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Prediction of screw withdrawal resistance for plywood laminated panels and sandwich panels

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Abstract: Sandwich panels are favorable materials for structural or non-structural components due to durability, lightness, and longevity in service life. This study aimed to predict screw withdrawal resistance of the plywood laminated medium-density fiberboard and particleboard, and sandwich panels. In predicting the screw withdrawal resistance, withdrawal load capacity, density, and withdrawal stiffness of the materials in each layer, screw penetration depth, and screw diameter were considered. Moreover, the screw withdrawal strength of the panels was examined. Screw withdrawal tests of panels were conducted according to TS EN 13446 standard. The test results showed a proportional correlation between the density and screw withdrawal strength of the panels. The highest screw withdrawal strength was obtained for sandwich panels made of plywood and medium-density fiberboard (12.51 MPa). Furthermore, the difference between experimental and predicted screw withdrawal resistance changed from 0.20% to 24.86%. Besides, there was no statistically significant difference between the screw withdrawal strength of the top and bottom face-laminated panels. The test results showed that both face laminated panels (sandwich panels) had higher screw withdrawal strength, density, and experimental and predicted screw withdrawal resistance compared to one face laminated panels.
Keywords: Screw withdrawal resistance, Screw withdrawal strength, Sandwich panels, Plywood, Medium-density fiberboard, Particleboard.

Kontrplak ile lamine edilmiş panel ve sandviç panellerin vida tutma direncinin tahmin edilmesi

Özet: Sandviç paneller dayanıklılığı, hafifliği ve servis hayatının uzun olması nedeniyle yapısal veya yapısal olmayan elemanlar için uygun malzemelerdir. Bu çalışmada, kontrplak ile lamine edilmiş MDF ve yonga levha panelleri ile sandviç panellerin vida tutma kapasiteleri tahmin edilmiştir. Bu malzemelerin vida tutma kapasiteleri tahmin edilirken, panellerin her bir katmanında bulunan kontrplak, MDF ve yonga levha malzemelerinin vida tutma kapasiteleri, yoğunluğu ve vida çekme rijitliği ile vida penetrasyon derinliği ve vida çapı dikkate alınmıştır. Ayrıca, panellerin vida tutma dayanımları da belirlenmiştir. Tüm testler TS EN 13446 standardına göre yapılmıştır. Deney sonuçları panellerin vida tutma dayanımları ve yoğunluğu arasında doğrusal bir ilişki olduğunu göstermiştir. Vida tutma dayanımı en yüksek olan panel kontrplak ve MDF kullanılarak hazırlanan sandviç panellerde elde edilmiştir (12,51 MPa). Çalışma sonuçlarına göre malzemelerin deneysel ve tahmin edilen vida çekme kapasiteleri arasındaki fark %0,20 ile %24,86 arasında değişmektedir. Bununla birlikte alt veya üst yüzü lamine edilmiş panellerin vida tutma dayanımları arasında istatiksel olarak bir farklılık olmadığı gözlemlenmiştir. Çalışma sonuçları, sandviç panellerin tek yüzü lamine edilmiş panellere göre daha yüksek vida tutma dayanımı ve yoğunluğu göstermektedir. Ayrıca, sandviç paneller için hem deneysel hem de tahmin edilen vida çekme kapasiteleri de tez yüzü lamine edilmiş panellerden daha yüksektir.
Anahtar kelimeler: Vida çekme kapasitesi, Vida çekme dayanımı, Sandviç paneller, Kontrplak, MDF, Yonga levha

1. Introduction

In governing the regulation and the environmental issues regarding energy consumption and resource depletion, materials with more durability, lighter, longer service life, less carbon footprint, and sustainability have been raised for structural application (Basha et al., 2022). Therefore, sandwich panels have increasingly become prominent in construction as structural or non-structural components. Sandwich panels consist of a face layer with high stiffness and durability, and a core layer with low density, thermal expansion, etc. (Lakreb et al., 2015). According to structural purposes, the core material may differ. Core material would be made of lighter material to propose acoustic isolation and thermal expansion or denser material to propose higher mechanical properties. The significant advantage of sandwich panels is their high stiffness/strength ratio to weight (Susainathan et al., 2017). On the other hand, the damage tolerance at the low-velocity impact is the major drawback of the sandwich panel due to fiber breakage, delamination, etc. (Basha et al., 2022).

