ISPARTA UYGULAMALI BİLİMLER ÜNİVERSİTESİ

Turkish Journal of Forestry | Türkiye Ormancılık Dergisi
2024, 25(1): 100-106 | Research article (Araştırma makalesi)

The performance of 3d printed dowel with three different surface designs in furniture joints

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Abstract: The shear strengths of the joints produced by using Poly Lactic Acid (PLA), PLA+ Thermoplastic Polyurethane (TPU), and resin (Acrylic Photopolymer) with three different surface design of the dowels including, grooved, straight, and cross were investigated compared, wood and plastic dowels. The Results indicated that among L-type furniture joints, those manufactured from PLA and conventional wood dowels displayed the highest shear resistance, followed by L-type furniture joints with dowels made from PLA+TPU, resin, and plastic. Generally, differences in dowel patterns did not have a statistically significant impact on the shear resistance of L-type joints, except for the straight pattern dowels made of resin, which exhibited a statistically higher shear resistance than the grooved pattern dowels. Regarding the failure mode results, only PLA, PLA+TPU, and wooden dowels showed signs of elongation and crushing within the dowel holes. Conversely, in joints using dowels produced from resin and plastic, the dowels broke under shear stress, without displaying elongation, and did not leave any evidence of crushing in the dowel holes. Overall, the results of the study indicated that dowels made only PLA exhibited similar shear resistance compared to conventional wood dowels. Additionally, the study demonstrated that 3D-printed dowels were stronger than conventional plastic dowels.
Keywords: Dowel, Furniture joint, 3D printing, PLA, TPU, Resin

Üç farklı yüzey tasarımına sahip 3d baskılı kavelaların mobilya birleşme yerlerindeki performansları

Özet: Yivli, düz ve çapraz olmak üzere üç farklı yüzey tasarımına sahip kavelaların sadece PLA, PLA+TPU, Reçine (Akrilik Fotopolimer) kullanılarak üretilen birleşim yerlerinin makaslama (kesme) mukavemetleri ahşap ve plastik kavelalarla karşılaştırılarak incelenmiştir. Sonuçlar, L tipi mobilya birleşme yerlerinde PLA ve geleneksel ahşap kavelalardan üretilenlerin en yüksek kesme direncini sergilediğini, bunu PLA+TPU, reçine ve plastikten yapılan kavelalardan üretilen L tipi mobilya birleşme yerlerinin izlediğini göstermiştir. Genel olarak, yivli desenli kavelaların istatistiksel olarak daha yüksek kesme direnci sergileyen reçineden yapılmış düz desenli kavelalar dışında, kavela desenlerindeki farklılıklar L tipi birleşme yerlerinin kesme direnci üzerinde istatistiksel olarak anlamlı bir etkiye sahip olamamıştır. Kırılma modu sonuçlarına ilişkin olarak, yalnızca PLA, PLA+TPU ve ahşap kavelalarda, kavela deliklerinde uzama ve ezilme belirtileri görülmüştür. Bunun tersine, reçine ve plastikten üretilen kavelaların kullanıldığı birleşme yerlerinde kavelaların kesme gerilimi altında uzama göstermeden kırılmış ve kavela deliklerinde herhangi bir ezilme izi bırakmamıştır. Genel olarak çalışmanın sonuçları, yalnızca PLA'dan yapılan kavelaların, geleneksel ahşap kavelalarla karşılaştırıldığında benzer kesme direnci sergilediğini göstermiştir. Ayrıca çalışma, 3D baskılı kavelaların geleneksel plastik kavelalardan daha güçlü olduğunu göstermiştir.
Anahtar kelimeler: Kavela, Mobilya birleşme yeri, 3D baskı, PLA, TPU, Reçine

1. Introduction

Mostly, furniture consists of three basic constructions: box, frame, and combined ones. Furniture made of panels such as MDF or particle board is called box construction, furniture made of solid timber is called frame construction, and furniture made of any kind of forest products is called combined construction (Örs and Efe, 1998). In frame construction furniture, especially in the frame parts of furniture such as upholstered armchairs and sofas, frame elements are attached to each other at various points with different joining methods such as mortise-tenon, dowel, nail, screw, staple, etc. Among these joining methods, dowel is a solid wood pegs that has been used for years in furniture industry (Efe and Kasal, 2003; Chen et al.,2019). They are still one of the popular wood connectors in furniture joints. A shear load is one the common force actions on dowel connection in furniture frame. Therefore, the shear behavior of a dowel with different materials is needed to be researched.

