# DEFLECTION PERFORMANCE OF MEDIUM DENSITY FIBERBOARD AND PARTICLEBOARD SHELVES JOINED ABS, PLA, AND WOOD-PLA FILAMENT PINS

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**Abstract.** This study determined the deflection performance of melamine-faced medium-density fiberboard and particleboard shelves supported by acrylonitrile butadiene styrene, polylactic acid (PLA), or WOOD-PLA pins. The study was based on the BS EN 16122 standard and TS EN 9215 to assess deformation subjected to increasing loads. Material type, filament fill, and filament material type significantly affected deflection with $R^2$ and adjusted $R^2$ values of 96.1% and 94.2%, respectively.

***Keywords:*** Shelves, 3D printer, joints, deflection, wood.

## INTRODUCTION

Wall and floor cabinets serve as storage units in various spaces, such as kitchens, bathrooms, and offices. These cabinets are typically constructed in the form of box furniture. Owing to their versatile nature, furniture units can be subjected to various loads with varying sizes and qualities, depending on the intended purpose of the furniture (İmirzli 2008). Shelves can deflect to varying degrees depending on the material composition and load. Understanding these effects is an important aspect of proper design. Shelves are normally supported by pins of varying materials including wood, metal, or plastic. Metal or wood pins are normally fabricated from larger pieces, whereas plastic pins are extruded or cast.

The evolution of three-dimensional (3D) printing has created an exciting new opportunity to create pins with more specific properties tailored to the specific application. Three-dimensional printing provides greater flexibility in controlling the microarchitecture to fabricate cellular structures than conventional manufacturing methods (Compton and Lewis 2014). There are many 3D printing methods, including stereolithography, inkjet printing, fused deposition modeling (FDM), selective laser sintering, and laminated object manufacturing.

Objects that are already fabricated include functional parts, such as toys, tools, household items, and customized scientific instruments (Perce 2017). Three-dimensional fused filament fabrication (FFF) printers have the potential to be used not only for conventional prototyping but also for small-scale manufacturing (Pearce et al 2010; Perce 2017).

Polylactic acid (PLA), a bio-based polymer, is one of the most widely used thermoplastics to fabricate objects with 3D FFF printers. PLA develops strong bonds between successive layers of melt materials during printing because the glass transition temperature is low enough to facilitate effective bonding between layers, yet high enough to ensure that the printed parts maintain their shape when subjected to moderate operating temperatures. PLA is already used in disposable packaging applications and is currently being investigated for more durable applications (Harris and Lee 2010; Mannoor et al 2013; Wertz et al 2014; Notta-Cuvier et al 2014, 2015; Bouzouita et al 2016; Nagarajan et al 2016).

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Layer height, printing orientation, density and infill type, and number of outline perimeters strongly influence the mechanical properties of finished parts in additive manufacturing printing. Pandzic et al (2019) examined the influence of density and infill type on the tensile properties of PLA specimens and showed that an increase in infill density PLA-improved mechanical properties.

PLA has the potential to either replace conventional petrochemical-based polymers for industrial applications or as a leading biomaterial for numerous medical applications (Drumright et al 2000; Lopes et al 2012). Economic, environmental, and safety challenges have encouraged packaging producers and scientists to partially substitute petrochemical-based polymers with biodegradable ones. PLA is a high-strength, thermoplastic, high-modulus polymer that can be made from annually renewable resources. It is easily processable on standard plastic equipment to yield molded film, fibers, or parts (Garlotta 2002; Czuba 2014).

Blend materials can be applied in many industrial applications due to their higher strength-to-weight ratios than base materials. Applications requiring high tensile strength can include these filament materials among thermoplastics (Blok et al 2018).

Yildirim et al (2019) studied the properties of dowels produced in 3D printers for fixed construction furniture corner joints using a diagonal pressure test. They produced two different acrylonitrile butadiene styrene (ABS) and PLA 8 mm diameter dowels using a 3D printer using the FDM method. The long side of the dowels was produced parallel (tangent) and perpendicular (radial) to the ground plane. The main construction material was medium-density fiberboard (MDF Lam) coated with synthetic resin paper (melamine). The dowel was produced in the 3D printer as the joining element and L-type construction was prepared using polyurethane glue as the adhesive.

The most common printing filaments used in FDM are PLA and ABS, as they have shown impressive results against various stresses. ABS has high strength, whereas PLA (Garric et al 2008; Zhang et al 2019) is flexible. Blending them together can produce a product with improved strength and mechanical properties (Dizon et al 2018).

Wood is an organic material, and its powder can be used for printing in combination with different materials. The thermoplastic composite industry uses wood owing to its affordability, renewability, high modulus, and excellent machinability (Ayrilmis 2018; Deb and Jafferson 2021). Adding wood to PLA decreases filament costs, but further investigation into the mechanical characterization of 3D-printed PLA-wood composites is required.

Previous studies have primarily focused on optimizing and characterizing fully dense material parts (Lanzotti et al 2015; Song et al 2017).

