

Shear Resistance and Surface Design of 3D Printed Dowels Made from Different Materials in Glued Scots Pine Furniture Joints

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The shear resistance was measured for Scots pine (*Pinus sylvestris*) furniture joints assembled using straight, cross, and grooved-patterned dowels fabricated via 3D printing with Poly Lactic Acid (PLA), tough PLA, Poly Amide (PA), and tough resin. Results indicated that the highest shear value was given by the straight dowels joints produced from tough resin with an average value of 2845 N. This was followed by the shear resistance values of grooved dowels with 2819 N and cross dowels with 2725 N. The shear performances of the Scots pine joints produced from tough resin dowels were followed by the shear performances of the joints with different patterns produced from tough PLA, PLA, and PA, respectively. No statistical difference was observed in the shear resistances of the joints produced from dowels with different surface patterns. The shear performance of the tough resin dowels joints was higher than those of the solid wood and PA dowels used in the market. Joints with tough resin and tough PLA dowels exhibited both glue line separation and wood rupture near the dowel edge, whereas PA and PLA dowels primarily failed due to glue line separation.

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INTRODUCTION

Furniture units can be subject to variable loads depending on different usage scenarios. While these loads can be light in some cases, they can sometimes reach quite heavy levels (İmirzi 2008). For example, light loads can be considered as a person sitting normally on a sofa, while heavy loads can be considered as a child jumping on the sofa. Therefore, the basic design criteria include the safe carrying of the design loads by the carrier systems and the absence of any structural defects during use. It is important to conduct strength analyses and apply various test methods under the effect of the loads applied to the connection points in box furniture (Eckelman 1991).

One of the most common techniques in box furniture connections is dowel joining. Dowels are cylindrical solid or plastic devices that bring at least two or more furniture components together with glue or a different binding agent (Efe 1994). While solid dowels

have been used as connecting materials for years, plastic dowels are used both as a guide and as the main joining element in different joining techniques.

Furniture members could be attached to one another with a large variety of glued or unglued joint methods *via* various types of fasteners, such as dowels, nails, screws, staples, or metal. Glued dowel joints are one of the most popular methods for assembling the components together in furniture manufacturing (Kasal *et al.* 2020). Structural failures usually arise from the joints, which are the weakest points in a furniture frame. Therefore, dowels must be both strong enough to transmit shear loads and durable enough to prevent slippage in the joints. The design of the hardness and strength properties of dowel joints plays an important role in the overall stability of the structure. Zaborsky *et al.* (2018) stated that dowel joint strength was higher with an annular ring at right angle. In the field of furniture strength design, dowel connections have been examined due to their affirmative durability and ease of attach (Vassiliou *et al.* 2016; Uysal and Tasdemir 2022).

Three-dimensional (3D) printing, also known as Additive Manufacturing (AM), is a method of building products by layering materials. This process, which is often referred to as fast prototyping, appeared at the beginning of 90s with the development of computer technology (Sagias *et al.* 2018; Maciag *et al.* 2019). Today, the 3D printers are rapidly advancing in various sectors and attracting attention as a widespread technology. With the advancement of technology and efficiency of use, these printers offer new opportunities in design and production (Aydın *et al.* 2018). Traditionally produced fasteners are generally costly and time consuming to produce. Thanks to the 3D printers, the design and production of these parts can be optimized; production costs are reduced by reducing fill rates and it becomes possible to produce parts in a shorter time. With these features, 3D printers provide significant advantages to designers, manufacturers, and consumers (Hacıoğlu *et al.* 2016; Yıldırım *et al.* 2019).

Connection techniques in furniture have traditionally been based on screws, nails, staples, and similar mechanical elements. However, these connection techniques can be time-consuming and can also lead to visual deterioration or weak connections. Recently, there has been an increase in the use of 3D printing technology in various industries, including furniture manufacturing. The ability to design custom-fit connector by 3D printing allows for the designing of stronger and more aesthetical furniture connections (Aydın 2015; Aydın and Aydın 2022). It is realized that limited studies are available on the shear resistances of glued joints with 3D printed dowel produced from Poly Lactic Acid (PLA), tough PLA, Poly Amide (PA), and tough resin with different surface patterns such as grooved, cross, and straight.

