Evaluation of 3D-Printed Pin Materials on the Deflection of Medium-density Fiberboard and Particleboard Shelves

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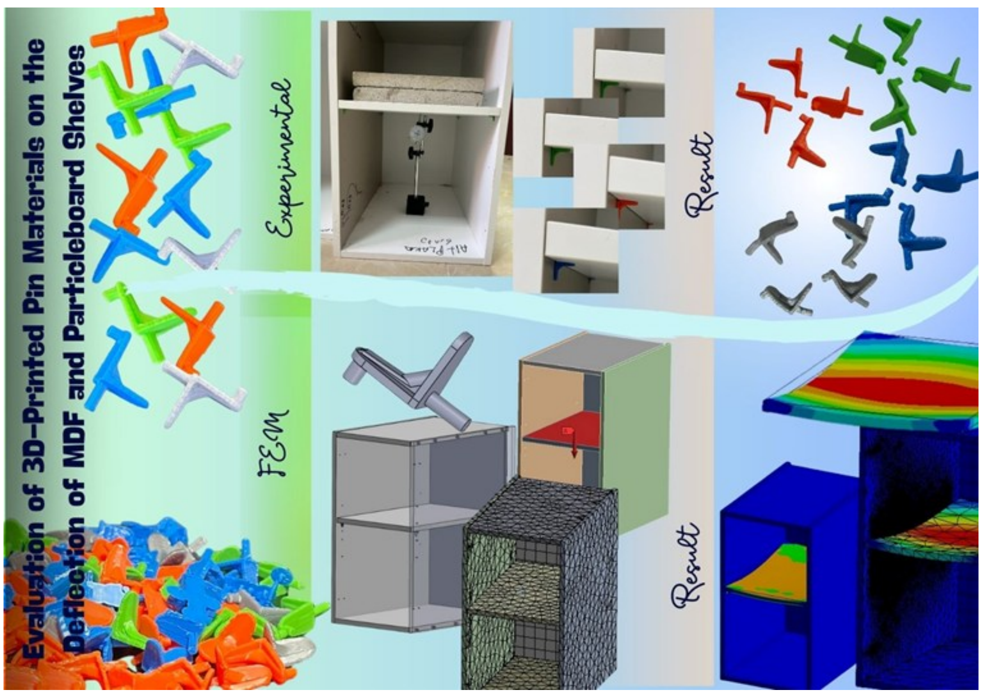
GRAPHICAL ABSTRACT



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Sedanur Seker *

The deflection behavior and safety performance were studied for medium-density fiberboard (MDF) and particleboard (PB) shelves reinforced with metal, polylactic acid (PLA), and polyethylene terephthalate glycol (PETG) pins. Experimental testing and finite element analysis (FEA) were used to assess the effects of shelf material, pin material, and filament color on the global mid-span deflection of the shelf, load capacity, and safety factors. Results indicated that MDF shelves exhibited lower deflection and higher load-bearing capacity than PB shelves, highlighting the importance of material density and homogeneity. Metal dowels provided the lowest deformation and highest safety factors for both shelf types, followed by PLA and PETG pins. Variations in filament color and pigment caused only minor differences in PLA pins, while finite element simulations closely matched the experimental results, confirming the reliability of computer-aided analysis for predicting deflection behavior and preventing material damage. Experiments conducted in accordance with BS EN 16122 (2012) and TS EN 9215 (2005) demonstrated that material and filament characteristics significantly affected deflection (R^2 = 96.1%, adjusted R^2 = 94.2%), and that MDF panels reinforced with high-strength, preferably metal, pins provide safe and durable shelf systems with a minimum safety factor of ≥ 2 to 3.

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Keywords: Shelf deflection; PETG; PLA; Safety factor; FEM; Coloured filament

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INTRODUCTION

Modular cabinet systems are widely used in indoor spaces, such as homes, offices, stores, and workshops, to improve organization and enable efficient storage. These systems are typically composed of prefabricated box-type furniture elements and are manufactured with different load-bearing capacities depending on their intended use (Mokhtar *et al.* 2025).

Shelves may deform due to the type of material used and the weight applied. Therefore, the design of shelf support systems is crucial. Shelves are typically supported by pins made of metal, plastic, or composite materials. While metal pins are produced through turning or pressing, plastic pins are made using injection molding or extrusion techniques (Eckelman 2003; Bas *et al.* 2024). The appropriate selection of pins is a key factor in maintaining the durability of the system. Accordingly, mechanical performance of shelving systems manufactured from different materials is commonly assessed through a combination of experimental testing and numerical approaches, including the Finite Element Method (FEM).

Denizli *et al.* (2003) demonstrated that shelf deflection resistance is significantly influenced by panel thickness, material type (*e.g.*, MDF, particleboard), and the choice of support systems. More recently, Erdinler *et al.* (2023) evaluated the impact of load and material density on the deflection performance of cabinet doors, reporting statistically significant findings. Slonina and Smardzewski (2022) conducted both experimental tests and finite element method (FEM) analyses on screw, nail, and eccentric connectors, revealing a high level of consistency between the two approaches. Similarly, Kłos and Langová (2023) found that screws offer superior deflection resistance compared to alternative fasteners. Eckelman (1987) and Eckelman *et al.* (2004) highlighted the long-term rigidity offered by mortise-and-tenon joints, while Cai and Wang (1993) successfully modeled semi-rigid corner joints using FEM, achieving high accuracy with minimal error margins. In another study, Yu *et al.* (2011) applied static and modal analyses through ANSYS to minimize design flaws in furniture joints. Chen and Kuo (2018) examined the relationship between shelf height and deflection, whereas Fariz *et al.* (2023) confirmed that a parametrically designed TV stand could safely support loads up to 100 kg. Zhang *et al.* (2024) improved computational efficiency by utilizing simplified FEM models for bamboo/oriented strand board (OSB) joint configurations. Li *et al.* (2022) performed a comparative analysis of mortise-tenon and dowel joints, and Matwiej *et al.* (2025) conducted stress and deformation simulations on upholstered furniture frames using FEM techniques. Furthermore, Kuskun *et al.* (2023) refined the design of auxetic dowels and reported that these fasteners exhibited enhanced performance compared to conventional fastening elements.