Recent studies have characterized the effects of build orientation (flat, on-edge, or upright), layer thickness (0.06 to 0.24 mm), and feed rate (20-80 mm/s) on the mechanical performance of PLA samples manufactured with a low-cost 3D printer using tensile and three-point bending tests. Upright samples exhibited interlayer failure with lower strength and stiffness performance for built orientations. Upright samples also exhibited increased tensile and flexural strengths as layer thickness increased. On the other hand, iTensile and flexural strengths decreased as the feed rate used to produce these samples increased (Chacón et al 2017).

Afrose et al (2014) investigated the tensile properties of dog-bone-sized PLA thermoplastic material printed in different build orientations processed by a Cube-2 3D Printer. The ultimate tensile stress of PLA samples built in the X-direction (PLA-X) was highest at 38.7 MPa and ranged from 60% to 64% of the raw PLA material, whereas values were lower at 31.1 and 33.6 MPa for PLA-Y and PLA-45, respectively. The study suggested that although different build orientations have varying effects on the strength and toughness of printed parts, a balance can be achieved by considering the specific application requirements.

Tymrak et al (2014) quantified the basic tensile strength and elastic modulus of printed components using realistic environmental conditions for standard users of a selection of open-source 3D printers. They found average tensile strengths of 28.5 MPa for ABS and 56.6 MPa for PLA with average elastic moduli of 1807 and 3368 MPa, respectively.

Tensile strength, flexural properties, fracture toughness, and compressive properties, as well as impact strength, have also been investigated (Guntekin 2003; Imirzi 2008; Wang et al 2017). Mechanical properties of fully dense parts fabricated with an optimal selection of process parameters are comparable to parts fabricated with conventional methods such as injection molding.

Eckelman (2003) stated that shelf deflections between 1/200 and 1/500 of the shelf length were within acceptable limits. He stated that deflections up to 1/180 of the shelf length were pleasing to the eye, but ratios at or below 1/165 were aesthetically pleasing (Eckelman 2003).

Jivkov et al (2010) examined the deflection properties of shelves made of melamine-coated particleboard (PB) and fiberboard under distributed load by placing two to three slats of plywood in channels drilled on the lower surfaces of the shelves. The incorporation of three slats beneath the shelf structure resulted in a 20% improvement in deflection properties compared with standard PB. Moreover, they also found that fiberboard exhibited a 30% increase in deflection properties with the same support (Jivkov et al 2010).

Tankut et al (2008) reported a 33% improvement in deflection when screws were placed behind the shelves to improve the deflection properties of fiberboard and PB (Tankut et al 2008). Joining elements of in-cabin shelves used as cargo racks were produced with three different filaments in a 3D printer.

The furniture industry employs various joint assembly methods, including those that involve plastics, metals, and other materials. The goal of this study was to determine the deflection of PB and MDF shelves supported by pins composed of different material types.

## MATERIALS AND METHODS

### Materials

***Wood cabinet and shelves.*** Typical wooden cabinets of MDF and PB (1800 mm (height) × 450 mm (width) × 450 mm (thickness)) were chosen randomly. The shelves in these cabinets were made of 18-mm thick MDF and PB materials (Fig 1).

A total of 36 shelves manufactured with two different materials were tested. Density, MC, MOR, and MOE values of the shelves were 0.716 $g/cm^3$, 6.98%, 28.48 $N/mm^2$, 6028.72 $N/mm^2$, respectively, for MDF and 0.63 $g/cm^3$, 9.02%, 12.86 $N/mm^2$, 5821.2 $N/mm^2$, respectively, for PB.

***Fasteners.*** The cabinets featured MDF and PB shelves secured in place by shelf pins. The load-bearing capacity of the shelf pins is often more important than the overall durability of the shelf itself. The shelf pin design used in this study (Fig 2[a] and [b]) is a widely adopted product utilized by numerous companies.

In-fill percentages of the printer shelf fastener were 30% or 40%. Various pins were produced using different fill levels to determine the most suitable fill rate for the desired conditions. The filaments used for 3D printing included PLA, ABS, and PLA-Wood materials from a filament manufacturing company in Turkey (Porima Polymer Technologies Inc., Yalova, Turkey).

Forty-eight PLA filament pins were (1.75 mm in diameter) used to mount MDF and PB shelves at 30% and 40% fill to the cabinet. Figure 3 shows pins made of PLA filament with 30% or 40% fill (Nikon SMZ-445).

ABS, a commonly used thermoplastic, is used in a broad range of products from television remote controls to the automotive industry. ABS has high flexural strength and elongation before breaking. In the study, 48 ABS shelf pins were used to mount MDF and PB shelves at 30% and 40% fill to the cabinet. Figure 4 shows pins made of ABS filament with 30% or 40% fill.

PLA/wood filaments incorporate 30% wood reinforcement materials into their composition,

Figure 1. Examples of the test shelves along with side views of the MDF and PB shelves.

enabling the printing of products with greater resolution, reduced mass, superior thermal properties, and a realistic wood texture than standard PLA filaments (Chacón et al 2017).