In this study, the shear performances of dowels produced with the 3D additive manufacturing method from PLA, tough PLA, PA, and tough resin materials, and with different surface geometries were investigated on L-type joints made of solid Scots pine material by including polyvinyl acetate (PVA) glue. The purpose of these mechanical tests is to determine the effect of the type of material used and the surface geometry of the dowel on the shear strength of the connection and to reveal the most suitable dowel design for furniture joint.

EXPERIMENTAL

Materials

In this study, Scots pine wood with a density of 0.45 g/cm^3 was conditioned in a chamber controlled at $20^\circ\text{C} \pm 5^\circ\text{C}$ temperature and $65\% \pm 5\%$ relative humidity and used for dowel joints. The wood was cut to the dimension of $52 \text{ mm} \times 152 \text{ mm}$. These samples were used to form a joint with the help of PVA glue. 3D printed dowels with different properties produced by the additive method. Figure 1 shows the pictures of the preparation of Scots pine samples and joints. As shown in Fig. 1, the samples were precisely cut, marked, and drilled to create dowel holes.

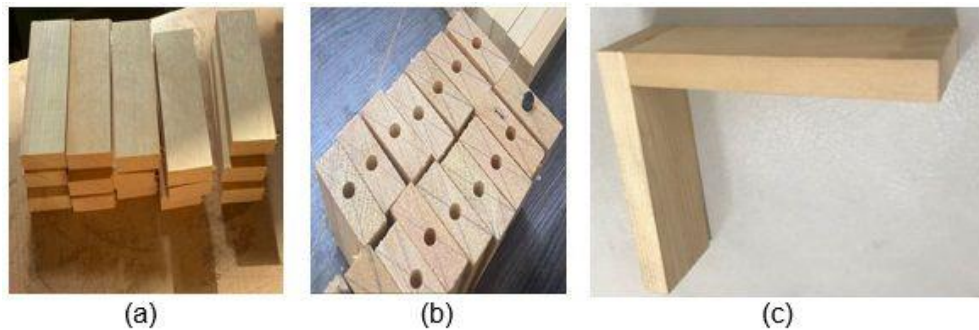


Fig. 1. Scots pine samples of joints a) the member with connection hole on surface, b) the member with the connection hole on cross section, c) connected members.

3D Dowel design

The dowel models were designed in three different surface geometries: grooved, cross, and straight, using SolidWorks 2021 version, a CAD program. Different surface geometries were designed to see the holding ability of the differently designed dowel teeth. These dowels were modeled to be the same in size. The depth of the geometric shapes used on the surface was determined to be 1.0 mm. The designed dowel shapes are shown in Fig. 2.

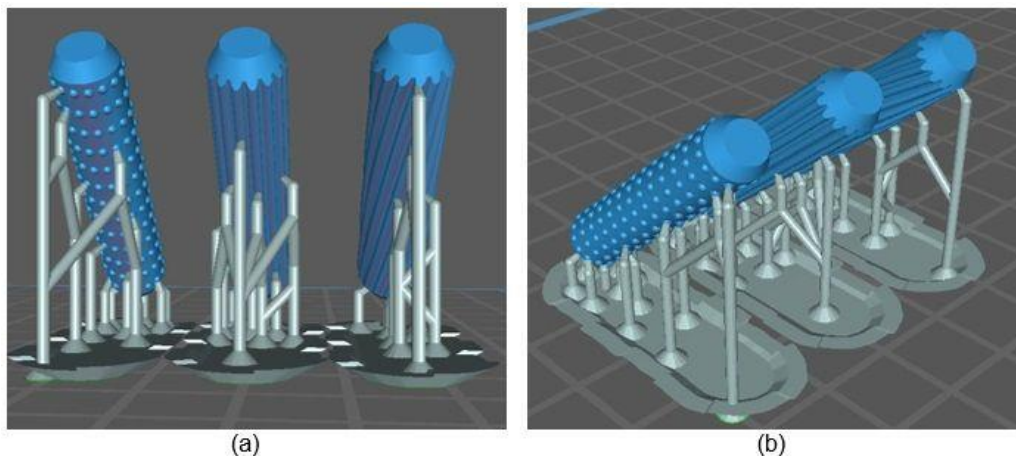


Fig. 2. Designed dowels: a) front view, and b) cross view

The 3D-modeled dowels were converted to STL (Standard Triangle Language) format to be transferred to slicer programs that allow the control of the production

parameters of 3D printers during the production process. Two 3D printer types were used for production: DLP (Digital Light Processing) and FFF (Fused Filament Fabrication).