With the advancement of technology, many new materials have been integrated into production processes. In addition to applications in medical implants (Schubert *et al.* 2014), automobiles, and artificial organs (Ngoa *et al.* 2018), three-dimensional (3D) printing technology has increasingly been adopted in the furniture industry (Sun ve Zhao 2017). 3D printing offers numerous advantages, including design flexibility, waste avoidance, rapid prototyping capabilities, task-specific performance, lower material costs, lightweight construction, high-strength printed components, and the ability to produce complex and intricate geometries (Tofail *et al.* 2018; Islam *et al.* 2024). Various 3D printing technologies are available, including stereolithography (SLA), inkjet printing, and fused deposition modeling (FDM). Chacon *et al.* (2017) explored the impact of feed rate, build orientation, and layer thickness on the mechanical characteristics of PLA produced using affordable 3D printers. Upright samples showed lower strength due to interlayer failure, but increasing layer thickness improved strength, while higher feed rates reduced strength. Afrose *et al.* (2014) found that PLA printed in the X-direction had the highest tensile strength (38.6 MPa), while other orientations had lower values. Ymrak *et al.* (2014) reported mean tensile strength values of 28.5 MPa for acrylonitrile butadiene styrene (ABS) and 56.6 MPa for polylactic acid (PLA), accompanied by elastic moduli of 1807 MPa and 3368 MPa, respectively. PLA and ABS are among the most widely utilized filaments in fused deposition modeling (FDM) because of their satisfactory mechanical performance under diverse loading conditions. The ABS is generally characterized by its relatively high strength, whereas PLA is often preferred for its greater flexibility (Zhang *et al.* 2019). Moreover, combining these materials has been shown to produce components with increased strength and improved overall mechanical properties (Dizon *et al.* 2018). Yildirim *et al.* (2019) examined 3D-printed ABS and PLA dowels in fixed L-type furniture corner joints using diagonal compression tests. Dowels (8 mm diameter) were produced *via* FDM in both tangential and radial orientations. The MDF laminated panels coated with melamine paper were used, and joints were assembled with polyurethane adhesive. Moreover, the integration of such manufacturing technologies, along with the application of FEM simulations, has received increased attention in recent years.

Studies have shown that when 3D-printed shelf units are combined with topology optimization techniques, material usage can be significantly reduced without compromising structural integrity. For example, in a study conducted by Fenni *et al.* (2024), it was demonstrated that 3D-printed shelf consoles subjected to topology optimization using FEM-based static analysis achieved weight reductions of up to 70% while maintaining deflection resistance. Similarly, Gebrehiwot *et al.* (2024) investigated the bending stiffness of 3D-printed PLA stiffeners; it was determined that PLA parts exhibit higher bending moments compared to traditional miter joints but are not as durable as adhesive joints. These results highlight design considerations for the use of 3D-printed parts in load-bearing furniture components.

Aiman *et al.* (2020) conducted a comparative evaluation of furniture joints manufactured using conventional materials and production techniques *versus* those produced by FDM. The study concluded that joints fabricated from waste-based materials through FDM exhibited satisfactory functional performance and met acceptable quality standards. Several researchers have employed the FEM in theoretical studies aimed at optimizing object designs by eliminating stress concentration areas, thus minimizing the potential for operational failures (Santana *et al.* 2018; Kasal *et al.* 2023; Erdinler and Seker 2024).

In the furniture industry, shelving systems employ various joining techniques using materials such as plastics, metals, and composites. This study experimentally investigated the deflection response of particleboard (PB) and MDF shelves supported by pins manufactured using 3D printing technology and corroborated the experimental results using FEM simulations.

EXPERIMENTAL

Materials

Wood cabinet, shelves, and pins

Cabinets constructed from MDF and particleboard (PB), with overall dimensions of 800 mm (height), 600 mm (width), and 450 mm (depth), were randomly selected for inclusion in this study. The shelves installed in these cabinets were fabricated from MDF and PB panels with a thickness of 18 mm each. Testing was conducted on a total of 60 shelves, each representing one of the two material types. The measured density, moisture content (MC), modulus of rupture (MOR), and modulus of elasticity (MOE) values were 0.722 g/cm³, 7.02%, 29.48 N/mm², and 6130 N/mm² for MDF, and 0.65 g/cm³, 8.12%, 13.9 N/mm², and 5920 N/mm² for PB, respectively (Fig. 1).

In this study, MDF and PB shelves were mounted to cabinets using shelf pins. In shelving systems, the load-carrying capacity of the pins is typically more critical than the overall structural strength of shelves. The shelf pin configuration adopted (Fig. 2a) was chosen because it represents a design commonly employed by numerous manufacturers. These pins were redesigned using 3D printing technology and printed specifically for this study. The in-fill percentage of the 3D-printed shelf fastener was set to 50%. The filaments employed for the 3D printing process consisted of PLA and PET-G in two different colors and were supplied by a filament manufacturing company based in Turkey (Porima Polymer Technologies Inc., Yalova, Turkey), as illustrated in Figs. 2c and 2d. Samples used in the study were designed in the SolidWorks design program, and the designs saved in STL format were printed using the Creality K1 MAX device after G code assignment was made with the Creality Print 6.0 program (Fig. 2b).