Forty-eight 3D-printed PLA/wood shelf pins were used to mount MDF and PB shelves with 30% or 40% fill to the cabinet (Fig 5).

## Test Method

***Test method for shelves.*** The study was based on BS Standard EN 16122 (2012) while TS EN 9215 (2005) was followed to measure shelf deformation with increasing loads. Eighty kilogram square meter of test load was added for every 40 mm of shelf length and held for 7 d resulting

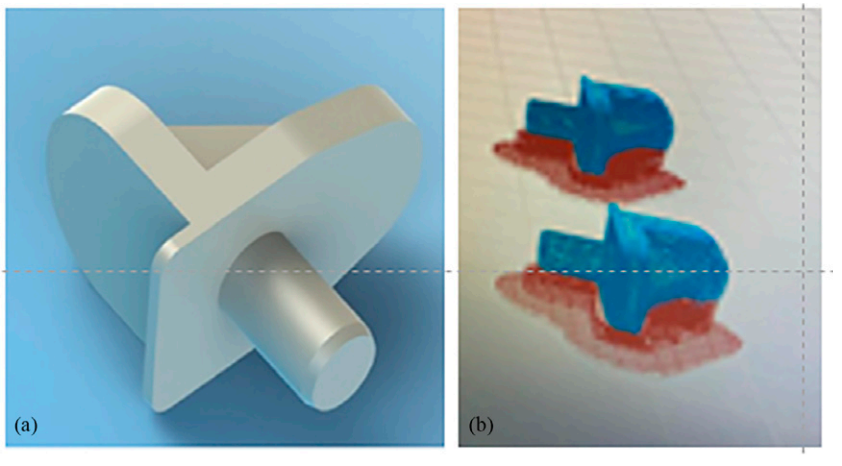



Figure 2. Example of (a) the model pin and (b) the pin as modeled using 3D printer software.

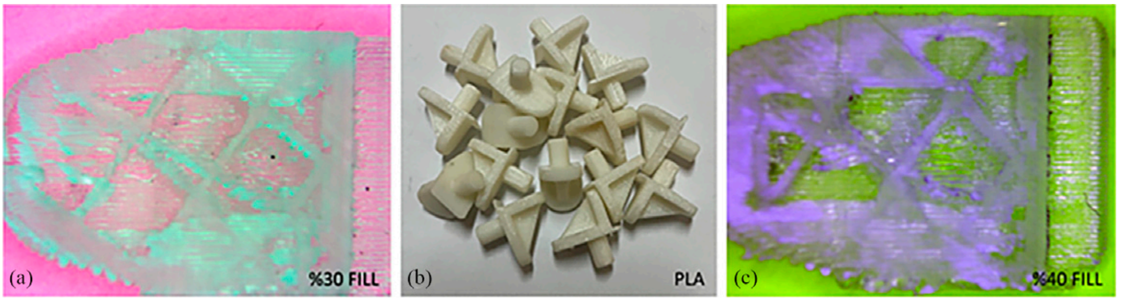


Figure 3. Examples of (b) PLA filament pins along with microscopic images of pins with 30% or 40% fill ratios (a and c, respectively).


Figure 4. Examples of (b) ABS filament pins along with microscopic images of pins with 30% or 40% fill ratios (a and c, respectively).

in a total load of 12.8 kg. However, the test was repeated two times since the material used was new and not of the type of glass, metal, or plastic specified in the standard. Total deflection was recorded at the end of 7 d.

The first deflection measurements were made at midspan (shelves) on unloaded racks, then again after applying the uniform load using a deflection yoke equipped with a comparator (Devotrans digital indicator) to measure center deflection to the nearest 0.001 mm. Measurements were taken at the midpoint along the shelf length where maximum deflection occurred (Fig 6).

Wood and wood-based materials tend to deform when under long-term loading. Deflection takes place as a result of the changes in molecular structure. In this study, deflection tests were conducted on shelves that were subjected to a distributed and fixed loading for 7 d. Deflection at the time of initial loading is fast (primary deflection), and then declines to a slower steady rate (secondary deflection) (Guntekin 2003).


Figure 5. Examples of (b) PLA-WOOD filament pins along with microscopic images of pins with 30% or 40% fill ratios (a and c, respectively).

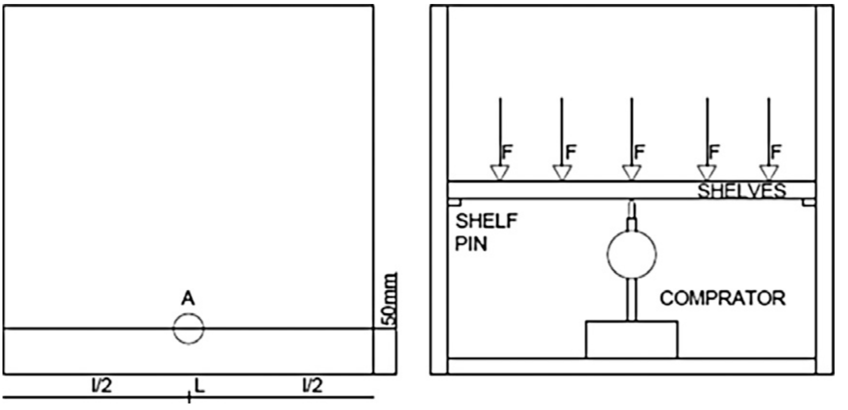


Figure 6. Diagram showing the load pattern for the shelves along with the comparator used to measure the deflection.

