointing, Surface preparation, PLA+, Tensile strength

Mobilya Uygulamaları için FDM Tabanlı PLA+-Ahşap Hibrit Bağlantıların Yapışma ve Eğilme Davranışının İncelenmesi

ÖZET

Bu çalışmada, FDM baskılı güçlendirilmiş polilaktik asit (PLA+) bağlantı elemanları ve sarıçam (*Pinus sylvestris* L.) ağacından oluşturulan hibrit bağlantıların yapışma mukavemeti ve eğilme performansı üzerindeki farklı yapıştırıcı sistemlerinin (izosiyanat ve poliüretan (PU) D4) ve yüzey hazırlama işlemlerinin (zımparalanmış/zımparalanmamış) etkileri deneysel olarak incelenmiştir. Yüzey pürüzlülüğü (Ra), yapıştırmadan önce bir profilometre ile ölçülmüş, çekme testleri ASTM D3164-03'e göre, üç noktalı eğilme testleri ise ASTM D790-17'a göre yapılmıştır. Eğilme testleri, gerçek dünya kullanım koşullarını temsil etmek üzere PLA+ katmanının çekme ve sıkıştırma bölgesinde bulunduğu iki farklı yükleme konfigürasyonunda uygulanmış ve kırılma yüzeyleri optik mikroskop kullanılarak incelenmiştir. Elde edilen veriler, çok faktörlü varyans analizi (ANOVA) ve ardından Tukey HSD testleri kullanılarak istatistiksel olarak değerlendirilmiştir. Çekme testi sonuçları, izosiyanat bazlı yapıştırıcı ve zımparalanmış yüzey kombinasyonunun en yüksek yapışma mukavemetini (5.99 MPa) ve maksimum gerilimi (11.99 MPa) sağladığını göstermiştir. PU D4 bazlı yapıştırıcı genel olarak daha düşük performans göstermiş ve PU sisteminde zımparalamanın maksimum gerilim üzerinde anlamlı bir etkisi bulunmadığı görülmüştür. Üç noktalı eğilme testlerinde, yapıştırıcı türü birincil faktör olarak ortaya çıkarken, yüzey işleminin eğilme gerilimi üzerindeki etkisi ihmal edilebilir düzeyde kalmıştır. Kırılma modu analizleri, izosiyanat ile yapıştırılmış bağlantılarda ağırlıklı olarak alt tabaka kırılması şeklinde ve PU D4 ile yapıştırılmış bağlantılarda ise yapıştırıcı tabakası içinde kohezif kırılma olduğunu ortaya koymuştur. Bu bulgular, izosiyanat bazlı yapıştırıcıların mobilya ve özel üretim uygulamaları için FDM tabanlı hibrit bağlantıların yapısal performansını önemli ölçüde iyileştirdiğini göstermektedir.

Anahtar Kelimeler: Eriyik katmanlı modelleme (FDM), Hibrit birleştirme, Yüzey hazırlığı, PLA+, Çekme dayanımı

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1. INTRODUCTION

Additive manufacturing (AM) technologies have revolutionized industry by enabling the rapid and low-cost prototyping of complex geometries that are difficult or impossible to produce with traditional manufacturing methods [1–3]. Among these technologies, Fused Deposition Modeling (FDM) has found widespread use, from the automotive to the furniture industry, due to its low cost and variety of materials [1,2,4]. While wood maintains its position as a fundamental raw material in the furniture industry due to its sustainability and aesthetic qualities, the integration of polymer parts produced using 3D printers with wood components to create hybrid structures offers significant advantages such as design flexibility and reduced production time [1,5,6].

Research on the use of 3D-printed polymer connectors instead of labor-intensive and time-consuming mortise-tenon joining methods in traditional furniture production focuses on improving the structural performance of such joints [1,7]. However, the insufficient adhesion strength of thermoplastic parts produced by 3D printers with wood materials poses a critical challenge for the structural integrity and durability of the product [3,5]. Furthermore, the generally low surface energy of polymers makes it difficult for the adhesive to wet the surface and for mechanical interlocking to occur [3,6].

The importance of surface preparation processes to increase adhesion strength is emphasized in literature. Mechanical abrasion (sanding) has been shown to significantly improve adhesion strength by expanding the adhesive contact surface on the polymer surface and optimizing mechanical interlocking [5,8]. Adhesive selection is another key factor affecting the performance of such heterogeneous bonds. Polyurethane (PU) based adhesives and isocyanate-containing systems stand out as high-performance solutions in bonding wood and polymer composites [7,9].

Although polylactic acid (PLA) is the most widely used polymer in 3D printing due to its biodegradable and non-toxic nature, research on modified derivatives such as PLA plus (PLA+) is increasing in order to improve its mechanical properties. Various studies exist in the literature on the tensile and flexural strengths of PLA and wood-reinforced PLA (wood PLA) materials [8,10–13], however, more scientific data is needed on the interaction of PLA+ parts with wood under sanding and different types of adhesives (isocyanate and PU D4) to improve their adhesion performance.

The use of additive manufacturing technologies in the furniture industry focuses particularly on the production of fasteners with complex geometries [1,7]. These parts, which are difficult and time-consuming to produce using traditional methods, can be produced using the FDM method thanks to easily printable polymers such as PLA. However, the literature draws attention to the problem of "adhesion resistance" in bonding polymer parts produced by 3D printers to wood [5,14].

In their study, Kariz et al. [14] examined different parameters in bonding parts produced from ABS material on a 3D printer to beech wood. The researchers tested single-component and two-component polyurethane (PU) adhesives and reported that the two-component PU adhesive provided the highest bond strength.

In another study conducted by Kariz et al. [5], the effect of surface preparation processes on the adhesion of PLA, wood-reinforced PLA, and ABS materials to wood was investigated. The study confirmed that mechanical abrasion (sanding) increased the roughness on the polymer surface, enabling mechanical locking of the adhesive and increasing the adhesion strength in all material groups. It was stated that the bond strength reached its highest values, especially on sanded and plasma-treated surfaces.

In their study, Khosravani et al. [15] focused on the structural integrity of connections made from PLA material and argued that adhesive thickness plays a critical role in adhesion performance. As a result of tensile tests, it was determined that an adhesive thickness of 0.2 mm was the optimum value providing the highest mechanical strength. In addition, it was reported that modifications in the connection geometry (such as stepped structures) can increase the load-carrying capacity by up to 40%.

Tomec et al. [6] investigated scenarios where PLA was printed directly onto the wood surface (direct 3D printing). In this study, it was found that pretreatment by applying PVAc glue to the wood surface increased the adhesion strength to 5.4 MPa by creating an interface between the molten PLA and the wood fibers. This finding demonstrates the importance of adhesives in improving the chemical and mechanical compatibility between the polymer and the wood.

Hajdarevic et al. [7] tested the performance of 3D-printed ABS connectors, which are planned to replace mortise-and-tenon joints in furniture production. Bending and tensile tests revealed that the 3D-printed connectors could withstand seating loads but exhibited 42-51% lower strength in backrest tests compared to traditional wood joints. This highlights the need for optimization of adhesive and surface treatment protocols used during the assembly phase. Research on isocyanate (pMDI)-based adhesives shows that these resins can form strong chemical bonds with the hydroxyl groups of wood and provide high thermal and mechanical

resistance by creating polyurethane bridges [9]. However, the performance of these systems in the assembly of 3D-printed PLA+ connectors stands out as an area requiring further investigation in the current literature.