The production process was carried out on Phrozen Mega 8K S as a DLP type printer (Phrozen, Taiwan) and Ultimaker 5 S as a FFF type printer (Ultimaker, Netherlands). The dowel designs were transferred to slicer programs suitable for each printer, and Chitubox software (Shenzhen CBD Technology Co., China) was preferred for the DLP type printer and Cura software (Ultimaker Cura, USA) was preferred for the FFF type printer.

The raw materials used in production vary according to the printer type. Tough resin from Anycubic was used in the DLP type printer, and Tough PLA, PLA, and PA filaments of Ultimaker brand with a diameter of 2.85 mm were used in the FFF type printer. Each printer has a different production method and requires its own production parameters. Similarly, the raw materials used also require different production parameters. Details regarding these parameters are given in Table 1.

Table 1. 3D Dowel Production Parameters

	Raw Material	Parameter	Unit	Value
FFF Type Printer	PLA	Layer thickness	mm	0.1
		Infill pattern	-	Concentric
		Infill density	%	100
		Cooling rate	%	100
		Print temperature	°	200
		Table temperature	°	60
		Print speed	mm/s	60
	Tough PLA	Layer thickness	mm	0.1
		Infill pattern	-	Concentric
		Infill density	%	100
		Cooling rate	%	100
		Print temperature	°	235
		Table temperature	°	60
		Print speed	mm/s	50
	PA	Layer thickness	mm	0.1
		Infill pattern	-	Concentric
		Infill density	%	100
		Cooling rate	%	80
		Print temperature	°	245
		Table temperature	°	80
		Print speed	mm/s	40
DLP Type Printer	Tough Resin	Layer thickness	mm	0.1
		First layer exposure time	s	40
		Exposure time	s	4

In addition, post-processing was applied to the dowels produced in DLP type printers. In this process, the dowels were washed in Phrozen brand cleaner and curing devices for 20 min to remove the residual liquid resin on them. Then, the curing process was carried out by exposing them to ultraviolet light with a wavelength of 403 nm in the curing device for 5 min. The dowels were produced from PA, PLA, tough PLA, and tough resin materials with diameters of 6 mm and lengths of 30 mm. The surfaces of the dowels were designed in three different ways: grooved, cross, and straight. Figure 3 shows the pictures of the dowels produced within the scope of this study. Each figure shows cross, straight and grooved dowel design in order. Figure 4 shows solid wood and plastic dowels obtained from market with only straight surface design.

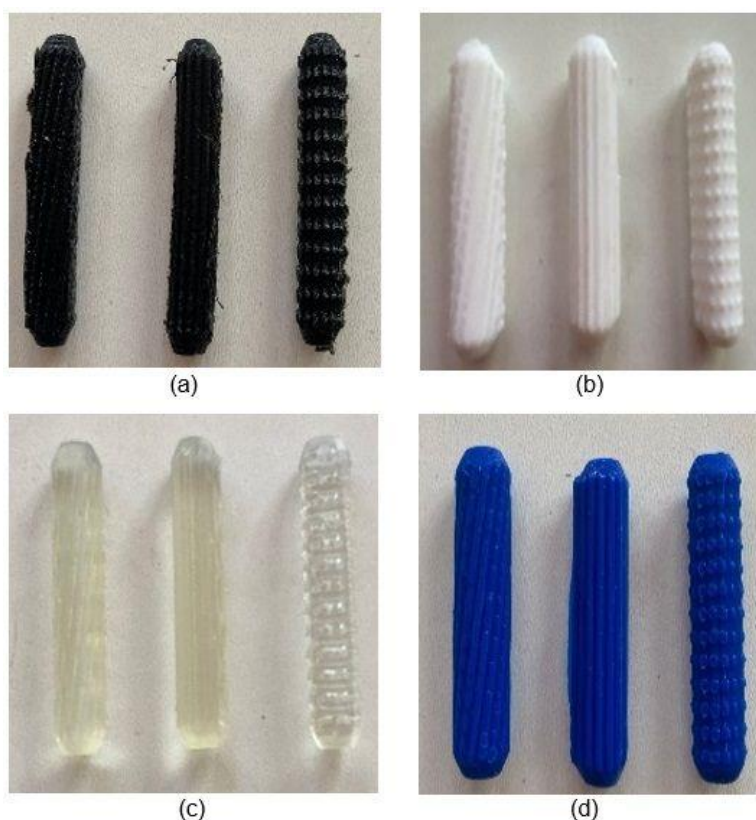


Fig. 3. Images of 3D-printed dowels: (a) PA, (b) PLA, (c) Tough Resin, and (d) Tough PLA