Fig. 1. Representative MDF and PB shelves used in the experiments, illustrating cabinet dimensions and side-view configurations of the shelf specimens

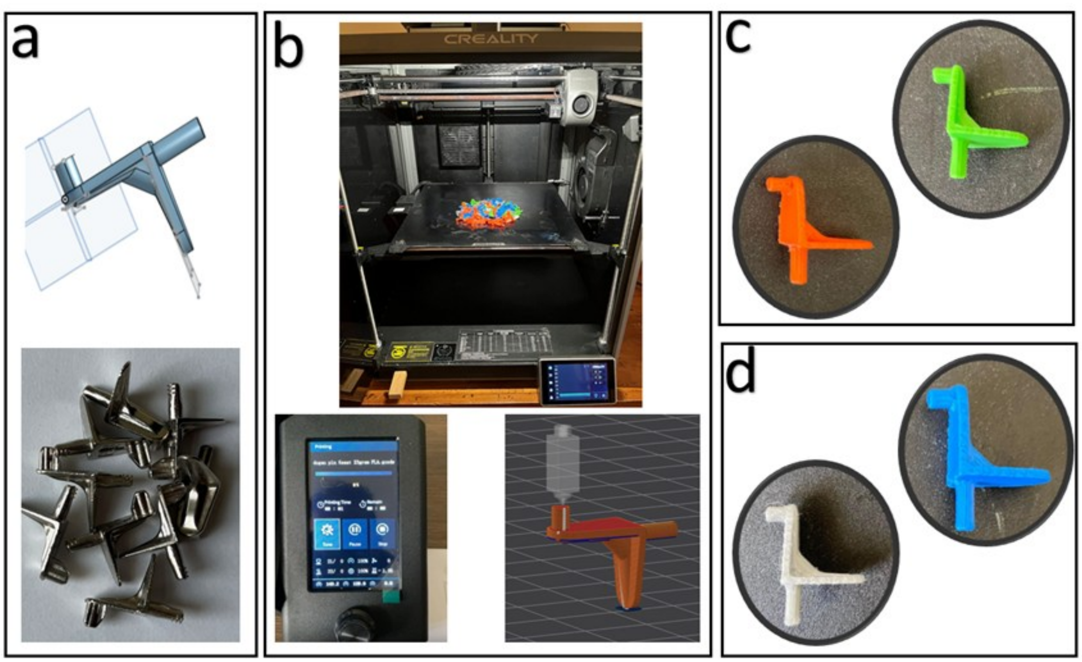

Fig. 2. Preparation of the samples: a. the pin from which the sample was taken, b. the sample pin ready for printing, c. green and orange pins produced from PLA material, d. blue and gray pins produced from PETG material

The primary objective of this study was to examine the behavior of different colors of various filament materials; thus, the 3D printer machine settings were kept constant, as shown in Table 1. The parameters that differ for PET-G and PLA filaments are also presented in Table 1.

Table 1. FDM Parameters Constant During Process

Parameters	Values	
	PETG	PLA
Layer Height	0.2 mm	
Nozzle Diameter	0.4 mm	
Printing Speed	60 mm/sn	
Outer Shell Peed	200 mm/sn	
Inner Shell Peed	300 mm/sn	
Infill Speed	250 mm/sn	
Pattern	Monotonic	
Nozzle Temperature	260 °C	200 °C
Plate Temperature	65 °C	50 °C
Bottom Top Layers	3 Layers	
Support	Tree (manual)	

Test Method for Shelves

The experimental procedures were carried out in accordance with BS EN 16122 (2012), and TS EN 9215 (2005) was followed to determine the shelf deflection under progressively increasing loads. A test load of 80 kg/m² was applied for each 40 mm increment of the shelf length and sustained for a duration of 7 days, resulting in a total applied load of 12.8 kg. Because of the use of new materials that did not correspond to the glass, metal, or plastic categories specified in the standard, the test was performed twice. All tests were conducted under controlled laboratory conditions in accordance with ISO 554, at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 %. The total deflection was measured at the end of the 7-day loading period. The visual documentation of each test conducted in accordance with the experimental design is presented in Table 2.

Table 2. Experimental Configurations and Visual Documentation of Shelf Deflection Tests

Material	Colour	Number of Samples	Test Level
PLA	Green	24	7 day
	Orange		
PET-G	Blue		
	Grey		
Metal	Sılver	12	

The initial deflection values were recorded at the midspan of the shelves prior to loading, followed by additional measurements after the application of a uniformly distributed load. The central deflection was determined using a deflection fitted with a comparator (Devotrans digital indicator) with a measurement accuracy of 0.001 mm. All measurements were conducted at the midpoint of the shelf length, corresponding to the location of the maximum deflection (Fig. 3). Under sustained loading conditions, wood and wood-based materials exhibit time-dependent viscoelastic behavior, manifested through distinct creep phases. This creep response is typically classified into three stages: primary creep, characterized by a rapid initial deformation that gradually decreases; secondary creep, marked by an approximately constant deformation rate; and tertiary creep, which involves an accelerated deformation process that ultimately leads to failure (Han *et al.* 2022). Although the applied weights were dimensionally rigid, they were used in accordance with the standard test setup and arranged to ensure a quasi-uniform load distribution over the shelf surface. Local contact effects were assumed to be negligible with respect to the global mid-span deflection, which governed the structural response evaluated in this study.