In furniture and similar structural applications, the same connection detail can be subjected to bending and impact loads from different directions during use. This is also true for hybrid PLA+-wood joints. The connection line can sometimes be stressed with the PLA+ side remaining in the tension zone, and sometimes with the wood side remaining in the tension zone. Therefore, in this study, three-point bending tests were performed in two different loading configurations: one with wood on top and PLA+ underneath, and another with PLA+ on top and wood underneath. The effect of the loading direction on the stress distribution and fracture behavior within the joint was investigated. This study aims to make a unique contribution by determining the most efficient adhesive (PU D4 and isocyanate) and surface treatment (sanding) combination for bonding 3D-printed PLA+ parts to wood, both for industrial and individual users, in light of existing literature data. In this study, the term 'hybrid joint' refers to furniture connections in which a 3D-printed PLA+ connector element is bonded to a solid wood member using structural adhesive, so that the load-carrying capacity of the joint arises from the combined action of the polymer connector, the wood substrate and the adhesive interface. The connector itself is fully manufactured from PLA+ using the FDM process, while the mating part is Scots pine therefore, the joint combines two dissimilar materials and is classified as a wood-polymer hybrid connection.

The main objective of this study is to experimentally analyze the effects of different adhesive systems (isocyanate and PU D4) and mechanical surface preparation processes (sanded/unsanded) on the adhesion strength and bending performance of furniture joints made of PLA+ produced by the FDM method, when joined to wooden furniture elements. Accordingly, the interaction of FDM-printed PLA+ samples with wooden parts was investigated under combinations of isocyanate and polyurethane (PU D4) based adhesives and sanded and unsanded surface preparation. In this study, PLA+ was selected instead of standard PLA because it provides higher impact resistance, improved interlayer adhesion and slightly increased toughness, which are beneficial for load-bearing connector elements in furniture joints, while preserving the low printing temperature, bio-based origin and general safety profile of conventional PLA. Standard tensile tests and three-point bending tests were applied to measure the static load behavior of the prepared hybrid joints in furniture use scenarios. In addition to the bonding performance, the effect of sanding on surface roughness (Ra) was quantitatively evaluated using a profilometer, fracture surfaces were examined in terms of fracture modes under an optical microscope, and the obtained data were statistically interpreted using multi-factorial analysis of variance (ANOVA). With the increasing popularity of personal 3D printers, individuals can now design their own plastic connectors, assemble them with wooden parts, and create unique furniture at home. The data from this study will provide a scientific basis not only for mass production processes in furniture factories but also for the bonding techniques necessary for individual users with home 3D printers to repair broken connectors or securely bring their own designs to life.

2. MATERIAL AND METHOD

2.1. Materials

In this study, Scots pine (*Pinus sylvestris* L.), a tree species widely found worldwide and in Türkiye and frequently used in the furniture industry, was selected as the wood material. Scots pine timber, obtained from Yörüs Forest Products in Yenice district of Karabük province, Türkiye, was prepared according to the standards (ASTM D790-17) to measure its tensile strength (ASTM D3164-03) and three-point bending strength. PLA+ polymer stands out as one of the most preferred polymers in 3D printing technologies due to its easy printability, low processing temperatures, and bio-based structure [16,17]. The PLA+ filament used in this work is a modified polylactic acid grade with additives that enhance toughness and layer adhesion compared with common PLA, making it more suitable for functional 3D-printed connectors subjected to mechanical loading. The PLA+ filament used in the study has a diameter of 1.75 mm, a density of 1.24 g/cm³, a tensile strength of 78 MPa, elongation at break of 14%, and a bending strength of 90 MPa. The white filament, sold under the trade name ESUN, was obtained from the manufacturer's official website.

Test samples were produced using an FDM type Xperia 3D printer (Yapılcın Makine Sanayi A.Ş., Çorum, Turkey). The samples were modeled in Autocad (student version, Autodesk, San Rafael, CA, USA) and then prepared for printing using Simplify3D (Cincinnati, USA) slicing software. The 3D-printed samples were printed with a double-walled (two outer walls) orthogonal (rectilinear) infill geometry with 100% infill, using a 0.4 mm nozzle and a 0.2 mm layer thickness. Following the filament manufacturer's recommendations, the nozzle temperature was set to 210°C and the bed temperature to 60°C during printing. Two adhesives most commonly used in furniture and plastic part assembly were selected. The first group of adhesives used is Selsil

Ninja (Sel Dış Tic. Ve Kimya San. A.Ş., Istanbul, Turkey), a two-component, isocyanate-based adhesive. In the second group, Somafix D4 (S605, Soma Kimya A.Ş., Istanbul, Turkey), a single-component polyurethane-based wood adhesive, was used. Somafix S605 is a polyurethane adhesive with high water resistance, classified as EN 204 D4, developed for wood joining. Before bonding, 3D-printed PLA+ plastic parts and wood samples were divided into two groups. One group was lightly sanded manually with silicon carbide (SiC-P240) sandpaper to increase surface energy. Before and after surface preparation, the surface roughness of the samples was measured and recorded using a Mitutoyo SJ-301 profilometer. Figure 1 shows an example of single lap bonding.

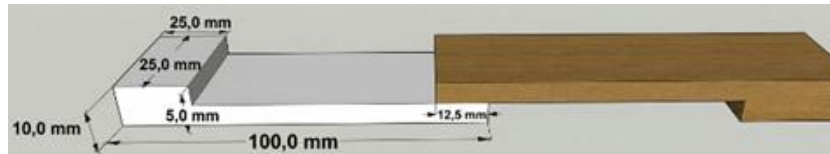


Figure 1. Single lap joint bonding process.

Sanded specimens were cleaned of dust by air purging. The bonding process was performed at room temperature. A thin and continuous film of adhesive was applied to both the PLA and Scots pine surfaces, in accordance with the manufacturer's recommendations, using a spatula to ensure uniform coverage. The adhesive film thickness was controlled to be approximately 0.15–0.20 mm, which corresponds to an application amount of about 150–200 g/m². After application, the PLA and wood parts were positioned so that the overlap area coincided and the alignment of the joint was checked. To maintain intimate contact during curing, the assemblies were placed on a flat reference surface and sufficient dead weights were placed on the overlap region to generate an estimated contact pressure in the range of 0.5–0.7 MPa. This pressure level is compatible with typical furniture manufacturing practices and the technical data sheets of the selected adhesives. The bonded samples were conditioned at 20 °C and 65% relative humidity for 7 days to ensure full curing of the adhesive and moisture equilibrium of the wood before mechanical testing.

The hybrid connector element used in the experiments consists of a single-lap joint geometry printed entirely from PLA+ and bonded to a Scots pine specimen, forming a wood–PLA+ hybrid joint representative of furniture fasteners where polymer and wood components work together structurally.