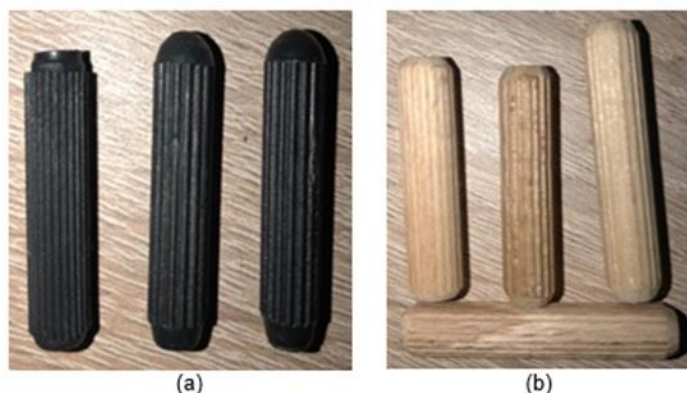


Fig. 4. Images of Commercially obtained dowels: (a) Plastic, (b) Solid wood

Method

Experimental design

In this study, three different dowel surfaces made from different materials were used in 3D printers. Therefore, the experimental design involved 3 different surface patterns, 4 different materials, and 5 repetitions, for a total of 60 joints in a way of $3 \times 4 \times 5$. In addition, solid wood dowel and plastic dowels were obtained from the market and tested with 5 repetitions. Therefore, 10 Scots pine joints were prepared, and a total of 70 joints were prepared for this study. These joints were produced to compare their shear performances. Commercially available dowels used for comparison had only a straight surface pattern, unlike the 3D-printed dowels with various patterns.

Shear test

The samples were subjected to loading at a speed of 2.5 mm/min in the Zwick Universal testing machine according to the ASTM D 143 (2010) standard, the maximum loads, and failure modes were recorded. Figure 5 shows the testing process of the joints in the Zwick Universal testing machine. According to the Fig. 5, the loading was applied to the full joint instead of shearing, and the performances of the dowel in the joints were examined.

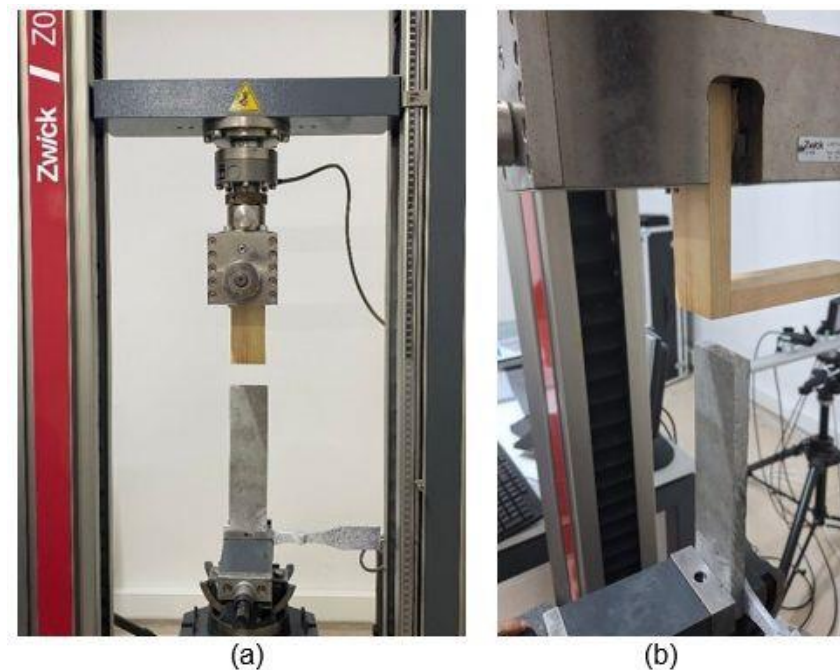


Fig. 5. Zwick Universal test machine: a) front view, and b) cross view

Statistical Analysis

SAS Software 9.4 (SAS Institute Inc., Cary, USA) statistical package program was used in the analysis of the data. The effects of dowel production material and different dowel surface patterns on the shear strength values of Scots pine joints made of different materials such as PLA, PA, tough PLA and tough resin were considered at a confidence level of 5%.