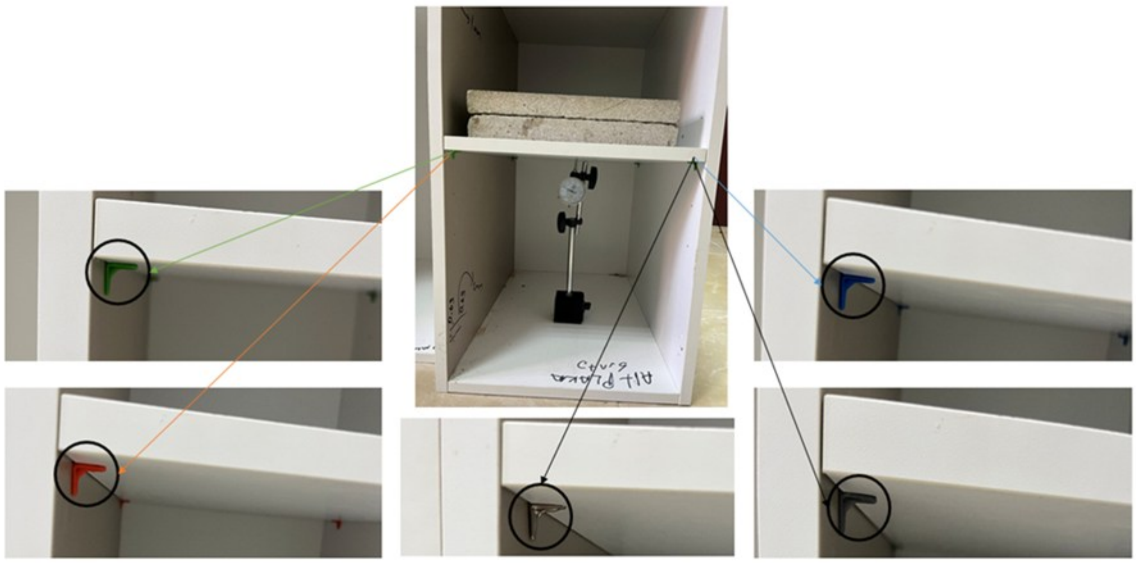

Fig. 3. Illustrating the shelf loading arrangement, the comparator utilized for deflection measurement, and the positioning of the pin samples

The collected data were analyzed using multivariate analysis of variance (ANOVA) tests. After identifying statistically significant differences among the groups, univariate analyses were conducted to ascertain the differences between the mean values, with the significance level set at $\alpha = 0.05$. All statistical analyses were performed using the SPSS 31.0.0.0 2023 software.

In the final phase of the study, all components of the specimens, including the cabinet, shelves, and pins, were three-dimensionally modeled and assembled using SolidWorks design and assembly software (Fig. 4a). The models were developed to replicate the experimental conditions, and numerical analyses were subsequently performed using the FEM in ANSYS Workbench 21. The geometry, loading conditions, meshing process, and contacts of the shelves are illustrated in Fig. 4b. A triangular mesh structure, set at the maximum mesh density, was employed to evaluate different intervals. The MOR, density, MOE, and moisture content (MC) of the MDF and PB shelves were determined through laboratory testing, whereas the technical properties of the filaments were obtained from the manufacturer. These parameters were subsequently used to calculate the deflections of both shelf types (Fig. 4b). Additionally, the material strength under the applied loads and boundary conditions was evaluated using the safety factor method. A safety factor (SF) greater than 1 indicates that the structure is safe; an SF equal to 1 represents the limit state, and an SF less than 1 indicates an unsafe condition. The obtained results were interpreted to assess the compliance of the design with safety and performance criteria.

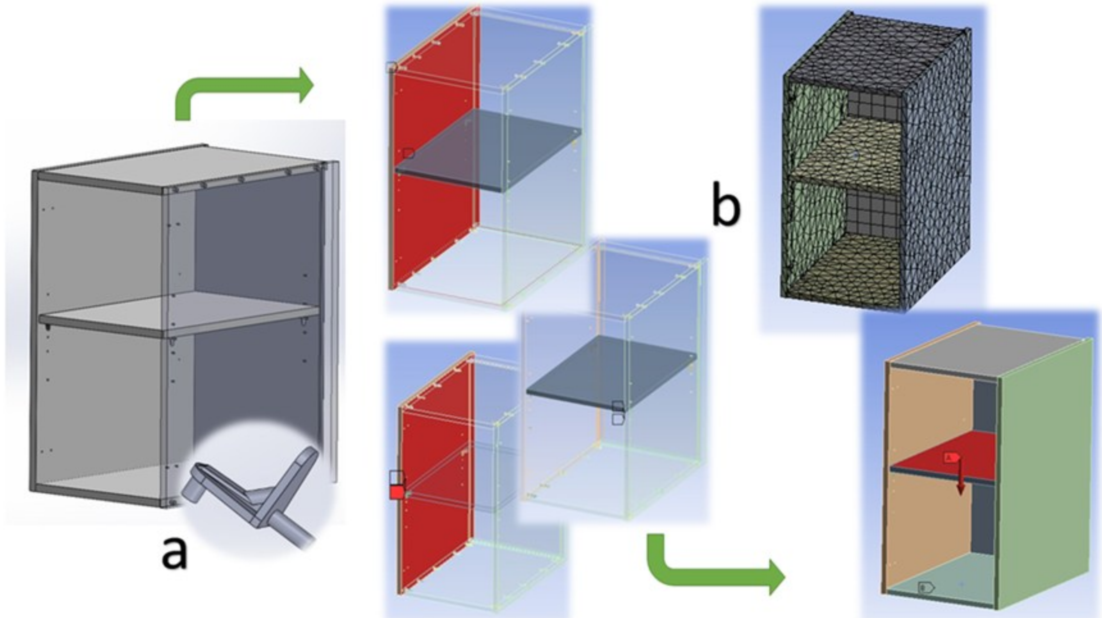

Fig. 4. 3D modeling and assembly of the samples: (a) complete model in SolidWorks, (b) shelf geometry, loading conditions, meshing process, and contacts

RESULTS AND DISCUSSION

In both material types (PB and MDF), the mid-span of the shelves and the regions where the pins were connected were identified as the most frequently damaged areas following the tests. During the testing process, standard loads were applied using pins produced from PLA (green, orange) and PETG (blue, grey) materials, and the deformations occurring in these regions were measured. The BS 16122 (2012) standard testing procedure was followed, and measurements were taken at 7-day intervals. After a 7-day loading period, distinct deflection responses were observed for the MDF and PB shelves. The findings indicate that the deformation levels varied depending on the type of pins used as fastening elements, and that differences in filament color and material type resulted in varying deformation behaviors (Fig. 5).