Three-dimensional (3D) printing also known as Additive Manufacturing (AM), is a technique for constructing parts by layering the material. This process, often referred to as rapid prototyping (Dul et al., 2016, Kuo et al., 2016; Zou et al., 2016, Skorski et al., 2016, Levenhagen and Dadmun, 2018, Sagias et al., 2018; Hamzah et al., 2019; Maciag et al., 2019), emerged in the 80s alongside the development of computer technology (Sagias et al., 2018; Maciag et al., 2019). On contrast to the traditional subtractive production methods

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Received (Geliş tarihi): 07.11.2023, **Accepted** (Kabul tarihi): 21.12.2023

Citation (Atıf)**:** Demirel, S., Kuvel, N.T., Çava, K., Aslan, M., 2024. The performance of 3d printed dowel with three different surface designs in furniture joints. Turkish Journal of Forestry, 25(1): 100-106.
DOI: 10.18182/tjf.1387389

involving cutting, engraving, and material removal (Kariz et al., 2017), AM offers the advantage of producing highly intricate geometries that would be impractical or prohibitively expensive to create using conventional techniques (McCullough and Yadavalli, 2013; Carutasu et al., 2015; Raj et al., 2018). As a result, 3D printers have gained widespread adoption across various fields, including decorative (Chen et al., 2018), industrial, automotive, and medical fields (Alaboodi and Sivasankaran, 2018; Vlasceanu et al., 2018; Hossain et al., 2021). Furniture production always follows fashion trends and innovations in technology. Three-dimensional printing is one of the new manufacturing techniques. Therefore it is always useful to get into furniture manufacturing world with 3D printing method.

Furniture joint techniques have traditionally relied on mechanical fasteners such as screws and nails. These methods can be time-consuming and can result in weak or unsightly joints. In recent years, there has been an increase in the use of 3D printing technology in various industries, including furniture manufacturing. The ability to create custom-fit fasteners using 3D printing allows for the creation of stronger and more aesthetically pleasing furniture connections (Aydın, 2015; Yılmaz Aydın, 2022).

In this study, it is aimed to investigate the shear performance of 3D printed dowel furniture joints. The specific aim of the study: 1) Three different surfaces designed for dowel were determined to see differences in shear strength. 2) Five different dowel material performances were determined to see differences on shear strength. Additionally, determination of the ratio of proportional limit to ultimate load of each different type of dowel material was specifically aimed.

2. Material and methods

2.1. Materials

2.1.1. Preparation of samples

Three different materials were used in the production of the dowel which are Poly Lactic Acid (PLA, PLA+ Thermoplastic Polyurethane (TPU, and Resin (Acrylic Photopolymer). The dowels were produced in the Research Center Laboratories at Karadeniz Technical University.

Three dimensioned printed dowels are in the same size with commercial ones.

Dowel pins were produced using FFF type Creality brand CR-6 SE model 3D printer. Specimens produced using PLA and a mixture of 50% TPU with a hardness value Shore 80A and 50% PLA thermoplastic filaments.

The designed dowels were saved in STL (Standard Triangle Language) format and then transferred to a slicer program called Cura, which allows the production parameters of 3D printers to be controlled. 3D printed parts show orthotropic properties, so the infill pattern and direction of the prints should be directly effective in terms of mechanical properties (Aydın and Yılmaz Aydın, 2022). In this context, lines were chosen as the filling pattern in the production of the samples and the print angle [0°] was chosen to be perpendicular to the load to be applied as shown in Figure 1.

The printing parameters used in the production of the samples are given in Table 1.

L-type joints were prepared from beech wood (*Fagus orientalis*) which is mostly used in furniture frame production (Demirel and Kalayci, 2019; Demirel and Bas, 2021), and this beech wood was attached by using produced PLA, PLA+TPU, and resin dowels and commercially supplied wooden and plastic dowels. The dimensions of each beech member were 52 mm in width and 152 mm in length.