RESULTS AND DISCUSSIONS

Table 2 shows the shear resistance results of the joints produced from all the types of dowels. According to these results, dowel joints produced from grooved and straight patterned tough resin yielded the highest shear resistance values mathematically. This was followed by grooved PA dowels with grooved pattern and tough resin dowels with cross patterns. Then, grooved and tough PLA dowels with cross pattern took their place in the ranking and the lowest shear value was obtained when PA dowels with cross pattern were used.

Table 2. Shear Strength Values of Joints Made of PLA, Tough PLA, PA, and Tough Resin with Dowels

Sample No	PLA			Tough PLA			PA			Tough Resin		
	Grooved	Cross	Straight	Grooved	Cross	Straight	Grooved	Cross	Straight	Grooved	Cross	Straight
1	2790	2604	2670	2546	2360	2581	2899	1731	2760	2300	3093	2580
2	3195	2604	2058	2164	2485	2603	2483	2280	2765	3010	3064	2765
3	2361	2519	3105	2709	2475	2873	2656	2271	2453	3362	2262	3330
4	2052	2834	1911	1915	2312	2533	2716	2248	2333	2825	2501	2691
5	2400	2326	2381	2259	1914	2726	2658	1969	2603	2598	2719	2857
Average	2560 (ABC)	2577 (ABC)	2425 (BCD)	2319 (CD)	2309 (CD)	2663 (ABC)	2682 (AB)	2100 (D)	2588 (ABC)	2819 (A)	2728 (AB)	2845 (A)
Std	441	183	480	314	233	137	149	243	190	403	549	290
COV	17	7	20	14	10	5	6	12	7	14	22	10

Letters in parentheses indicate statistical differences, std: Standard deviation, COV: Coefficient and variation

When comparing the dowels with different surface patterns produced from the same material, no statistical difference was observed among the shear strength values of the dowel joints made of PLA, tough PLA, and tough resin using different surface patterns such as grooved, cross, and straight. However, it is apparent from the table that the grooved and straight patterned dowels made of PA provide statistically greater shear strength than the cross ones.

As shown in Table 2, and the shear strength values of the joints made of grooved and cross patterned dowels were mathematically higher than the straight ones, although not statistically relevant. However, it was generally observed that using different surface patterns in dowels made of PLA had no effect on the shear strength statistically. In the study of Demirel *et al.* (2024), no statistical difference was observed among the shear strength values of grooved, cross, and straight dowel joints made of PLA without glue.

The shear test results of joints made of tough PLA are also shared in Table 2. As shown, grooved and cross patterned samples yielded low shear strength values close to each other, while straight patterned dowel joints yielded higher values. However, it was observed from the table that there was no statistical difference, and different dowel surface patterns did not affect the shear strength of the joints. In the study of Demirel *et al.* (2024), no statistical difference was observed among the shear strength values of grooved, cross, and straight dowel joints made of PLA without glue.

The shear test results of the dowel joints made of made of PA are indicated in Table 2. Results showed that the shear strength values of the joints made of grooved and straight

patterned dowels were close to each other and there was no statistical difference, while they were statistically higher than those made of cross patterned dowels.

The shear results of the joints with dowels made of tough resin are shown in Table 2. As shown in the table, the shear resistance values of the joints produced from grooved, cross, and straight patterned tough resin dowels were close to each other and no statistical difference was observed. Demirel *et al.* (2024) made a comparison of the shear resistance values of grooved, cross, and straight dowel joints made of resin and the shear resistance values of the straight patterned dowels were statistically higher than the grooved ones. The resin material is more brittle than tough resin and it broke during the assembly phase when produced in cross patterned dowels. The shear resistance values of the beech joints produced from cross patterned resin dowels were approximately 752 N which is approximately one out of four of the current study results. Because tough resin material was used in this study compared to resin one used the study of Demirel *et al.* (2024).