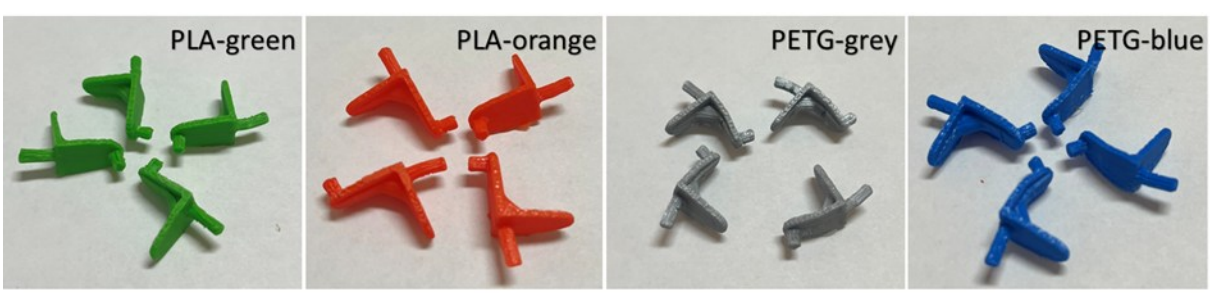

Fig. 5. Effect of pin material and filament color on shelf deflection of MDF and PB under long-term loading

According to the ANOVA results, the factors shelf material type, pin material type, and pin material color had statistically significant effects on deflection (deformation), and a Two-Way ANOVA was applied for these factors (Table 3). The analysis showed that metal pins produced the lowest deformation values for both MDF (0.7550 mm) and PB (0.8242 mm) shelf materials. Following metal pins, the group with the next lowest deformation values was the green PLA filament, with 0.7600 mm for MDF and 1.0500 mm for PB shelf material.

Table 3. Results of Two-way ANOVA for Deflection as a Function of Shelf Material and Pin Characteristics

MDF				PB				Total			
		Mean	SD			Mean	SD			Mean	SD
PETG	Grey	1.06	0.05	PETG	Grey	1.36	0.15	PETG	Grey	1.21	0.19
	Blue	1.40	0.05		Blue	1.70	0.10		Blue	1.55	0.17
	Total	1.23	0.19		Total	1.53	0.21		Total	1.38	0.25
PLA	Green	0.76	0.10	PLA	Green	1.05	0.05	PLA	Green	0.90	0.17
	Orange	0.89	0.02		Orange	1.30	0.10		Orange	1.09	0.23
	Total	0.82	0.09		Total	1.17	0.15		Total	1.00	0.21
Metal	-	0.75	0.01	Metal	-	0.85	0.02	Metal	-	0.80	0.05
	Total	0.75	0.01		Total	0.85	0.02		Total	0.80	0.05
Total	Grey	1.06	0.05	Total	Grey	1.36	0.15	Total	Grey	1.21	0.19
	Blue	1.40	0.05		Blue	1.70	0.10		Blue	1.55	0.17
	Green	0.76	0.10		Green	1.05	0.05		Green	0.90	0.17
	Orange	0.89	0.02		Orange	1.30	0.10		Orange	1.09	0.23
	-	0.75	0.01		-	0.85	0.02		-	0.80	0.05
	Total	0.93	0.24		Total	1.18	0.32		Total	1.06	0.30

SD: Standard deviation

Table 4. Mean Deflection Results for MDF and PB Shelves According to the Pin Material and Filament Color

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3.209a	9	0.357	73.287	< 0.001	0.962
Intercept	41.889	1	41.889	8610.67	< 0.001	0.997
Shelf material	0.623	1	0.623	127.971	< 0.001	0.831
Pin Material	0.000	0	.	.	.	0.000
Material Colour	0.459	2	0.229	47.169	< 0.001	0.784
Shelf material * Pin Material	0.000	0	.	.	.	0.000
Shelf material * Material Colour	0.010	2	0.005	1.004	0.380	0.072
Pin Material * Material Colour	0.000	0	.	.	.	0.000
Shelf material * Pin Material * Material Colour	0.000	0	.	.	.	0.000
Error	0.126	26	0.005			
Total	44.018	36				
Corrected Total	3.335	35				
R^2= 0.962 (adjusted R^2 = 0.942)						

The statistical results of the mean deflection values obtained for the variables shelf material, pin material, and pin material color are presented in Table 4.

Following the significant ANOVA result, *post-hoc* tests were conducted to determine which material types accounted for the differences. The Tukey HSD results showed that the METAL (M = 0.804), PLA (M = 1.002), and PET-G (M = 1.383) groups were placed in separate homogeneous subsets, indicating that all three material types differed significantly from one another ($p < 0.05$). The lowest value was observed in the METAL group, whereas the highest value was found in the PET-G group. The Duncan test also supported these findings. (Table 5).

Table 5. Table of *Post-hoc* Tests

Post-hoc Tests	Pin Material	N	Subset		
			1	2	3
Tukey HSD a,b	METAL	12	0.8042		
	PLA	12		1.0017	
	PET-G	12			1.3833
	Sig.		1.000	1.000	1.000
Duncan a,b	METAL	12	0.8042		
	PLA	12		1.0017	
	PET-G	12			1.3833
	Sig.		1.000	1.000	1.000
a. Uses harmonic mean sample size = 12, b. Alpha = 0.05					

The specimens tested under a 7-day loading period were reproduced in the ANSYS finite element analysis (FEA) environment and analyzed under identical loading conditions. The resulting deformation ranges showed close agreement with those obtained from experimental tests.