2.2. Experimental Setup

Tensile tests of the conditioned specimens were performed according to ASTM D3164-03 and 3-point bending tests according to ASTM D790-17 standards on a 5 kN capacity universal testing machine (Shimadzu, Kyoto, Japan) [16,17]. For the purpose of performing mechanical tests, a total of 60 specimens were prepared, with 5 specimens per group (4 groups x 5 repetitions = 20 specimens for tensile tests, and 2 x 4 groups x 5 repetitions = 40 specimens for bending tests, with the wooden specimen at the bottom and top).

The tensile speed for tensile tests was 1.27 mm/min as specified in the relevant standard, and the bending speed was 0.01 mm/min (Procedure A) as specified in the standard. Figure 2 shows images of the tensile and 3-point bending tests of the glued specimens.

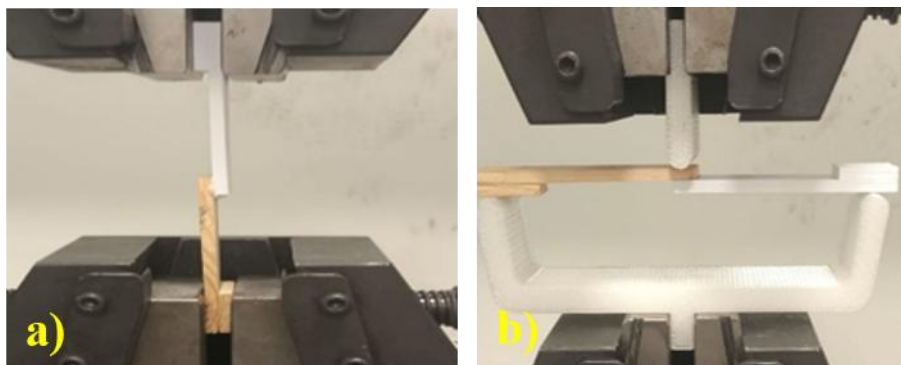


Figure 2. (a) tensile test, (b) 3-point bending test experiments of hybrid specimens.

Three-point bending tests were performed in two different loading directions to more accurately represent the real-world operating conditions of hybrid joints. In the first configuration, the specimens were supported

with the wood side facing upwards and the PLA+ side facing downwards, and the load was applied from the center. In the second configuration, the specimens were inverted, with the PLA+ side facing upwards and the wood side facing downwards. This allowed us to evaluate the effect of different material combinations in the tensile zone during bending on the stress distribution within the joint, the maximum bending strength, and the fracture mode. Following mechanical tests, the fracture surfaces of the hybrid joints were examined under an optical microscope to investigate the effect of adhesive type and surface preparation on the fracture behavior. Images were examined using a universal optical microscope (600x-1000x). Representative samples were selected from each of the four combinations (isocyanate/PU D4 x sanded/unsanded), and images of both PLA+ and Scots pine surfaces were obtained. Fracture modes were evaluated in three categories based on the classification defined in the ASTM D5573-19 standard: (i) adhesive fracture (separation at the adhesive–substrate interface, as defined in ASTM D5573-19), (ii) cohesive fracture (rupture within the adhesive layer itself), and (iii) substrate fracture (rupture in the wood fibers) [18]. Additionally, fracture samples obtained after tensile and three-point bending tests were photographed at a macro scale to determine the fracture location (PLA+ side/adhesive line/wood side). Data from tensile and three-point bending tests were analyzed using multi-factorial analysis of variance (ANOVA) to examine the effects of adhesive type and surface preparation factors. The effect of loading direction (wood on top/PLA+ on top) was also considered in the bending tests. A statistical significance level of $p < 0.05$ was accepted, and in cases where significant differences were found, the multiple comparison (Tukey) test was applied to determine the differences between group environments. All statistical calculations were performed using SPSS 22 software. In the three-point bending tests, a total of 40 specimens were tested, corresponding to 2 loading configurations (wood-on-top / PLA-on-top) $\times$ 4 adhesive–surface combinations (isocyanate-sanded, isocyanate-unsanded, PU D4-sanded, PU D4-unsanded) $\times$ 5 replicates per group ($n = 5$), yielding $N = 40$ for the bending ANOVA.

For each adhesive–surface preparation combination and loading configuration, five specimens ($n = 5$) were prepared and tested. This replication number provides a balanced dataset for multifactorial analysis of variance and allows the detection of statistically significant effects of adhesive type and surface treatment on adhesion and flexural response, while remaining compatible with the time and material constraints of the experimental program. Nevertheless, the sample size should be interpreted as capturing the mechanical behavior of the tested Scots pine batch, and not the full range of variability that may occur in different wood sources.

3. RESULTS AND DISCUSSION

3.1. Surface Roughness (Ra) Results

To determine the effect of surface preparation, surface roughness (Ra) measurements taken from the bonding area before and after sanding are given in Table 1.

Table 1. Surface roughness values (Ra).

	PLA+	Scots pine
Before Sanding (μm)	2.20	3.91
After Sanding (μm)	1.51	1.74

Before sanding, the average roughness of the PLA+ surface was $2.20 \mu\text{m}$, while after sanding it decreased to $1.51 \mu\text{m}$. Similarly, on the Scots pine surface, it decreased from $3.91 \mu\text{m}$ to $1.74 \mu\text{m}$. In terms of percentage, the decrease on the wood surface (approximately 55%) is significantly higher than the 31% decrease on the PLA+ surface. This suggests that Scots pine initially had a more heterogeneous surface structure, and sanding provided a more thorough surface restructuring on the wood side. Furthermore, sanding not only reduced the Ra value but also removed the oxide layer, pressure-induced irregularities, and loose wood fibers, creating a cleaner and more reactive adhesion surface on both materials. The reasons why adhesion performance increased despite the decrease in Ra value are discussed in the discussion section.

At first glance, the decrease in arithmetic surface roughness (Ra) after sanding may appear contradictory to the observed improvement in tensile bond performance. However, the profilometer Ra parameter primarily quantifies the average vertical deviations of the surface profile from a reference line at the measurement scale and does not directly reflect the effective microscopic contact area at the adhesive–substrate interface. Mechanical abrasion removes loosely attached fibers, machining defects and contamination, producing a cleaner and more uniform surface that promotes better wetting of both the wood and PLA substrates by the adhesive and increases the real contact area at the micro-scale. As a result, even though the measured Ra values are reduced, the continuity of the adhesive layer and the density of chemical and mechanical interactions across the interface are enhanced, leading to higher tensile strength of the hybrid joints.

This study shows that a significant reduction in wood surface roughness after sanding contributes to an increase in bond strength. These results are consistent with findings reported in studies where PLA boards are bonded with industrial adhesives and in the wood bonding literature, indicating that improved surface cleanliness and roughness increase bond strength [19,20].

3.2. Tensile Test Results

The adhesion performance of hybrid samples prepared in accordance with the ASTM D3164-03 standard was evaluated by tensile testing [16]. The average adhesion strength values and fracture behaviors obtained from the tensile test are presented in Table 2, and the relevant stress-strain graph is shown in Figure 3.

Table 2. Effect of adhesive type and surface treatments on tensile strength, strain and adhesion strength of hybrid joints.