Table 3. Shear Strength Values of Dowel Joints Made of PLA, Tough PLA, PA, and Tough Resin, Solid and Commercially Available Plastic

PLA	Grooved	2560 (ABCD)
	Cross	2583 (ABCD)
	Straight	2425 (BCDE)
Tough PLA	Grooved	2319 (DE)
	Cross	2309 (DE)
	Straight	2663 (ABCD)
PA	Grooved	2682 (ABCD)
	Cross	2100 (E)
	Straight	2583 (ABCD)
Tough Resin	Grooved	2819 (AB)
	Cross	2728 (ABC)
	Straight	2845 (A)
Solid wood	Straight	2360 (CDE)
Plastic	Straight	2041 (E)

Letters in parentheses indicate statistical differences

As shown in Table 3, the highest shear resistance values were mathematically obtained from the joints assembled with dowels produced from tough resin. Then, PA and PLA dowels showed mathematically higher shear resistance values than those produced from tough PLA. When looking at Table 3, when the SAS statistical analysis result was compared with the least significance difference (LSD 398), the shear resistance values of the joints produced from straight patterned dowels produced from tough resin yielded statistically higher values than PLA straight, PA cross, solid, and plastic dowels. However, in the study of Demirel *et al.* (2024), the grooved pattern dowels joints produced from resin without glue yielded the lowest shear resistance value, while the cross ones produced from resin yielded lower shear resistance values than those produced from other PLA and PLA+ Thermoplastic Polyurethane (TPU) materials. However, in this study, the strongest dowel materials for the joints were those made with tough resin, which yielded the highest value. As seen in the table, the shear values of the joints produced from PA dowel with cross pattern and market plastic dowel were the lowest and did not show any statistical difference between them. In fact, as a result of the observations made in this study, it is thought that the market plastic dowel was also produced from PA material. In general, it is believed that the dowels produced in this study yielded values that were either greater or close to the

shear resistance given by the dowel joints (either wood or plastic) on the market. On the other hand, the joint prepared for this study yielded higher shear resistance values than the dowels called market plastic dowels.

Load-Displacement Curve

Figure 6 shows a typical load-displacement curve of the joint evaluated in this study. As observed in Fig. 6, the load-displacement curve of the joint produced from PLA is in a sharp-peaked curve at the maximum point. The dowel produced from tough material such as tough resin yielded a shaper peak in the load displacement curve compared to not the dowel produced manufactured from not tough ones. Demirel *et al.* (2018) studied the shear strength performances of staple-glued OSB joints in their study and obtained load-displacement curves with a sharp-peaked line, as observed in this study. Uysal (2024) observed a sudden decrease after ultimate load in the load-displacement curve of dowel joints. This study is similar to literature studies in this sense.

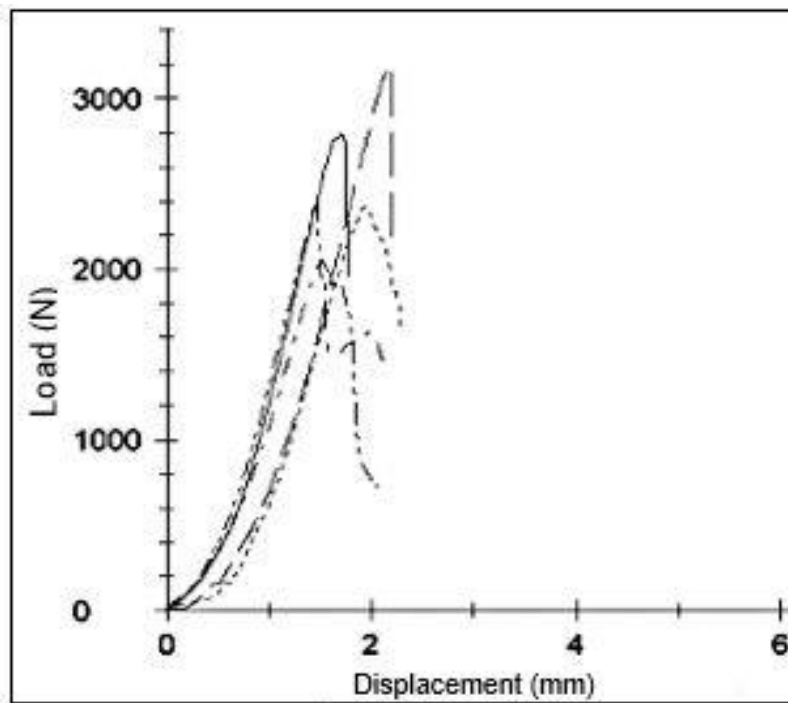


Fig. 6. Typical load-displacement curve of dowel joint tested in this study

Failure Mode

Figure 7 shows the general type of failure mode that were observed in the joint. Table 4 also shows failure modes for each tested joint. One is only glue separation, and the other one is glue separation and wood material rupture above dowel hole near material edge. First failure mode was mostly observed in the joint connected with PLA and PA dowel, the second failure mode was observed in the joint connected with tough PLA and tough resin. Because tough material is stronger, they also rupture material beside separation from glue.