The data were subjected to multivariate analysis of variance (ANOVA). When the difference between groups was significant, univariate analysis was used to determine the difference between means at $\alpha = 0.05$ using SPSS software.

***SolidWorks finite element analyses.*** The availability of computer-based finite element methods (FEM) allows even complex structures such as furniture construction to be analyzed without destroying the furniture. This method also helps to accelerate the engineering design of furniture. In this study, the FEM software SolidWorks (Dassault Systèmes SOLIDWORKS Corp, Waltham, MA) was used to analyze the shelf models. Geometry, loading, and the meshing process for the shelves are displayed in Fig 7 Triangular meshing structure, as maximum mesh, was used to evaluate several intervals. MOR, MOE, density, and MC values of MDF and PB shelves were determined by laboratory tests and for the filaments. Technical values from the supplier were used to determine the deflection values of both shelf types.

## RESULTS AND DISCUSSION

### Damage Symptoms and Deflection Values

The midpoint of the shelves and the connection pins in both PB and MDF were the most frequently observed damage locations. Standard loads, combined with pins made of ABS, PLA, and PLA-WOOD (Fig 8), were applied during the testing process, and deflection was measured using a comparator.

As part of the standard (BS 16122-2012) testing protocol, shelves were left under load for 7 d, and varying degrees of deflection was observed in the MDF and PB materials. The results demonstrated that the deflection of pins used as joining elements varied across different ranges (Fig 9) and were further impacted by the saturation point.

### Statistical Analyses Results

According to the ANOVA, shelf material type, fill, and filament material type factors had statistically significant effects on deflection. Two-factor ANOVA statistics were performed for shelf material, filament type, and saturation unrelated sample groups, and the mean and standard deviations of edge and fill (Table 1).

The average filament type deflections used in the tests and the fill ratios of these filaments were 1.3261 mm for MDF shelves and 1.6029 mm for PB.

The statistical results for the average deflection results according to shelf material, filament material, and fill variables are shown in Table 2.

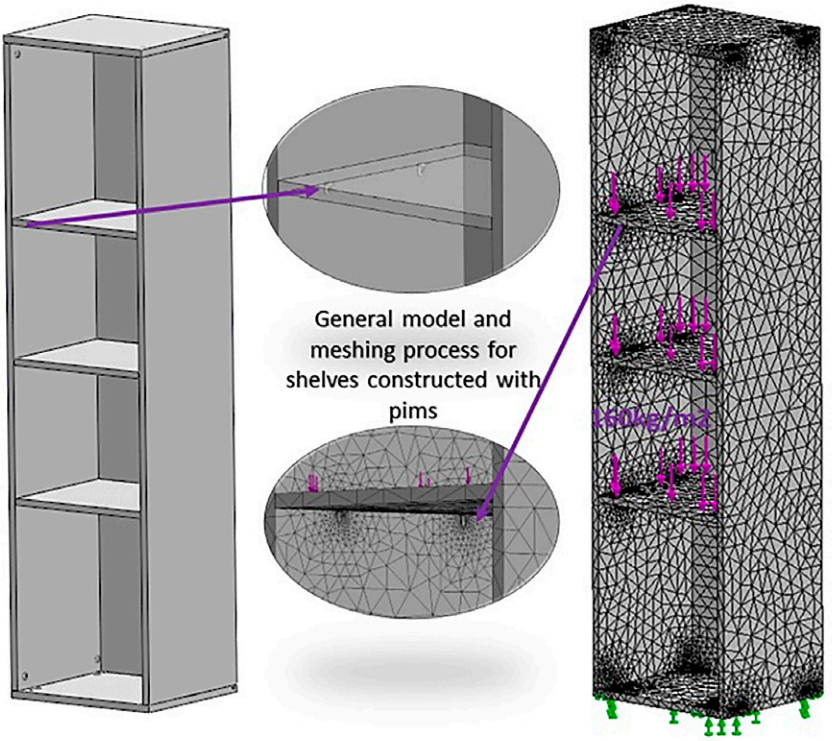


Figure 7. Diagram showing the shelving unit along with the meshing used for the model.


Figure 8. Photos showing the loads applied to a shelf unit as well as examples of shelves with the three-pin materials.