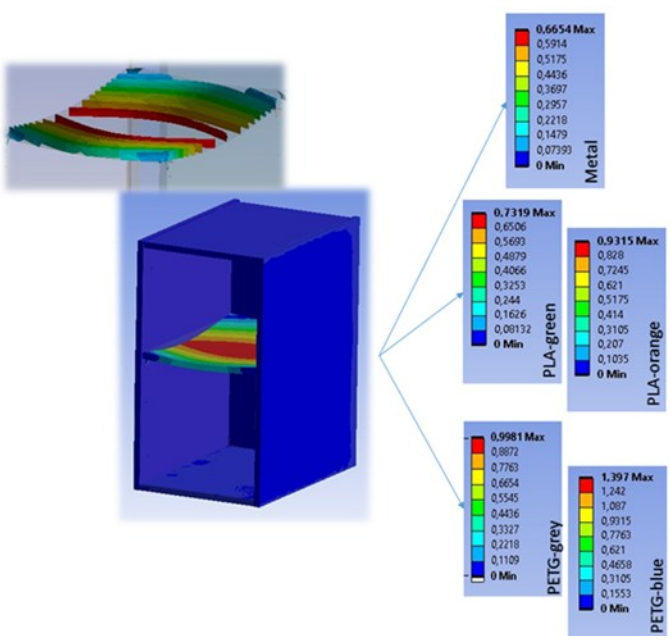

Fig. 6. Finite element analysis results showing the effect of the pin material–MDF interaction on the load–deflection behavior

The static load analysis performed on the four pins supporting the cabinet shelf was found to be consistent with the experimental results. For MDF shelves, the maximum deformation observed in PLA pins was 0.73 mm for PLA Green and 0.93 mm for PLA Orange. Although PETG materials possess higher stiffness compared to PLA, they exhibited greater deformation, with PETG Grey and PETG Blue reaching 0.99 mm and 1.39 mm, respectively. Metal pins, in contrast, demonstrated the lowest deformation at 0.66 mm, reflecting minimal displacement due to the material's high elastic modulus. These variations can be attributed to the interaction between the pin material and the MDF substrate, where differences in load transfer efficiency, stiffness, and material brittleness affect the overall deformation behavior (Fig. 6).

For PB shelves, the maximum deformation observed in PLA pins was 1.03 mm for PLA Green and 1.29 mm for PLA Orange. The PETG pins exhibited deformations of 1.26 mm for PETG Grey and 1.79 mm for PETG Blue, despite their higher stiffness relative to PLA. Metal pins showed the lowest deformation at 0.83 mm. The increased deformations compared to MDF shelves can be attributed to the lower density and heterogeneity of particleboard, which reduce its load-bearing capacity and result in greater deflection under identical loading conditions. The differences in pin material properties and the interaction with the PB substrate further influence the overall deformation behavior (Fig. 7).

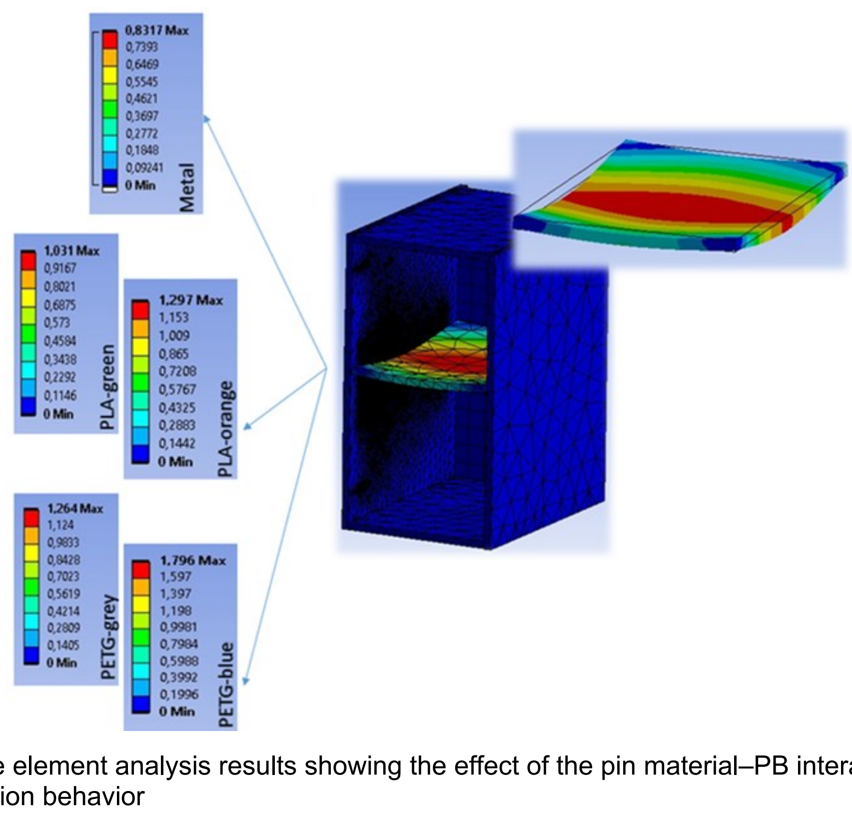

Fig. 7. Finite element analysis results showing the effect of the pin material–PB interaction on the load–deflection behavior

The SF analysis results revealed that PB and MDF exhibited significantly different safety performances depending on the type of pin used. In shelves with PLA pins, PB panels displayed extensive yellow–orange zones in central regions due to their lower strength, with safety factors approaching critical values, whereas MDF shelves showed reduced stress but SF remained at limited levels in central areas. For gray PETG pins, safety factors decreased further in PB panels compared to PLA, increasing structural risk, while MDF panels maintained moderate but acceptable safety performance.