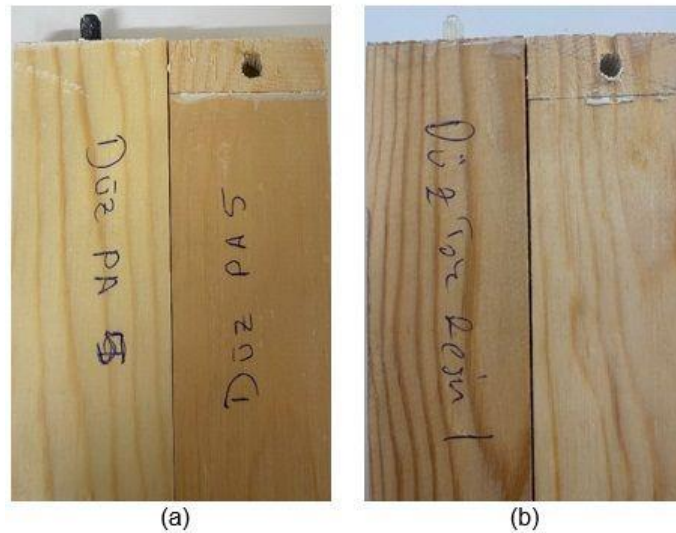


Fig. 7. Failure modes a) only glue separation between wood member; and b) glue separation and wood material rupture above dowel hole near material edge

Table 4. Failure Modes of Each Tested Dowel Joint

Sample No	PLA			Tough PLA			PA			Tough Resin		
	Grooved	Cross	Straight	Grooved	Cross	Straight	Grooved	Cross	Straight	Grooved	Cross	Straight
1	1	1	2	2	2	2	1	1	1	2	1	2
2	1	1	1	2	2	2	1	1	1	2	2	2
3	1	1	1	2	2	1	1	1	1	2	1	2
4	1	1	2	2	2	1	1	1	1	2	1	2
5	1	1	1	2	2	2	1	1	1	2	1	2

1 shows: Only glue separation, 2: shows: Glue separation and wood material rupture above dowel hole near material edge

CONCLUSIONS

The results of the study on the shear resistances of dowel joints made of different materials in Scots pine with glue are as follows:

1. The highest shear resistance was observed in joints using tough resin dowels, followed by tough poly(lactic acid) (PLA), PLA, and polyamide (PA) dowels. Then, this is followed by dowel-glued joints produced from tough PLA, PLA, and PA. There was no statistical difference among the joints produced from these three different materials, except for the cross patterned dowel joints produced from PA, which showed statistically less shear resistance. As it can be inferred from the results that using less costly PLA material can achieve the same performance in shear resistance, instead of using tough PLA material in dowel production.
2. When the difference between the dowel surface patterns is examined, no statistical difference was observed when the shear performances of the dowel joints produced from the same material, except for the shear performances of the joints with dowels made of PA. Likewise, the shear resistance values of the joints with grooved and

straight patterned PLA dowels were statistically higher than the shear resistance values of the joints with cross patterned PLA dowels.

3. When the performances of the dowel joints produced in this study are compared with the joints with dowels produced from solid and plastic materials used in the market, the shear resistance values of the dowel joints produced from tough resin were statistically higher than the dowel joints produced from market ones. The shear values of the dowels joints made of PLA, tough PLA, and PA did not show any statistical difference from the ones of the solid wood dowels joints used in the market, but they were statistically higher than the shear values of the dowel joints produced from market plastic.
4. The failure modes of the joints with dowels made of tough materials such as tough resin and tough PLA were generally observed as separation in the glue line and rupture of the Scots pine wood material near the upper edge of the dowel. For joints with PA and PLA dowels, failure occurred primarily through glue line separation without significant wood rupture.
5. When the load-displacement curves of the dowel joints were examined, a sharp-peaked curve was observed in most of the joints, resulting from the separation of the glue line.

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