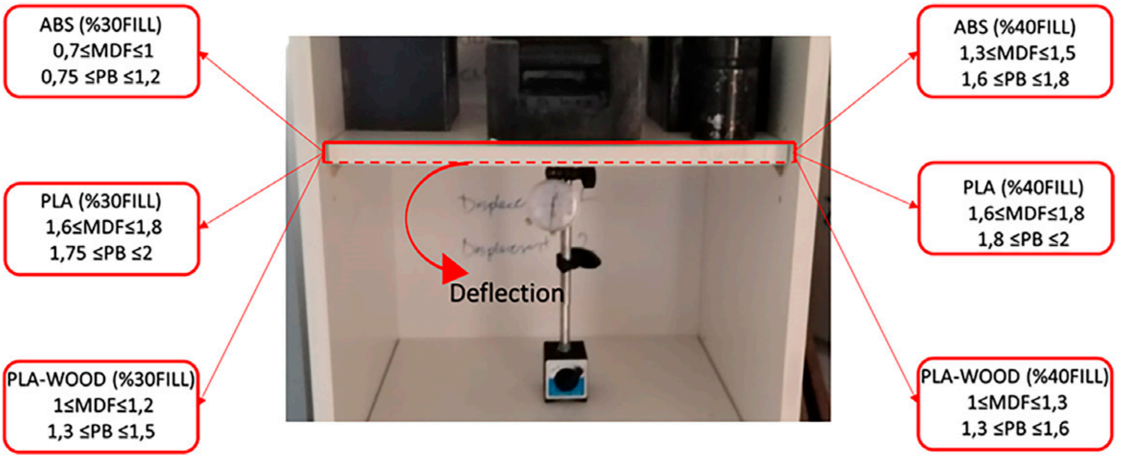


Figure 9. Data groups were obtained from test results of loads applied to shelves supported with PLA, ABS, or PLA-WOOD pins.

Table 1. Results of two-factor statistical analysis.

| MDF | | | | PB | | | | Total | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | | | Mean | SD | | | Mean | SD |
| ABS | %30 | 0.71 | 0.15 | ABS | 30% | 0.88 | 0.13 | ABS | 30% | 0.80 | 0.15 |
| | %40 | 1.43 | 0.08 | | 40% | 1.71 | 0.08 | | 40% | 1.57 | 0.17 |
| PLA | %30 | 1.66 | 0.08 | PLA | 30% | 1.83 | 0.13 | PLA | 30% | 1.75 | 0.13 |
| | %40 | 1.85 | 0.05 | | 40% | 2.36 | 0.15 | | 40% | 2.10 | 0.30 |
| PLA-WOOD | %30 | 1.19 | 0.15 | PLA-WOOD | 30% | 1.35 | 0.04 | PLA-WOOD | 30% | 1.27 | 0.13 |
| | %40 | 1.10 | 0.10 | | 40% | 1.40 | 0.14 | | 40% | 1.22 | 0.19 |
| Total | %30 | 1.19 | 0.43 | Total | 30% | 1.35 | 0.42 | Total | 30% | 1.27 | 0.42 |
| | %40 | 1.46 | 0.33 | | 40% | 1.88 | 0.44 | | 40% | 1.65 | 0.43 |
| Total | | 1.32 | 0.40 | Total | 1.60 | 0.50 | Total | 1.46 | .462 | 1.32 | 0.40 |

Table 2. Table of average statistics.

| Source | Type III sum of squares | *df* | Mean square | *F* | Sig. | Partial eta squared |
|---|---|---|---|---|---|---|
| Corrected Model | 6.975[a] | 11 | 0634 | 51.375 | 0.00 | 0.96 |
| Intercept | 73.556 | 1 | 73.556 | 5959.799 | 0.00 | 1.00 |
| Shelf_Material | 0.609 | 1 | 0609 | 49.367 | 0.00 | 0.68 |
| Filament_Material | 3958 | 2 | 1979 | 160.333 | 0.00 | 0.93 |
| Fill | 1190 | 1 | 1190 | 96.413 | 0.00 | 0.81 |
| Shelf_Material * Filament_Material | 0.026 | 2 | 0013 | 1040 | 0.37 | 0.08 |
| Shelf_Material * Fill | 0.088 | 1 | 0088 | 7157 | 0014 | 0.24 |
| Filament_Material * Fill | 0.896 | 2 | 0448 | 36.292 | 0.00 | 0.76 |
| Shelf_Material * Filament_Material * Fill | 0.024 | 2 | 0012 | 0.990 | 0.39 | 0.08 |
| Error | 0.284 | 23 | 0.012 | | | |
| Total | 81.923 | 35 | | | | |
| Corrected Total | 7259 | 34 | | | | |

[a] $R^2$ = 0.961 (adjusted $R^2$ = 0.942).

## Solid Finite Element Analysis

Samples tested for 7 d were modeled in the SolidWorks finite element analysis (FEA) program and subjected to the same load. Deformation ranges were similar to the actual tests. Pins made of ABS filament deflected 0.959 mm in MDF shelves at 30% fill, 0.959 mm in PB shelves, 1.03 mm in MDF shelves at 40% fill, and 1.35 mm in PB shelves, 1.72 mm in Fig 10.