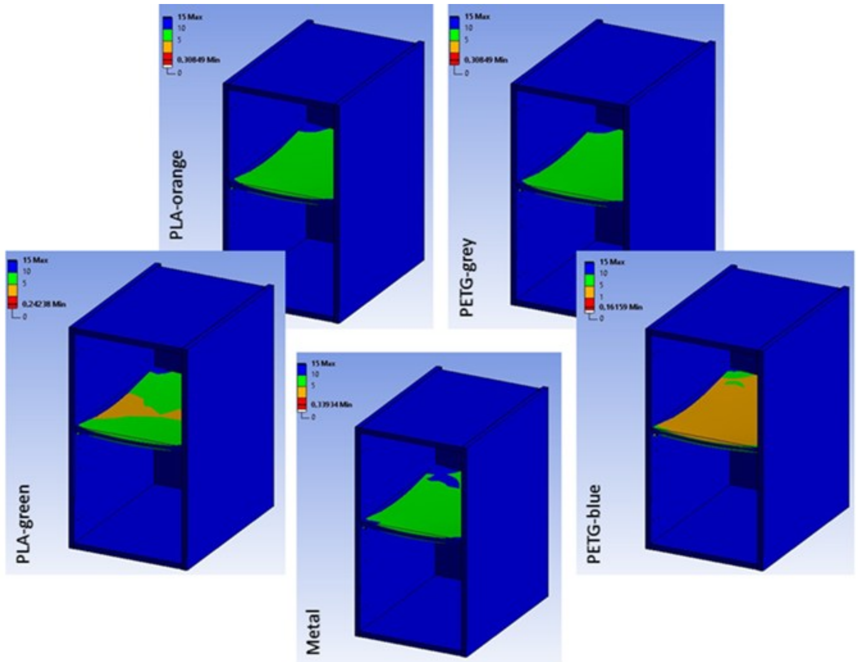

Fig. 8. The FEM analysis results illustrate the load–deflection behavior of the MDF shelves with different pin types, taking into account the corresponding safety factor distributions

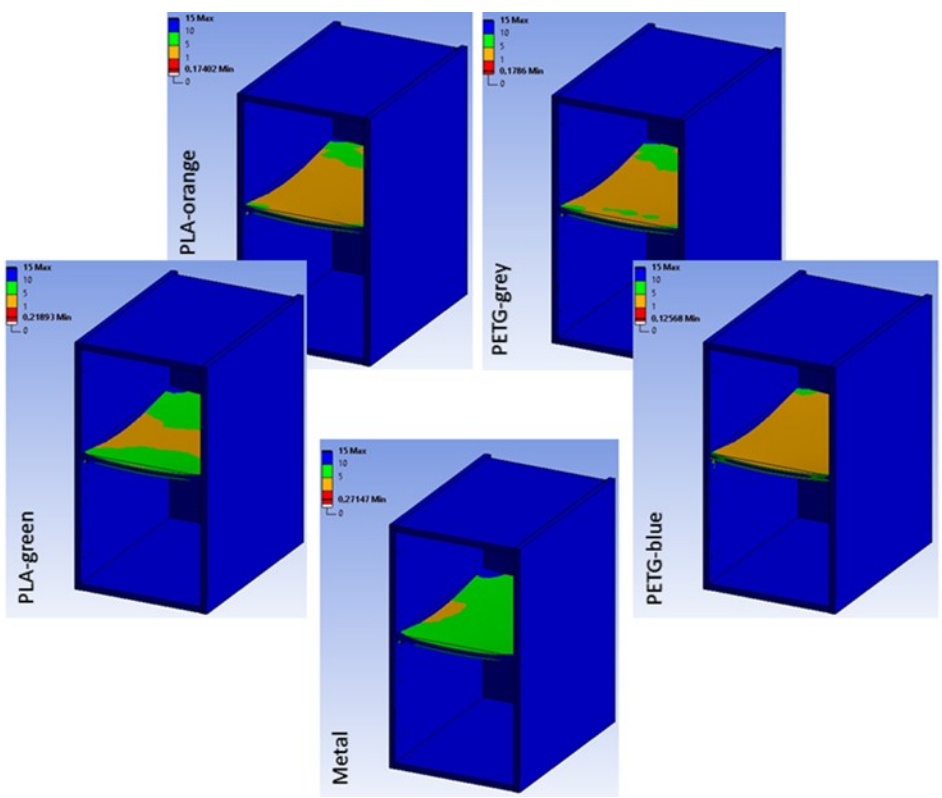

Fig. 9. The FEM analysis results illustrate the load–deflection behavior of the PB shelves with different pin types, taking into account the corresponding safety factor distributions

Blue PETG pins resulted in the lowest safety factors for both PB and MDF shelves, indicating higher stress concentration and notable structural risk. In contrast, metal pins provided the highest SF distribution in both shelf materials, particularly in MDF panels with extensive green zones demonstrating safe structural behavior, while PB panels exhibited only limited local stress regions. Overall, evaluating the interaction between shelf and pin materials revealed the following safety performance ranking: metal pin > green PLA > orange PLA ≈ gray PETG > blue PETG. This indicates that pin selection is critical, especially for lower-strength PB materials (Figs. 8, 9).