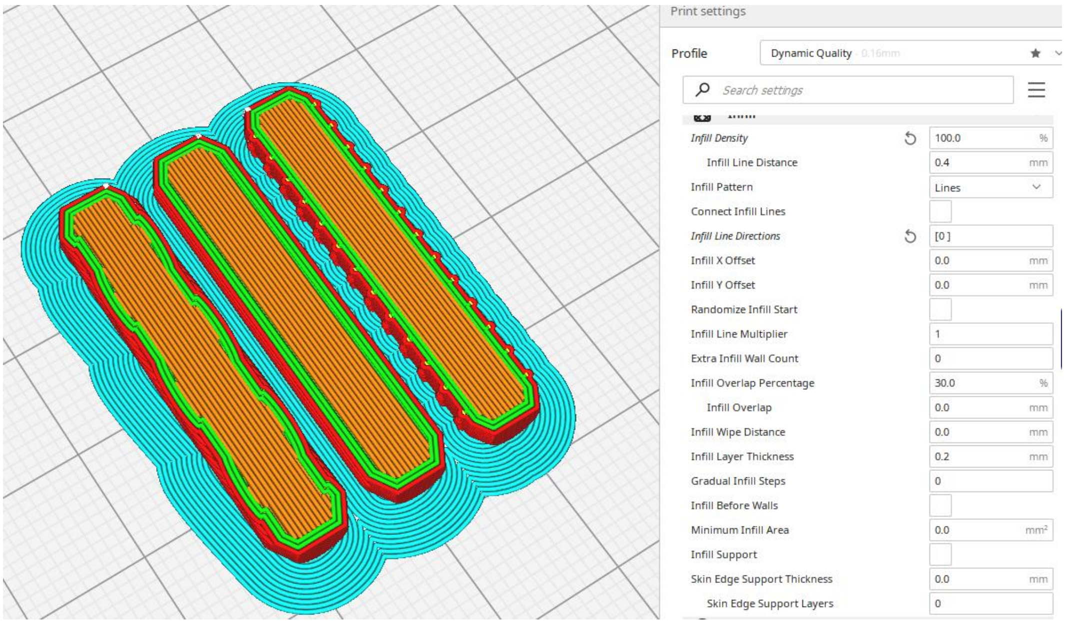

Figure 1. Infill line directions of 3 D printed dowels

Table 1. Printing parameters of the dowel specimens

Parameters	Unit	Value	
		PLA	PLA+TPU
Nozzle temperature	°C	205	230
Bed temperature	°C	60	80
Layer thickness	mm	0.1	0.1
Printing speed	mm/s	30	30
Infill ratio	%	100	100
Infill pattern	-	Lines [0°]	Lines [0°]

2.1.2. Dowel design

Dowel pins were designed using SolidWorks, a CAD program, in three different surface geometries: cross, straight and groove (dome), and in the same dimensions as shown in Figure 1. The depths of the geometries used on the surface are designed to be 2 mm. The shapes of the designed dowels are shown in Figure 2.

2.1.3. Shear test

MTS Universal testing machine was used to measure the shear performance of L-type joints manufactured with dowels printed with 3D technology. The test samples were subjected to shear test in order to find the maximum load occurring in the joints according to the type of dowel used. Loading was done at 2.5 millimeters/minute. As a result of the test, the maximum load (N) and the failure mode were determined, recorded, and illustrated. The MTS Universal testing machine, on which the shear test was performed, is shown in Figure 3.

2.1.4. Experiment design

A SAS statistical analysis 5×3 factors with 3 replicates per group was performed to evaluate the importance of the factors on the shear test of the joints created using dowels produced with 3D printers. Factors were determined as the materials used (PLA, PLA+TPU, Resin, Wood, Plastic) and the type or pattern of dowel (grooved, straight, cross).

3. Results and discussion

L-type furniture joints obtained by using dowels made of different materials were subjected to the shear test. Table 2 shows the average maximum shear resistance values of L-type dowel joints according to different material types (PLA, PLA+TPU, Resin, Wood, Plastic) and dowel types (grooved, straight, cross).