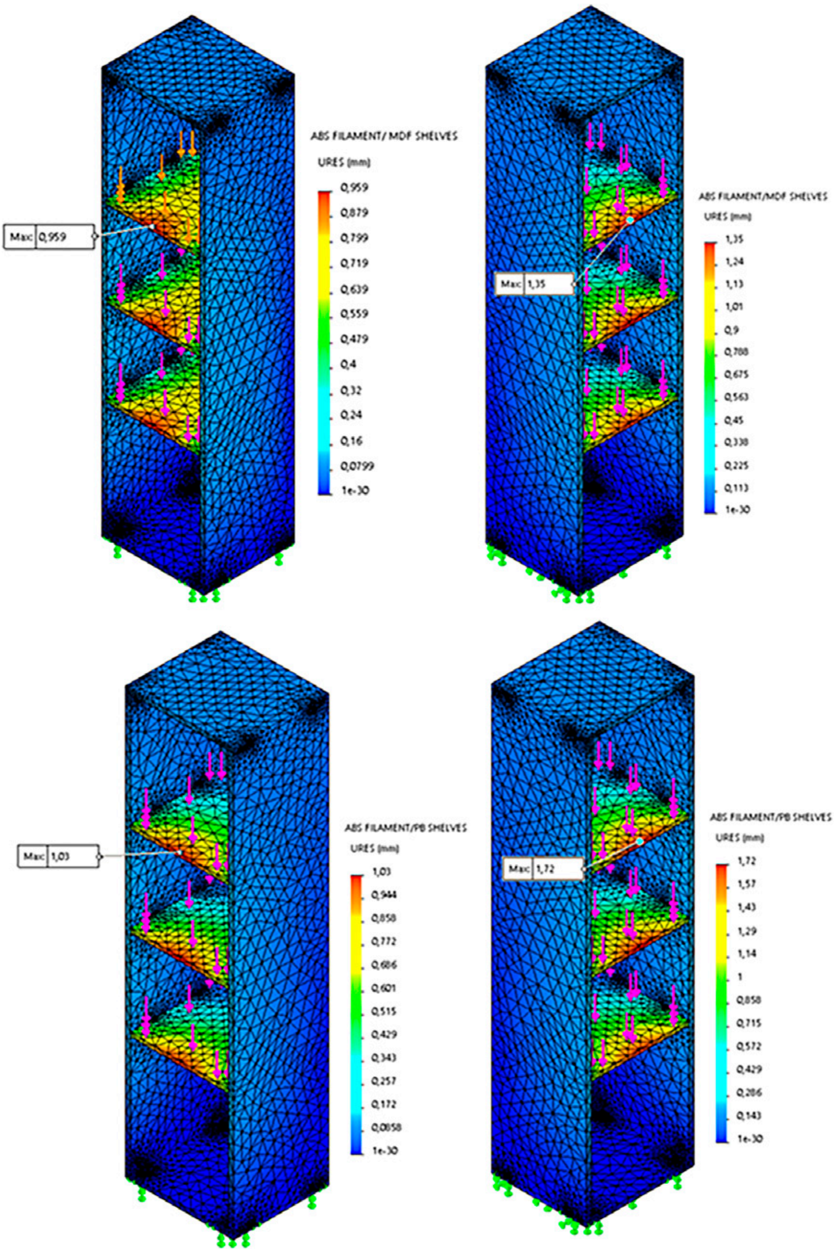


Figure 10. FEM analysis results show load–deflection of shelves with ABS pins.

Pins made of PLA filament gave a deflection of 1.65 mm in MDF shelves at 30% fill, 1.65 mm in PB shelves, 1.83 mm in MDF shelves at 40% fill, and 1.78 mm in PB shelves; 1.94 mm in Fig 11.

Pins made of PLA-WOOD filament deflected 1.40 mm in MDF shelves at 30% fill compared with 1.10 mm in PB shelves, whereas those at 40% fill deflected 1.37 mm in MDF shelves and 1.14 mm in PB shelves (Fig 12).