Glue Type	Surface Treatment	Stress (MPa)	S.D	Strain (%)	S.D	Tensile Strength (MPa)	S.D
Isocyanate	Sanded	11.99	1.12	3.08	0.14	5.99	0.56
	Unsanded	7.30	2.00	2.30	0.35	3.65	1.00
Polyurethane	Sanded	3.60	1.70	1.35	0.45	2.13	0.12
	Unsanded	1.74	0.19	0.77	0.13	0.92	0.10

Table 2, summarizing the data from the tensile test results, shows that both adhesive type and surface treatment have significant effects on both stress and strain values. In the group where the isocyanate-based adhesive was used on sanded surfaces, the highest performance was obtained with average values of 11.99 MPa maximum tensile stress, 3.08% strain, and 5.99 MPa tensile strength. In the group where the same adhesive was used on unsanded surfaces, these values remained at 7.30 MPa stress, 2.30% strain, and 3.65 MPa tensile strength, respectively, indicating a significant performance loss. This shows that mechanical surface preparation increases the adhesion strength for the isocyanate system by approximately twofold. A similar trend was observed in the samples using PU-based adhesive, but the overall strength levels remained lower compared to the isocyanate group. In sanded PU joints, the average maximum stress was 3.60 MPa, strain 1.35%, and tensile strength 2.13 MPa, while in the unsanded PU group, these values were measured as 1.74 MPa stress, 0.77% strain, and 0.92 MPa tensile strength. Thus, although the sanding process increased both the load-bearing capacity and deformation capability in the PU system, it did not reach the strength levels achieved by the isocyanate-sanded combination. Overall, the results show that the most suitable bonding combination in hybrid PLA+-Scots pine joints is isocyanate-based adhesive used with sanded surface preparation.

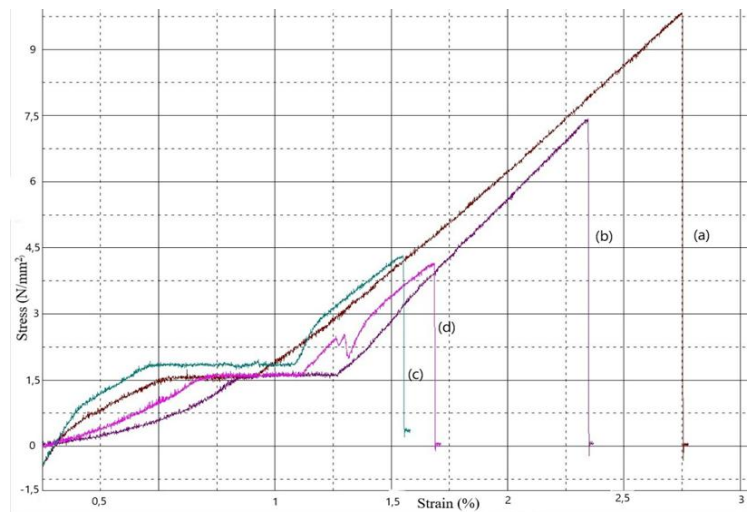


Figure 3. Stress-Strain graph of tensile test adhesion strength, (a) Sanded-Isocyanate, (b) Unsanded-Isocyanate, (c) Sanded-PU, (d) Unsanded-PU.

Figure 3 shows the tensile stress-strain curves for different glue and surface preparation combinations. The sanded-isocyanate group (a) exhibited the most rigid and ductile behavior, with both the highest initial slope and fracture strain reaching approximately 2.7%. Unsanded-isocyanate samples (b) had a similar linear slope but fractured at a lower maximum stress and shorter strain range, revealing that surface preparation limits the load-carrying capacity. Sanded PU joints (c) formed a weaker bond compared to the isocyanate system, with

lower initial rigidity and fracture stress. In the unsanded-PU group (d), both the stress level and strain dropped sharply in the early stages, with brittle and premature fracture behavior being dominant. Overall, the curves show that the sanding process significantly increases the bond rigidity and deformation capacity for both adhesive types, and the most stable and robust fracture behavior is obtained with the sanded isocyanate combination. The results of the two-way analysis of variance showed that both the adhesive type and the surface treatment, as well as the interaction between these two factors, had statistically significant effects on MaxStress, MaxStrain, and tensile strength ($p < 0.05$). Data from the two-way analysis of variance results for maximum stress values are given in Table 3.

Table 3. Results of the two-way ANOVA test for maximum stress.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	307.212 ^a	3	102.404	50.063	0.000	0.904
Intercept	758.542	1	758.542	370.830	0.000	0.959
Glue	243.465	1	243.465	119.023	0.000	0.882
Surface	53.696	1	53.696	26.250	0.000	0.621
Glue * Surface	10.052	1	10.052	4.914	0.041	0.235
Error	32.728	16	2.046			
Total	1098.483	20				
Corrected Total	339.941	19				

a. R Squared = 0.904 (Adjusted R Squared = 0.886)

The results of the two-way analysis of variance for maximum tensile stress showed that the type of glue, surface treatment, and the interaction of these two factors were statistically significant ($p < 0.05$). The type of glue factor was found to have a very high level of effect on the maximum stress ($F(1,16):119.02$; $p < 0.001$; partial $\eta^2:0.882$); the main effect of surface treatment was also found to be significant ($F(1,16):26.25$; $p < 0.001$; partial $\eta^2:0.621$). In addition, the significant result of the glue $\times$ surface interaction ($F(1,16):4.91$; $p = 0.041$; partial $\eta^2:0.235$) shows that the improving effect of sanding on the maximum tensile stress did not occur with the same intensity in isocyanate and PU systems. The results of the two-way analysis of variance for maximum strain values are given in Table 4.

Table 4. Results of the two-way analysis of variance for maximum strain values.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	15.600 ^a	3	5.200	57.226	0.000	0.915
Intercept	70.263	1	70.263	773.254	0.000	0.980
Glue	13.223	1	13.223	145.517	0.000	0.901
Surface	2.331	1	2.331	25.651	0.000	0.616
Glue * Surface	0.046	1	0.046	0.510	0.485	0.031
Error	1.454	16	0.091			
Total	87.317	20				
Corrected Total	17.054	19				

a. R Squared = 0.915 (Adjusted R Squared = 0.899)

The results of the two-way analysis of variance for maximum strain values show that both the adhesive and the surface treatment have statistically significant main effects, but the interaction between these two factors is not significant ($p > 0.05$). The F value for the adhesive type ($F(1,16):145.52$; $p < 0.001$; partial $\eta^2:0.901$) reveals that the isocyanate-based system provides a much more significant increase in maximum strain compared to the PU-based system. Similarly, the surface preparation factor also appears to have a strong effect on maximum strain ($F(1,16):25.65$; $p < 0.001$; partial $\eta^2:0.616$); however, the insignificance of the interaction term ($F(1,16):0.51$; $p = 0.485$; partial $\eta^2:0.031$) suggests that the sanding process provides a similar increase in strain for both adhesive types. However, a significant difference between the parameters is noticeable at this point. The fact that sanding causes a similar increase in strain in both adhesive systems indicates that its effect on deformation capacity is independent of the adhesive type, while its effect on tensile strength and maximum stress differs significantly depending on the adhesive type. In the PU D4 system, the increasing effect of sanding on maximum stress was not found to be statistically significant (Tukey, $p:0.210$), which reveals that the stress carrying capacity of PU D4 adhesive remains limited regardless of surface preparation.