The least significant difference (LSD) was determined as 290 N as a result of multiple comparison procedure at the 5 percent significance level. Statistical differences were determined by comparing the value with the average results. Accordingly, this two-way interaction was analyzed and results showed that the material type was found statistically significant. Therefore, this factor was analyzed.

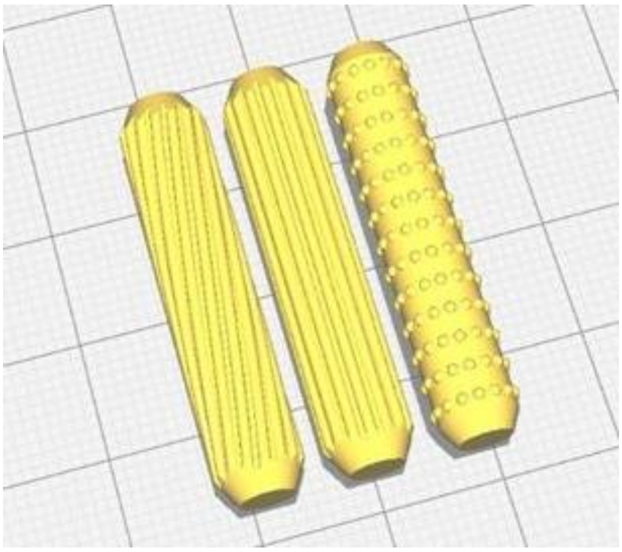

Figure 2. Designed Dowels

Figure 3. MTS Universal testing machine

Table 2. Average maximum shear resistance values in N of L-type dowel joints

Material type	Dowel type	Maximum average load (N)
PLA	Grooved (dome)	1 480 (A)
	Straight	1 627 (A)
	Cross	1 663 (A)
PLA+TPU	Grooved (dome)	774 (CB)
	Straight	946 (B)
	Cross	918 (B)
Resin	Grooved (dome)	412 (D)
	Straight	752 (CB)
Plastic	Straight	603 (CB)
Wood	Straight	1 503 (A)

Note: For Plastic and wood dowels, no grooved and cross dowels are available due to their commercial supplication not being produced. G: grooved, S: straight, C:cross, the letter A,B,C,D shows statistical differences.

3.1. Material type effect

When the difference between the values obtained as a result of the shear test of PLA, PLA+TPU, resin, wood, and plastic materials used in the production of dowels were examined statistically, L-type joints with dowels produced from only PLA and wood yielded the highest shear resistance values. Accordingly, dowels produced from only PLA can be used as a substitute for wooden dowels that have been used traditionally for years. Then, L-type joints consisting of dowels produced using PLA+TPU have the second-highest shear resistance values. The dowels produced from resin and plastic dowels used in the market have the lowest shear resistance values. Here, in fact, it can be said that the shear resistance values of the joints obtained from the dowels made of resin are mathematically higher than those produced from plastic, but as stated above, this value was not statistically significant.

3.2. Dowel type effect

The dowel pattern effect does not have a statistical significance. Likewise, the shear resistance values of L-type furniture joints produced from PLA dowels were mathematically the highest in cross-type dowels, followed by straight-type and grooved-type dowels. However, the shear resistance values of L-type furniture joints produced from PLA+TPU dowels were mathematically highest in straight-type dowels, followed by cross-type and grooved-type dowels. Finally, the shear resistance values of L-type furniture joints constructed from resin dowels were mathematically higher in straight-type dowels, but lower in grooved-type dowels. However, as stated before, these rankings were not statistically significant. Considering all different dowel type joints (PLA, PLA+TPU, Resin), the straight type dowel yielded mathematically the highest value compared to the others, followed by the cross type and grooved type. On the other hand, seeing the significant difference among surface designs of the dowel could be possible by using glue in dowels joint which allows to separate fixing ability of different dowel surfaces.

3.3. Joint failure modes

Figure 4 shows the failure modes encountered as a result of the shear test of L-type furniture joints printed from only PLA with dowel designs of the grooved, cross, and straight.

Figure 5 shows the failure modes encountered as a result of the shear test of L-type furniture joints printed from PLA+TPU with dowel designs of the grooved, cross, and straight.

Figure 6 shows the failure modes encountered as a result of the shear test of L-type furniture joints obtained from dowels made of plain-patterned wood.