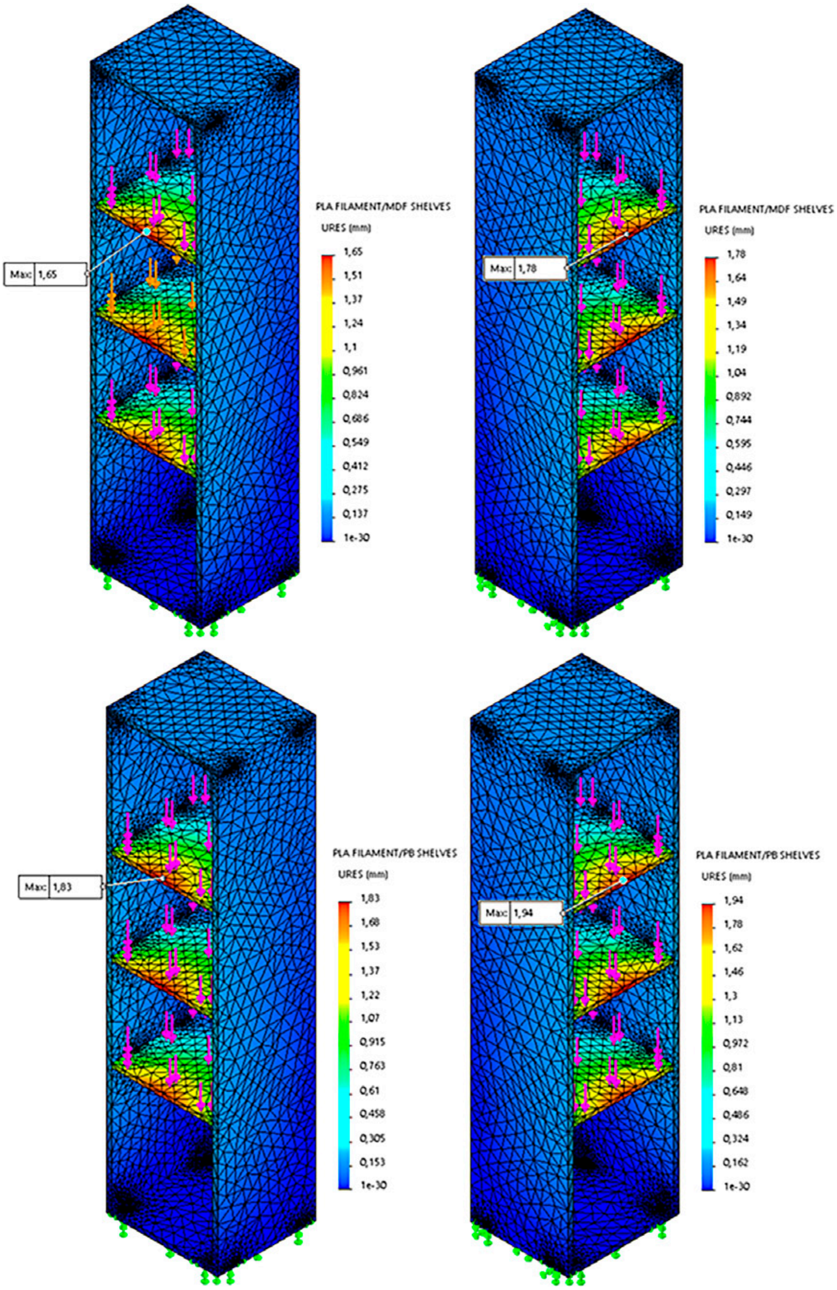


Figure 11. FEM analysis results show load–deflection of shelves with PLA pins.