The PLA pins exhibited lower deformation values compared to PETG pins. This finding is consistent with numerous international studies indicating that PLA has a higher elastic modulus than PETG. For instance, Travieso-Rodriguez *et al.* (2019) reported that PLA parts produced *via* FDM could reach an average elastic modulus of 2.7 to 3.2 GPa, whereas Budzinski and Federowicz (2025) reported values of 1.8 to 2.2 GPa for PETG. Similarly, Martins *et al.* (2024) indicated that PLA prints exhibit higher stiffness but lower ductility compared to PETG. In the current study, the small differences observed between PLA Green and PLA Orange are in line with studies reporting that pigment/color additives can influence the mechanical properties of polymers; Peloquin *et al.* (2023) demonstrated that pigment concentration can alter elastic modulus, yield strength, and fracture strain by 3 to 10%. Regarding the effect of shelf materials, MDF showed lower deformation and higher load-bearing capacity compared to PB, which is also consistent with recent findings on MDF and PB shelves supported by PLA, ABS, and WOOD-PLA pins (Erdinler and Seker 2023). This result aligns with multiple international studies on structural composite panels. Guan *et al.* (2019) reported that MDF exhibits significantly higher MOE and MOR values compared to PB and provides a more stable stress distribution under load. Additionally, Ayrilmis (2007) found that MDF exhibits lower residual deflection under loading; this observation corresponds directly with the current findings, where MDF showed 15 to 25% less deformation than PB. In applications with metal pins, deformation occurs almost entirely in the shelf material, confirming a well-established principle in connection mechanics: highly stiff fasteners (steel pins, screws, inserts, *etc.*) no longer act as deformation sources, and the system behavior becomes dependent on the panel's internal structure (density distribution, internal bond strength, and stress concentration around the hole). Dorn *et al.* (2013) demonstrated that the ultimate capacity in connections with steel pins is determined by the panel, not the pin. Moreover, Kuskun (2024) reported a strong correlation between pin/screw withdrawal capacity and panel density in both PB and MDF, noting that the panel becomes the weak link in the fastener–panel interface. Therefore, the very low deformation observed in metal pins, and because the limiting element is the shelf material in the current study, is fully consistent with the previous studies. Similarly, there are previous studies where MDF, due to its higher density and homogeneity, exhibits significantly higher joint strength compared to PB (Hu *et al.* 2023). The findings of Karatay *et al.* (2024) also indicate that MDF panels provide 16 to 92% higher mechanical strength than PB, and that joint performance is directly related to material density. Accordingly, the high safety factors observed in the metal pin + MDF combination in this study are consistent with the studies. Moreover, plastic pins with lower stiffness showed SF values approaching critical levels, suggesting that an SF of ≥ 2 to 3 is necessary for shelf design. In conclusion, ensuring safe and long-lasting shelf performance requires high-strength pins and, preferably, MDF panels, which is confirmed by both existing current study results.

CONCLUSIONS

The results of this study demonstrate that the selection of shelf and pin materials significantly affected deflection and safety performance. Experimental tests and finite element analyses revealed that the mid-span regions of the shelves and the pin connection points are the most critical areas. These findings highlight the importance of appropriate material and fastener selection for designers and manufacturers.

1. The data indicate that medium-density fiberboard (MDF) shelves exhibited significantly lower deflection and higher load-bearing capacity compared to particleboard (PB) shelves. This difference can be attributed to the higher density and homogeneity of MDF. Therefore, MDF shelves are recommended for applications requiring high mechanical strength and minimal deformation. In contrast, PB shelves, due to their lower density and heterogeneous structure, show greater deflection under identical loading conditions and may approach critical safety factor values. When PB shelves are used, design considerations, such as increased pin density or reinforcement in critical regions, should be implemented to mitigate deformation.
2. Metal pins consistently provided the lowest deformation and highest safety factors for both MDF and PB shelves due to their high elastic modulus and material strength. The PLA pins, particularly green PLA, demonstrated moderate performance and may be suitable for light to moderate load applications. In contrast, PETG pins, especially blue PETG, exhibited higher deformation and lower safety factors, likely due to their brittleness and interaction with the shelf substrate. Consequently, metal pins are strongly recommended for critical load-bearing applications, PLA pins can be used under lighter loads, and PETG pins should be applied with caution, particularly for lower-strength PB shelves.
3. Filament color and type produced minor but statistically significant variations in pin deformation, especially for PLA. Green PLA pins exhibited slightly lower deflection compared to other colors, suggesting that filament selection may provide an additional optimization factor in performance. Designers should consider filament properties alongside material choice when aiming for optimized shelf performance.
4. The mid-span regions and pin connection points were identified as the most vulnerable areas. Therefore, reinforcement in these regions or increasing pin density is recommended to minimize deflection and prevent material failure. Safety factor analysis indicated that metal pins combined with MDF panels provide the highest structural safety, whereas PB panels exhibited localized regions approaching critical safety limits. Designers should optimize load distribution and implement reinforcement measures to ensure structural reliability.
5. The adequacy of the simulation models was evaluated using R-square (R^2) and adjusted R-square (adj-R^2) values, which were 94.1% and 96.2%, respectively, demonstrating a high level of model reliability. The analysis showed that metal pins produced the lowest deformation values for both MDF (0.7550 mm) and PB (0.8242 mm) shelf materials. Following metal pins, the group with the next lowest deformation values was the green PLA filament, with 0.7600 mm for MDF and 1.0500 mm for PB shelf material. This confirms that the finite element models accurately predicted the deformation and stress distribution observed in experimental tests, reinforcing the value of computer-aided simulation in shelf design.

6. The high agreement between finite element method (FEM) simulations and experimental results demonstrates the reliability of computer-aided analysis for developing safe and durable shelf designs. The FEM allows for the simulation of interactions between shelf material, pin type, filament color, and loading conditions, enabling the identification of potential deformation zones and optimization prior to manufacturing. This approach offers significant advantages in reducing production costs and preventing material damage.

The findings suggest that high-strength pins, preferably metal, combined with MDF panels, provide a safe and durable shelving system. Material selection, pin type, and filament characteristics are critical design factors. Special attention to mid-span and connection areas enhances structural safety. These recommendations serve as a guideline for designing safe, long-lasting, and deformation-resistant shelving systems in furniture and storage applications.

Future studies may focus on optimizing the internal structure of additively manufactured shelf pins by varying infill ratios, infill patterns, and printing strategies. Such optimization could potentially enhance connector stiffness and load transfer efficiency without increasing material consumption. However, the present study deliberately employed a constant infill configuration to isolate the effect of pin material and ensure comparability with standardized furniture testing procedures. Subsequent research is planned to investigate the behavior of both connectors and adjacent wood material under load using numerical simulations. These studies provide deeper insights into material-dependent contact behavior and stress distribution and enable optimization of connector design.

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