Figure 7 shows the failure modes encountered as a result of the shear test of L-type furniture joints produced from dowels made of resin.

Figure 8 shows the failure modes encountered as a result of the shear test of L-type furniture joints made of plain-patterned plastic and obtained from commercially available dowels.

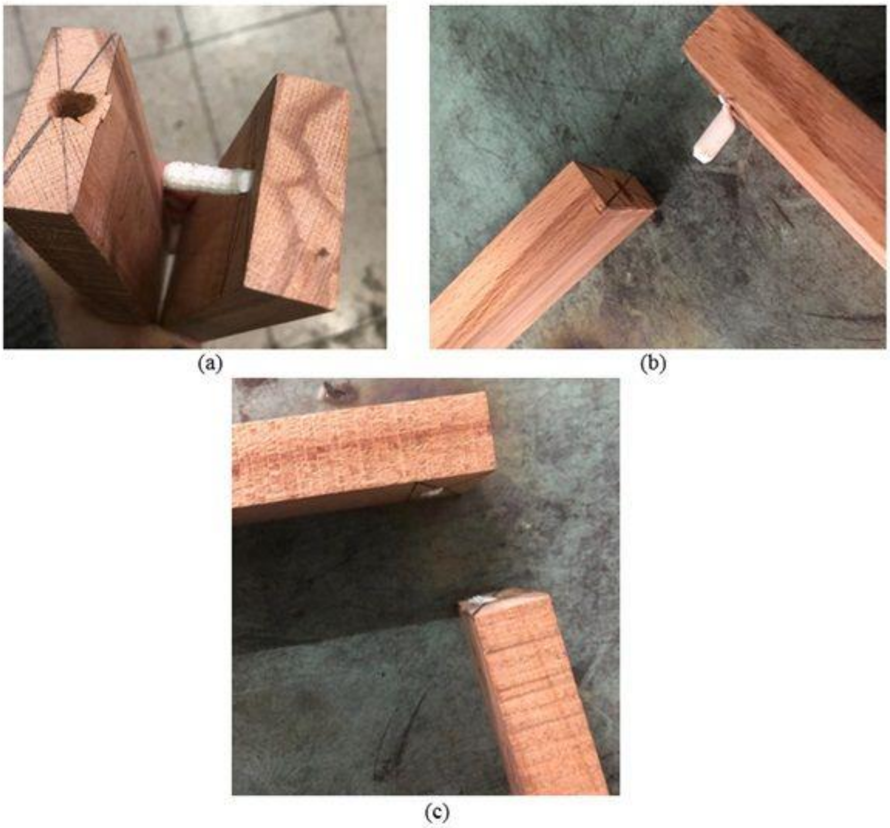

Figure 4. a) The failure mode of grooved (Dome) PLA dowel joint, b) The failure mode of straight PLA dowel joint, c) The failure mode of cross-PLA dowel joint.