The results of the two-way analysis of variance for tensile strength are given in Table 5.

Table 5. Results of the two-way analysis of variance for tensile strength.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	71.871 ^a	3	23.957	71.647	0.000	0.931
Intercept	201.227	1	201.227	601.790	0.000	0.974
Glue	54.463	1	54.463	162.878	0.000	0.911
Surface	15.804	1	15.804	47.264	0.000	0.747
Glue * Surface	1.604	1	1.604	4.797	0.044	0.231
Error	5.350	16	0.334			
Total	278.448	20				
Corrected Total	77.222	19				

a. R Squared = 0.931 (Adjusted R Squared = 0.918)

The results of the two-way analysis of variance for tensile strength showed that the type of adhesive, surface treatment, and the interaction of these two factors were statistically significant ($p < 0.05$). The adhesive type factor had a very strong effect on tensile strength ($F(1,16):162.88$; $p < 0.001$; partial $\eta^2:0.911$), and it was determined that samples using isocyanate-based adhesive exhibited significantly higher tensile strength compared to samples using PU-based adhesive. The main effect of surface preparation was also found to be significant ($F(1,16):47.26$; $p < 0.001$; partial $\eta^2:0.747$), and the tensile strength values obtained on sanded surfaces were significantly higher compared to unsanded surfaces. Furthermore, the significance of the glue $\times$ surface interaction ($F(1,16):4.80$; $p = 0.044$; partial $\eta^2:0.231$) indicates that the effect of sanding on increasing tensile strength is not at the same level in isocyanate and PU systems, and that it provides a much more significant increase in strength, especially in isocyanate-based combinations.

Since significant differences were obtained for both glue type and surface treatment factors in the two-way analysis of variance results, a Tukey HSD multiple comparison test based on one-way ANOVA was applied to determine in which combinations the differences between the group means occurred.

The results of the Tukey HSD test based on one-way ANOVA are given in Table 6.

Table 6. Tukey HSD test results.

Glue	Surface	Stress (MPa)	Strain (%)	Tensile Strength (MPa)
Isocyanate	Sanded	11.99 a	3.08 a	5.99 a
Isocyanate	Unsanded	7.30 b	2.30 b	3.65 b
PU	Sanded	3.60 c	1.35 c	2.13 c
PU	Unsanded	1.74 c	0.77 d	0.92 d

*Letters (a, b, c, d) indicate homogeneous subsets formed by the means in the respective columns according to the Tukey HSD test; there is no statistically significant difference between groups sharing the same letter in the same column.

*Differences between means with different letters in the same column are statistically significant at the $p < 0.05$ level according to the Tukey HSD test.

When the Tukey HSD results given in Table 6 are examined, it is seen that the highest performance in terms of all mechanical parameters was obtained in the samples bonded with isocyanate-based adhesive and sanded surface (a). This group gave statistically higher average values than all other combinations in terms of maximum stress, maximum strain, and tensile strength ($p < 0.05$). Isocyanate-unsanded samples (b) showed lower values than the isocyanate-sanded group in all three parameters, but significantly higher values than the PU-based groups. This shows that the isocyanate system offers superior adhesion performance compared to PU, even without surface preparation. PU-based sanded (c) and unsanded (d) samples differed statistically from each other in terms of maximum strain and tensile strength and gave significantly lower values compared to the isocyanate groups. In contrast, in terms of maximum tensile stress, the PU-sanded and PU-unsanded groups were in the same homogeneous subset ($p = 0.210$); In other words, the enhancing effect of sanding on the maximum tensile strength for the PU D4 system was not found to be statistically significant. This finding reveals that the mechanical stress-carrying capacity of the PU D4 adhesive remains limited under both surface conditions, and surface preparation alone does not compensate for the lack of strength in the PU system. Overall, the Tukey HSD results show that the influence of both adhesive type and surface treatment factors on tensile behavior is not limited to the main effects level, but is also clearly evident at the group-based combination level.

Previous studies on bonding PLA parts produced with FDM have also reported that adhesive type, bonding thickness, and surface preparation are decisive factors in determining tensile/shear strength [19–21]. The findings obtained in our study are consistent with these results.

3.3. 3-Point Bending Test Results

The bending strength and modulus of elasticity of hybrid PLA+-Scots pine joints were determined by three-point bending tests performed in accordance with the ASTM D790-17 standard. In this context, the average stress and modulus of elasticity values for two different loading configurations with different types of glue (isocyanate-PU) and PLA+ in the tensile region (PLA+ bottom) and in the compressive region (PLA+ top) are given in Table 7 [17].

Table 7. Bending Stress and Modulus of Elasticity Values of Hybrid Samples.

Glue Type	Surface Treatment	Tension/Compression Zone	Bending Stress (MPa)	Modulus of Elasticity (MPa)
Isocyanate	Sanded	Tensile	27.80	3015.11
	Unsanded	Tensile	32.59	3131.36
	Sanded	Compression	32.80	2559.81
	Unsanded	Compression	34.39	3055.27
PU D4	Sanded	Tensile	16.40	2338.36
	Unsanded	Tensile	12.44	2584.99
	Sanded	Compression	11.21	2058.50
	Unsanded	Compression	11.24	1720.80

Three-point bending tests revealed that the bending stress and modulus of elasticity of hybrid PLA+ Scots pine joints varied depending on the type of adhesive, surface treatment, and loading direction. In samples using isocyanate-based adhesive, bending stresses ranged from 27.80 to 34.39 MPa, with unsanded surfaces showing slightly higher or similar values compared to sanded surfaces in both loading configurations. In the PU D4 group, values remained in the range of 11.21-16.40 MPa, showing that sanded surfaces partially increased strength in the stress region, while the two surface conditions produced similar results in the compression region. Modulus of elasticity values ranged from 1720.80 to 3131.36 MPa. Generally, the isocyanate group exhibited higher stiffness values, while the PU D4 unsanded group showed the weakest stiffness value with the lowest modulus value of 1720.80 MPa in compressive loading. These results reveal the decisive role of adhesive type on both load-carrying capacity and rigidity in hybrid joints, as well as suggesting that the effect of surface treatment differs depending on the adhesive system and loading direction.

The higher bending performance obtained with the isocyanate-based adhesive in Table 7, compared with PU D4, can be attributed not only to improved surface roughness and mechanical interlocking, but also to the chemical bonding potential of isocyanate groups with the substrates. In wood-polymer systems, isocyanate-based binders and coupling agents have been reported to react with hydroxyl groups in lignocellulosic materials and to improve interfacial compatibility between wood flour and thermoplastic matrices, leading to increased bond strength and stiffness in wood-plastic composites [22]. This mechanism is consistent with the enhanced flexural load-carrying capacity observed in the PLA+-Scots pine hybrid joints bonded with the isocyanate adhesive in the present study.