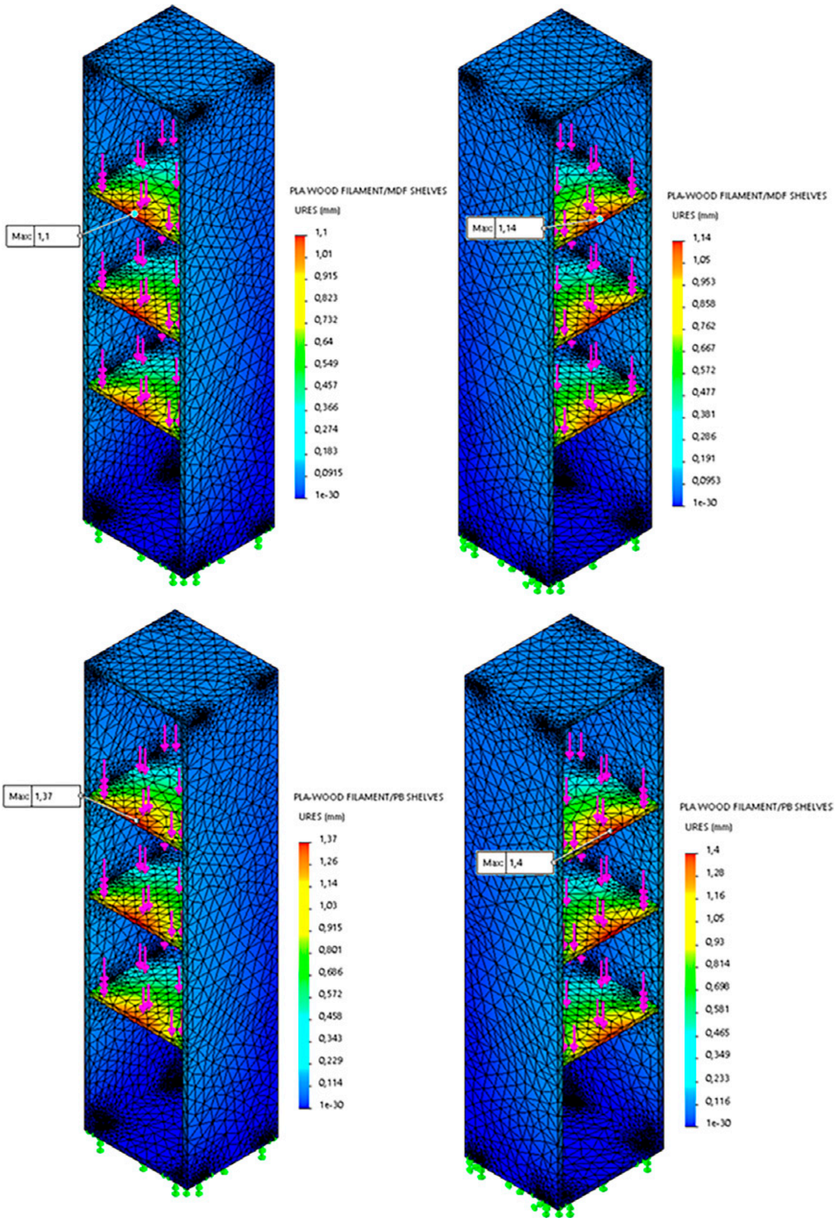


Figure 12. FEM analysis results show load–deflection of shelves with PLA-WOOD pins.

Emerging technology allows pins to be reverse-engineered to optimize properties for specific applications. For example, Koprnicky et al (2017) evaluated an upper extremity prosthesis made with 3D printing technology including bionic hands. Yildirim et al (2019) determined the effect of biscuit-type joining elements produced in 3D printers on the bending moment. Strength is targeted in "L" type corner joints. For this purpose, 18-mm thick MDF-lam, wood-based biscuits of ABS, or PLA were produced with a 3D printer.

The least amount of deflection in the current study was observed with ABS filament, followed by

PLA-WOOD and PLA. Zhang et al (2019) reported that ABS filament was more durable, while Ayrilmis (2018) noted that WOOD PLA was more durable than PLA. Assembly pins of ABS, PLA, and PLA-WOOD materials were produced with 30% and 40% saturation levels. Saturation level directly affected pin mechanics, which is consistent with the findings of Pandzick et al (2019). Finite element method (FEM) has been used in many fields, such as healthcare, construction, and automotive applications to optimize materials before actual production. The numerical modeling of 3D-printed natural fiber-reinforced plastic composites is still in its infancy, which underlines the need for further research. For example, Nagib et al (2023) evaluated a personalized polymeric 3D-printed, digitally planned surgical guide designed to achieve precision and predictability in nonstandard mini-implant orthodontic cases. The analysis was used to design a surgical guide for the placement of mini-implants as temporary crown supports. A FEM simulation was performed using Abaqus numerical analysis software. Finite element simulation revealed the maximum displacements and stresses in the surgical guide. Kuşkun et al. (2023) optimized the cross-sectional geometry for dowels created by 3D printing, and optimization supported by FEM analysis. Tankut et al (2008) determined the effects of various construction practices on the flexural properties of bookcases made of composite materials. They performed a deflection test on MDF and PB racks in 18 bookshelves using different fasteners. Each of the three cases was made for 1) determining the actual deflection of the leading edge of a shelf as a function of the reinforcement of the trailing edge; 2) evaluating the contribution of installing an intermediate shelf on the side walls to the bending of the walls; and 3) examining the effect of bezels on cheek deflection. The remaining six cases were used to investigate the effect of rack-to-sidewall joint stiffness on midspan rack deflection. The results of the study showed that the performance of existing designs could be improved by attaching the racks to the back of the chassis with screws, securely attaching the racks to the chassis edges, and increasing the chassis thickness, or MOE. The results showed that the PB material exhibited greater aberration, consistent with similar findings obtained using ANSYS software. These results are consistent with the findings of the present study.

## CONCLUSIONS

In the current study, the deflection values were directly proportional to the shelf and filament materials. Furthermore, deflection values were proportional to the filament material's fill content. MDF shelves were more durable under load than PB shelves. ABS pins experienced less deflection than those composed of PLA or PLA-Wood and would be recommended for shelves subjected to longer-term, heavier loads. Despite the presence of variables, the results indicated that shelves made of MDF were more durable under load than PB. Therefore, considering the typical loads encountered by shelves within cabinets during daily use, such as books, plates, detergents, etc., it is recommended to utilize MDF materials for enhanced durability. In the conducted study, the same load was uniformly applied for the same duration. Deflection values were recorded under conditions where ABS filament was utilized for both shelf materials, and it was found that deflection values were lower compared with those obtained using other filaments. ABS material pin fitting would be recommended for shelf construction for a longer duration of use. According to the experimental data, the deflection value of shelves supported by pins from ABS filaments was less than that of PLA and PLA-WOOD filaments. This result was also supported by the performed FEM analysis.

Accordingly, shelves can be simulated structurally under the actual realization of computer-aided analysis such as SolidWorks FEA for cost reduction and for the prevention of material damage likely to occur. The filament type used in the tests and the fill ratios of these filaments were 1.3261 for MDF shelf material and 1.6029 for PB material in the deflection test results. The results showed that the material type, filament fill, and filament material type were significant.

The adequacy of models was evaluated by the *R*-square ($R^2$) and adjusted *R*-square (adj-$R^2$) values. The results for these values were 96.1% and 94.2%, respectively.

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