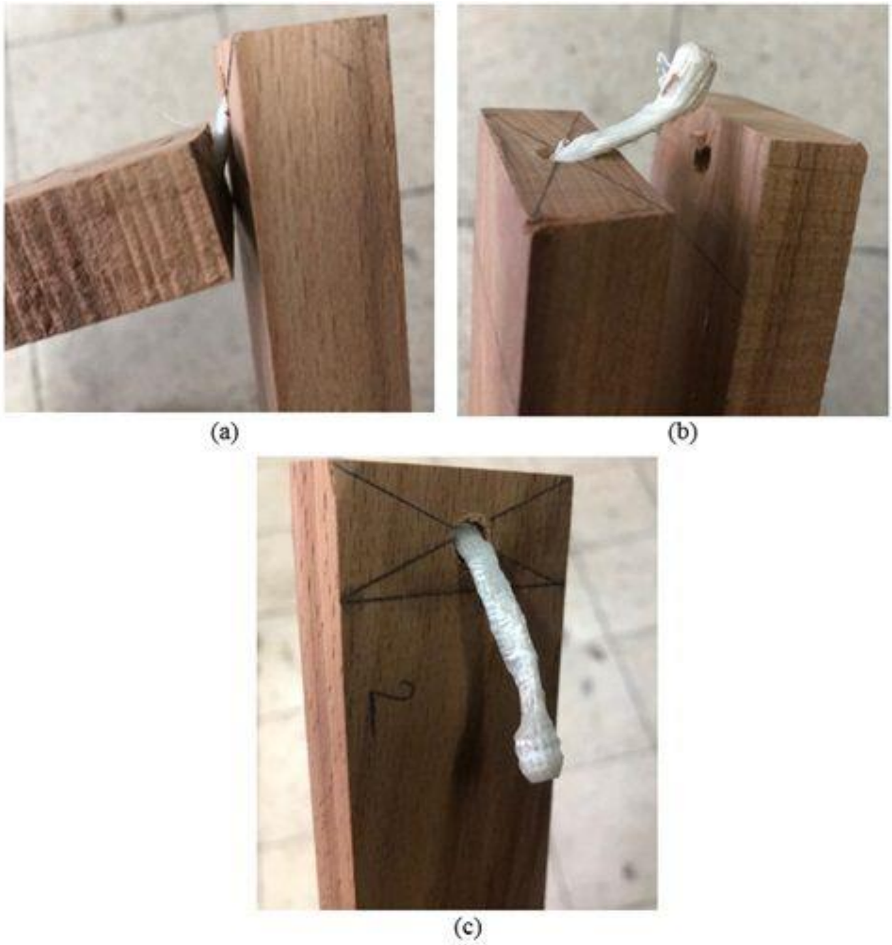

Figure 5. a) The failure mode of straight PLA + TPU (Tough) dowel joint, b) The failure mode of cross PLA + TPU (Tough) dowel joint, c) The failure mode of grooved (Dome) PLA + TPU (Tough) dowel joint.

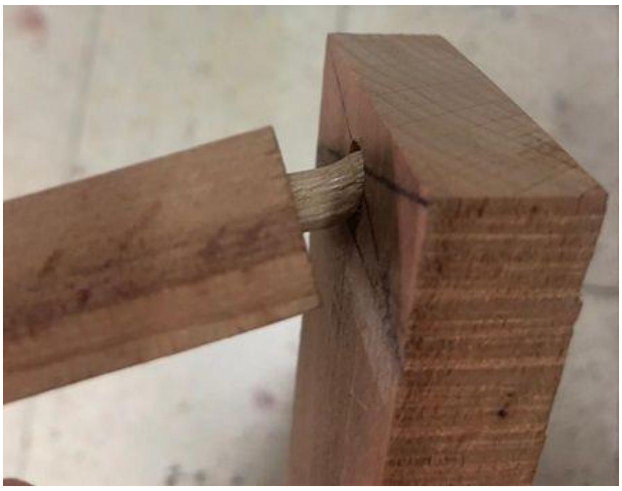

Figure 6. Wood Dowel Joint Failure

Figure 7. Resin Dowel Joint Failure

Figure 8. Plastic Dowel Failure

When the failure modes of L-type furniture joints are examined under shear test, the dowels produced from PLA showed elongation under load and were destroyed by crushing in the dowel holes. The dowels made from PLA+TPU were destroyed by elongation more than those made from only PLA ones, but the joint failure mode was similar to that of only PLA ones as shown in Figures 4 and 5. Similarly, wooden dowels showed a similar failure mode, showing slight shear and less elongation than PLA TPU dowels as shown in Figure 6. However, resin rupture was observed in the L- type furniture joints obtained from resin dowels, but no damage was observed in the dowel holes as shown in Figure 7. Actually, the resin dowels were more fragile compared to PLA and TPU ones. Additionally, cross ones were mostly broken compared to straight and grooved ones. A similar failure mode was observed in commercially available plastic dowels in Figure 8. Kasal (2008) investigated the effects of corner support element size on shear force carrying performance in T-type dowel-glued furniture joints were examined. In shear tests, dowel breakage (shear/ rupture) was observed in T-type joints made out of beech wood. This failure mode is consistent with the ones in this study.

3.4. Load-displacement curves for 3d printed dowel joints

The typical load-displacement curve for L-type furniture joints is shown in Figure 9.