The beneficial effect of sanding on bond performance was more straightforward under pure tensile loading, whereas in three-point bending some unsanded groups exhibited slightly higher maximum bending stresses. This apparent discrepancy can be attributed to the fundamentally different stress states in tension and bending. In the single-lap tensile tests, the joint is primarily subjected to normal stresses across the adhesive line, and the improved surface cleanliness, wetting and microscopic contact area obtained by sanding directly enhance the cohesive and substrate strength of the bond. In contrast, during bending the joint experiences a combination of tensile, compressive and shear stresses, and the location of the PLA+ and wood layers with respect to the tension and compression zones influences the stress distribution and failure mode within the hybrid assembly. In certain configurations, the higher local geometric roughness of unsanded surfaces may promote mechanical interlocking under bending and delay crack initiation, partially compensating for the lower tensile bond strength observed in these groups. Therefore, the effect of sanding is more monotonic and dominant in tensile tests, while in flexural tests it interacts with the stacking sequence and complex stress state, resulting in less uniform trends across all combinations.

The bending stress and modulus of elasticity values given in Table 7 show that there are significant differences in the bending behavior of hybrid joints depending on the adhesive type, surface treatment, and

loading direction. However, to determine which factors cause these differences and to what extent they are statistically significant, multi-factor analysis of variance (ANOVA) was applied. Thus, in addition to the main effect of each factor, the contribution of inter-factor interactions to bending performance was quantitatively revealed. Table 8 presents the results of the multi-factor analysis of variance (ANOVA) for bending stress.

Table 8. Results of multi-factor analysis of variance (ANOVA) for bending stress.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3849.865 ^a	7	549.981	66.435	0.000	0.936
Intercept	19568.966	1	19568.966	2363.826	0.000	0.987
Glue	3496.556	1	3496.556	422.365	0.000	0.930
Surface	3.387	1	3.387	0.409	0.527	0.013
Zone	0.117	1	0.117	0.014	0.906	0.000
Glue * Surface	56.325	1	56.325	6.804	0.014	0.175
Glue * Zone	114.196	1	114.196	13.794	0.001	0.301
Surface * Zone	0.387	1	0.387	0.047	0.830	0.001
Glue*Surface*Zone	27.677	1	27.677	3.343	0.077	0.095
Error	264.912	32	8.279			
Total	24118.999	40				
Corrected Total	4114.777	39				

a. R Squared = 0.936 (Adjusted R Squared = 0.922)

The results of the three-way analysis of variance given in Table 8 show that the significance of the glue type, surface treatment and loading area changes at different factor levels when the bending stress of hybrid PLA+-Scots pine joints is evaluated together. The statistical model created was found to be highly significant ($p < 0.001$). It is seen that 93.6% of the total variance values of the bending stress are explained. These values show that the three factors examined form an effective model in explaining the bending behavior. The glue type factor is seen to have a very strong and statistically significant effect on the bending stress ($F(1,32)=422.37$; $p < 0.001$; partial $\eta^2=0.930$). This result shows that hybrid joints formed with isocyanate-based adhesive exhibit higher bending strength compared to PU D4-based joints and that a large part of the variation in bending performance is determined by the glue type. However, the main effects of surface treatment ($F(1,32)=0.41$; $p=0.527$; partial $\eta^2=0.013$) and loading zone ($F(1,32)=0.01$; $p=0.906$; partial $\eta^2 \approx 0.000$) were not found to be statistically significant. This indicates that the sanding process or the positioning of the PLA+ layer in the stress/compression zone does not have a decisive effect on the average bending stress when evaluated alone, regardless of the type of adhesive. When all factors are considered together, it is seen that the bending behavior exhibits a more complex structure that cannot be explained by the main effects alone. The fact that the adhesive x surface interaction is significant ($F(1,32)=6.80$; $p=0.014$; partial $\eta^2=0.175$) shows that the effect of the sanding process on the bending stress does not occur in the same direction and with the same intensity in isocyanate and PU D4 systems, in other words, the effectiveness of surface preparation depends on the type of adhesive used. Similarly, the statistically significant finding of the glue x loading zone interaction ($F(1,32)=13.79$; $p=0.001$; partial $\eta^2=0.301$) reveals that the change in bending performance resulting from the positioning of the PLA+ layer in the tension or compression zone differs according to the type of glue, and that the advantage of the isocyanate system in different loading configurations becomes more pronounced compared to the PU D4 system. Furthermore, the surface treatment x loading zone interaction ($F(1,32)=0.05$; $p=0.830$; partial $\eta^2=0.001$) and the glue x surface treatment x loading zone triple interaction ($F(1,32)=3.34$; $p=0.077$; partial $\eta^2=0.095$) were not statistically significant, but the p-value of the triple interaction being close to the limit indicates that the trend created by the three factors together should not be completely disregarded.

Overall, the three-way ANOVA results show that the bending behavior of hybrid PLA+-Scots pine joints is predominantly determined by the type of adhesive, while other factors such as surface treatment and loading zone produce conditional effects that become significant only when evaluated together with the adhesive type. This finding indicates that combinations of factors, rather than a single factor, should be considered in optimizing hybrid adhesion performance, and highlights the need to evaluate group-based differences in detail using the Tukey HSD multiple comparison test. Table 9 presents the results of the multiple variance analysis for the modulus of elasticity.

Table 9. Results of the multiple variance analysis for the modulus of elasticity.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	8095655.609 ^a	7	1156522.230	12.057	0.000	0.725
Intercept	261995118.388	1	261995118.388	2731.403	0.000	0.988
Glue	4971449.376	1	4971449.376	51.829	0.000	0.618
Surface	337808.924	1	337808.924	3.522	0.070	0.099
Zone	1392740.192	1	1392740.192	14.520	0.001	0.312
Glue * Surface	149066.827	1	149066.827	1.554	0.222	0.046
Glue * Zone	174318.080	1	174318.080	1.817	0.187	0.054
Surface * Zone	880.013	1	880.013	0.009	0.924	0.000
Glue*Surface*Zone	478960.204	1	478960.204	4.993	0.033	0.135
Error	3069427.443	32	95919.608			
Total	274635323.635	40				
Corrected Total	11165083.052	39				

a. R Squared = 0.725 (Adjusted R Squared = 0.665)

The variance analysis results presented in Table 9 reveal that the glue type, surface treatment, and loading zone factors have different levels of effect on the modulus of elasticity in bending of hybrid adhesive joints when considered together. The model created was found to be statistically significant and explained 72.5% of the total variance in the modulus of elasticity ($R^2=0.725$; Adjusted $R^2=0.665$). The fact that this value is lower than the bending stress model value suggests that the modulus of elasticity is a more complex variable, not only limited to the factors examined, but also affected by the heterogeneous structure of the wood and microstructural variations caused by FDM printing. The glue type factor is seen to have a statistically significant and strong effect on the modulus of elasticity ($F(1,32)=51.83$; $p<0.001$; partial $\eta^2=0.618$). This result shows that hybrid joints prepared with isocyanate-based adhesive form a significantly more rigid interface compared to PU-based joints. Similarly, the main effect of the loading zone was also found to be significant ($F(1,32)=14.52$; $p=0.001$; partial $\eta^2=0.312$). The positioning of the PLA+ layer in the tension or compression zone significantly affects the rigidity of the joint during bending. This finding reveals that the region factor, which was not significant in the bending stress analysis, plays a decisive role in a parameter that directly reflects deformation elasticity, such as the modulus of elasticity. The main effect of the surface treatment was close to the statistical significance limit but was not significant ($F(1,32)=3.52$; $p=0.070$; partial $\eta^2=0.099$).