The proportional limit is the highest point of the linearity (Vaidya and Pathak, 2019). After this point, plastic behavior, sharp breaks, or failure are monitored (Niklas, 1996). The curves showed that the addition of TPU to PLA increased the proportional limit of the load-displacement curve in Figure 8b compared to the one in Figure 8a. Additionally, as seen in Figure 4, the elongation of the PLA+TPU dowel was more than the only PLA dowel as seen in Figure 3. Demirel and Kalayci (2019) investigated that the ratio of proportional limit to ultimate load of stapled furniture joint made of solid wood is around 0.5. A Similar to that ratio was obtained with the PLA+TPU dowel joint in this study as seen in Figure 8b. In the joints with resin dowel, a sharp cut was observed after the ultimate load in Figure 8c. On the other hand, the joints with wood dowel did not show a sharp cut similar to resin dowel. They still hold the joint member for a while as seen in Figure 8d.

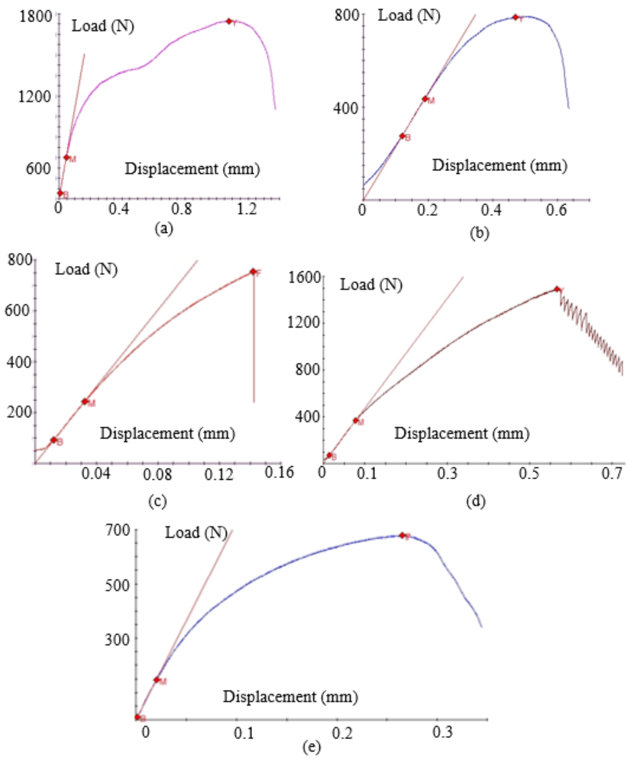

Figure 9. Typical load-displacement curve for L-joint a) with only PLA dowel, b) with PLA + TPU dowels, c) with resin dowel, d) with commercially available wood dowels e) with commercially available plastic dowel.

4. Conclusions

Within the scope of this study, the shear resistance values of the joints produced by using only PLA, PLA+TPU, resin, wood, and plastic dowels with the grooved, straight, and cross patterns were investigated.

- The results showed that only L-type furniture joints obtained from dowels made of PLA and wood showed statistically the highest shear resistance. Then it was followed by L-type furniture joints obtained from dowels made of PLA+TPU, resin, and plastic.
- In general, the difference in dowel pattern did not statistically affect the shear resistance of L-type joints, but only straight pattern dowels made of resin showed statistically higher shear resistance than grooved pattern dowels.
- Considering the results as the failure mode, the dowels were destroyed by showing elongation and crushing effect in the dowel holes only in the furniture joints made of PLA, PLA+TPU, and wooden dowels. However, in the dowel joints produced from resin and plastic, the dowels broke off with the shear effect without showing any elongation and did not leave a crushing effect on the dowel holes. As seen in the results of this study in general terms, the dowels produced from only PLA showed similar shear resistance compared to the conventional wood dowels. Additionally, this study showed that 3-D printed dowels were stronger than the conventional plastic dowels.
- The results of this study demonstrated the potential of 3D printing technology in the field of furniture manufacturing with different designs such as surface design for the dowel.

In addition, the use of 3D printing can significantly reduce the time and effort required for installation, leading to increased efficiency and productivity in furniture production. 3D printed connectors provide a strong and aesthetically pleasing alternative to traditional furniture connection methods. Further research is needed to fully understand the capabilities and limitations of 3D printing in furniture joints.

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