The interactions between glue x surface treatment and glue x loading zone were found to be statistically insignificant. However, the triple interaction between glue x surface treatment and loading zone was found to be significant ($F(1,32)=4.99$; $p=0.033$; partial $\eta^2=0.135$). This result shows that the observed differences in the modulus of elasticity cannot be explained by considering only two factors together; specific combinations of adhesive type, surface treatment, and loading zone produce a unique effect on the stiffness behavior. In particular, the modulus difference observed in extreme combinations such as isocyanate-sanded compression and PU-unsanded compression is thought to stem from this triple structure, which cannot be explained by the main effect alone or by binary interactions. In conclusion, the modulus of elasticity findings show that the stiffness behavior of hybrid joint combinations is primarily shaped by the adhesive type and loading zone, that surface preparation alone is not the determining factor, but that it makes significant contributions under specific combinations with the other two factors. This reveals that bending stress (maximum load-carrying capacity) and modulus of elasticity (stiffness) parameters are sensitive to different combinations of factors in the same experimental design, and emphasizes the need to optimize both strength and stiffness criteria together in hybrid joint design.

3.4. Fracture Mode Analysis

Following tensile and three-point bending tests, the fracture locations of the hybrid joints are shown in Figure 4 on a macro scale, while the microscope images of the adhesion regions at 600x, 700x and 1000x magnification are given in Figure 5.

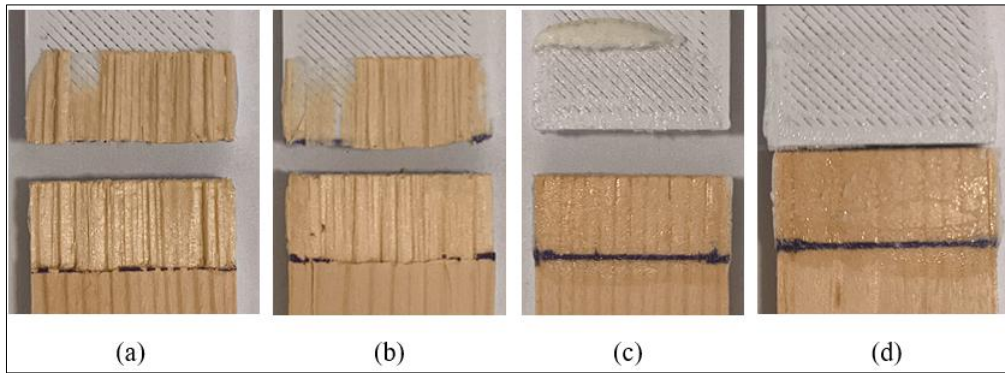


Figure 4. Macro fracture images, (a) Tensile sample (isocyanate-sanded), (b) Three-point bending test sample (isocyanate-unsanded), (c) Tensile test sample (PU-sanded), (d) Bending test sample (PU-unsanded).

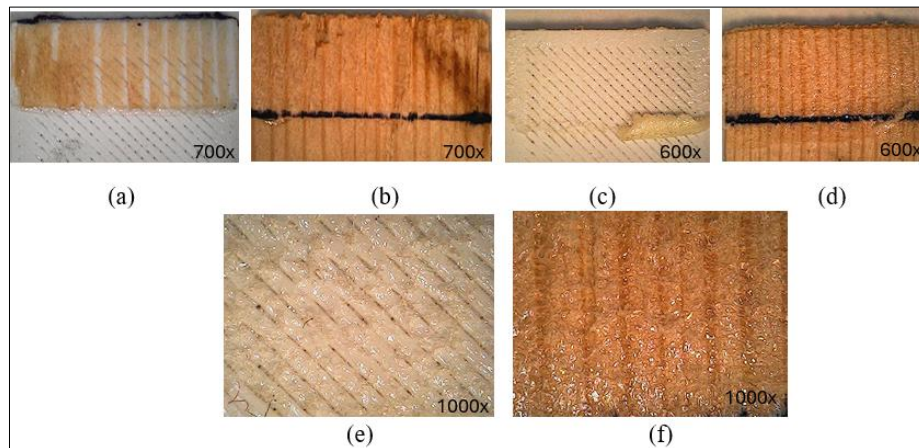


Figure 5. Microfracture images, (a) Tensile test specimen (isocyanate-PLA+ sanded), (b) Tensile test specimen (isocyanate-Scots pine sanded), (c) Tensile test specimen (PU-PLA+ unsanded), (d) Tensile test specimen (PU D4 Scots pine unsanded), (e) Bending test specimen (PU PLA+ unsanded), (f) Bending test specimen (PU Scots pine unsanded).

In both sanded and unsanded samples prepared with isocyanate-based adhesive (Figures 4a and 4b), it was observed that fracture occurred not at the adhesive line, but in the interior of the wood substrate. In the tensile test (Figure 4a), a portion of the Scots pine sample was carried without breaking off from the PLA+ surface, while in the three-point bending test (Figure 4b), fracture occurred in the wood core, outside the adhesive overlap zone. This finding indicates that the interface created with isocyanate provides a higher bond strength than the internal strength of Scots pine wood itself, and that the adhesive line ceases to be a limiting region in load transfer. When microfracture images are examined (Figure 5a), wood fiber remnants spread and adhered between the FDM printing lines on the PLA+ surface are clearly visible. This micro-scale fiber transfer indicates that, regardless of the sanding process, isocyanate forms polyurethane bridges by establishing strong chemical bonds with the hydroxyl groups of wood in both groups (sanded and unsanded), effectively providing mechanical interlocking. Furthermore, in samples prepared with polyurethane (PU D4) based adhesive (Figures 4c and 4d), fracture was found to occur characteristically along the adhesive line. After the tensile test, the PLA+ and wood pieces separated cleanly, and a large portion of the adhesive remained in foam form on the surface of the bonded pieces. Similarly, in the three-point bending test (Figure 4d), separation along the adhesive line emerged as the dominant fracture mode. In the microfracture images (Figures 5c-d-e-f), it was observed that the FDM lines on the PLA+ surface and the Scots pine surface were completely covered by a crystalline foamed PU layer, but no fiber breakage was observed. This observation shows that in the PU D4 group, the dominant fracture mode is cohesive (fracture within the adhesive layer itself), and the adhesion limit is lower than the strength of the wood substrate. The fracture mode findings are in complete agreement with the numerical results obtained from tensile and bending tests. In the isocyanate group, the fracture occurring within the substrate explains why the high strength values achieved by this group (11.99 MPa maximum stress, 5.99 MPa tensile strength) are significantly higher compared to the PU D4 group. In this scenario, the weak link in the hybrid joint is not the adhesive interface, but the Scots pine wood itself. In the PU D4 group, the fracture occurring at the adhesive line explains both the low strength values and the brittle and premature

fracture behavior observed, especially in the unsanded configuration (1.74 MPa maximum stress, 0.92 MPa tensile strength).

The adhesion strength and fracture modes obtained in our study are similar to the cohesive or in-wood fracture behaviors reported in the study by Karabag et al. [8] on bonding wood-reinforced PLA and Scots pine materials with adhesive.

Researchers investigated the bonding of two-component PU systems to beech wood and reported that two-component PU systems provided higher adhesion strength compared to single-component PU adhesives [14]. This demonstrates that adhesive chemistry is critically important for performance in heterogeneous polymer-wood joints. While the sanded isocyanate group exhibited significantly higher performance in the tensile test, it is noteworthy that in the three-point bending test, the unsanded isocyanate-based combinations yielded higher stress values compared to the sanded ones. This is thought to be due to the different stresses applied to the glue line in the tensile and bending tests. In the tensile test, the load is applied directly and uniformly to the bonding surface, so sanding directly affects the measurement by increasing mechanical interlocking in the glue line. In the bending test, however, the load is distributed across the entire specimen, and fracture may shift towards the wood or PLA+ side instead of the reinforced glue line. Under these conditions, the measured value reflects not only the adhesion performance but also the bending capacity of the materials themselves. Multi-factor analysis of variance (ANOVA) results also show that the effect of surface treatment on bending stress is not statistically significant. This finding indicates that sanding ceases to be a determining factor in bending conditions, and that adhesive type and loading direction play a dominant role.

In three-point bending tests, it is noteworthy that the configurations prepared with isocyanate adhesive and where the PLA+ layer is located in the compression region (top) yielded the highest strength (34.39 MPa). Hajdarevic et al. [7] reported that 3D-printed connectors can withstand settlement loads, but the strength decreases in different loading directions (back support). In our study, it was determined that the adhesive type has a very strong effect on bending strength ($p < 0.001$), but the position of the PLA+ layer alone does not create a statistically significant difference. The finding shows that in hybrid connector design, the quality of adhesion at the interface is more decisive for structural integrity than the position of the material.

Fracture mode analyses revealed that in joints formed with isocyanate-based adhesive, the dominant fracture mode occurred within the wood substrate, while in joints formed with PU D4, cohesive fracture predominated along the adhesive line. It is thought that isocyanate effectively penetrates the micro-voids between FDM printing layers and the wood surfaces, strengthening mechanical interlocking, and also forms chemical bonds with wood hydroxyl groups via polyurethane bridges. Interlayer voids and local delamination traces observed in micro (600x-1000x) microscope images are due to the anisotropic nature inherent in FDM technology [1]. Khosravani et al. [15] reported that such internal defects in 3D-printed parts can trigger stress concentrations at the adhesion line, leading to early failure onset, which justifies the adhesion line separations observed after tensile tests in the PU D4 group in our study. Furthermore, in the isocyanate group, fracture is observed to shift outside the adhesive overlap zone, towards the interior of the wood substrate. This suggests that the isocyanate reinforces the bonding area by filling these micro-voids and transfers the weak link from the adhesive interface to the substrate. In contrast, the cohesive fracture observed in the PU D4 group suggests that this system is more sensitive to surface preparation and that the low surface energy on the PLA+ surface restricts the effective wetting and penetration of the adhesive.

3.5. LIMITATIONS OF THE STUDY

This study was conducted at room temperature (20 °C) and 65% relative humidity, and the test conditions only included short-term static loading. The behavior of both adhesive systems under long-term loading, humidity cycling, or thermal change conditions may differ from the findings of this study. In addition, only mechanical sanding (SiC-P240) was evaluated as a surface preparation process; alternative surface activation methods such as plasma or chemical pretreatment were excluded. It is known in the literature that plasma treatment significantly increases the surface energy and therefore the adhesion strength at the polymer-wood interface. The absence of surface contact angle and surface free energy (SFE) measurements in this study means that only the topographic effect of the sanding process could be evaluated, and its chemical effect could not be fully determined. Finally, 5 samples were tested for each combination, and it is recommended to increase the number of samples in future studies to improve statistical reliability.

Another limitation of the present work is the relatively small replication number per group ($n=5$), especially in view of the known spatial and anatomical variability of mechanical properties in wood-based materials. Although the multifactorial ANOVA and effect size analysis revealed consistent and statistically significant influences of adhesive type, surface preparation and loading configuration on the adhesion and flexural response of the tested Scots pine joints, the findings should be interpreted as representative of the specific

material batch and geometry investigated. Future studies should therefore employ larger sample sizes and include different wood species and joint dimensions to further improve the robustness and generalizability of the conclusions.

4. CONCLUSIONS

This study experimentally investigated the effects of adhesive type and surface preparation on the mechanical performance of hybrid joints formed by PLA+ parts produced by the FDM method and Scots pine wood. The findings can be summarized as follows:

Adhesive type was the most decisive factor on both tensile and flexural strength. Isocyanate-based adhesive gave statistically significant higher strength values in all combinations compared to the PU D4 system. Adhesive $\times$ surface interaction was found to be significant for tensile strength and maximum stress, but insignificant for maximum strain. This result shows that although the contribution of sanding to mechanical stress and strength differed according to the adhesive type, the increase in strain occurred at a similar rate in both adhesives.

Sanding significantly increased the tensile strength in both adhesive types ($p < 0.001$). In particular, in the isocyanate group, sanding increased the tensile strength from 3.65 MPa to 5.99 MPa; In the PU D4 group, it increased from 0.92 MPa to 2.13 MPa. However, in terms of maximum tensile stress, the sanded and unsanded PU D4 samples were in the same homogeneous subset (Tukey HSD, $p = 0.210$); that is, although sanding increased the tensile strength in the PU system, it did not statistically significantly improve the maximum stress value. Overall, the PU D4 system lagged considerably behind the isocyanate group despite all the improvements obtained with sanding. The best combination was isocyanate + sanded surface. This group formed a statistically different class among all combinations with a maximum stress of 11.99 MPa and a tensile strength of 5.99 MPa (Tukey HSD, $p < 0.05$).

In bending tests, the positioning of the PLA+ layer in the stress or compression region alone did not create a significant difference ($p = 0.906$). However, the interaction between the glue and PLA+ position was found to be significant ($p = 0.001$), indicating that the isocyanate system is position-independent and determining in some configurations. • In terms of surface roughness, SiC-P240 sanding reduced the Ra value on the PLA+ surface from 2.20 μm to 1.51 μm , and on Scots pine from 3.91 μm to 1.74 μm , creating a more homogeneous adhesion interface.

These findings demonstrate that short-term mechanical sanding combined with isocyanate-based adhesive significantly improves the bonding reliability of FDM-produced PLA+ connectors to wooden furniture components. These results serve as a practical guide for both mass-producing furniture companies and individual users employing home 3D printers. Further research is recommended to investigate the effects of alternative surface activation methods such as plasma, dynamic and long-term loading conditions, and different wood types.

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