Lakreb et al. (2015) stated that an increase in the number of core layers, correspondingly, an increase in layers made of veneer, improved the mechanical properties of the sandwich panels, and most of the failure in bending occurred on cork agglomerate due to its low stiffness. Basha et al. (2022) highlighted that the fiber direction of the core material in regarding to those of the face material is crucial. However, the density and strength of the core material are less. Smardzewski (2019) studied sandwich panels with auxetic

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core and oval cells made of wooden honeycomb, resulting in the sandwich panels being considered a lightweight material and a better substitution compared to medium-density fiberboard (MDF) and particleboard (PB) in the furniture industry. Edgars et al. (2017) depicted that the strength-to-density ratios for sandwich panels were 60-80% higher than plywood, although they had less flexural strength than plywood. Peliński et al. (2020) stated that an increase in the thickness of outer layers improved the overall strength of the sandwich panels. Although material properties, layer thickness, and number of layers are vital for the sandwich panels, these materials would come together to construct a frame or walls for structural or non-structural purposes. Therefore, joinery systems have come into prominence, and screw-based joints are widely used joinery systems to join structural members.

Screw withdrawal resistance (SWR) is a significant mechanical property for wood-based structural materials due to the connection properties of the material. Besides, a designer should understand the fundamental design principals; namely, structural integrity and load-carrying capacity for connections of the wood-based structure should be maintained in service (Guo et al., 2018). SWR of the material depends on the density of the material, screw withdrawal orientation, screw type, screw diameter, screw threads, pilot hole diameter, and depth. Guo et al. (2018) examined the SWR of the conventional PB and oriented strand board (OSB) made of bamboo. They resulted that OSB had a higher SWS compared to PB due to different density, and an increase in screw diameter from 4 to 5 mm improved the SWR, but those of 5 to 6 mm reduced. In addition, an increase in pilot hole diameter adversely affected the SWS of the materials. Perçin and Uzun (2022) examined the effect of heat treatment on the SWR of laminated veneer lumber (LVL) reinforced with carbon fiber, and glass fiber. It was stated that an increase in temperature in heat treatment decreased the SWR of the LVL. However, SWR increased with the use of reinforcement, but there were no statistical differences to reinforce LVL with either glass-fiber or carbon-fiber. Birinci and Kaymakci (2023) ascribed that external weather conditions negatively affected the SWR of the plywood (PW), and there is no statistically significant difference between screwing samples before and after Freeze-Thaw Cycling.

Moreover, predicting SWR of materials have been studied. Eckelman (1975) predicted the SWR of the particleboards by considering density, internal bond strength, screw dimensions, and penetration depth. Conversely, Semple and Smith (2005) predicted the internal bond strength of PBs by using their SWR. Erdil et al. (2002) presented equations to predict the SWR of the PW and OSB from edge and face withdrawal; namely, the coefficient of determination in the expressions ranged from 0.57 to 0.78, so the prediction of the withdrawal resistance for wood-based composite material was somewhat variable. However, it could be acceptable in the design of screw-based joints. Pang et al. (2020) estimated the SWR of the hybrid cross-laminated timber (CLT) by using the SWR and density of the materials in each layer. They concluded that the differentiation between predicted and experimental values was around 13-14%. Darzi et al. (2018) defined ultra-light composite timber sandwich panels; namely, bamboo core sandwich and peeling core sandwich, to predict their strength and benchmarked their performance with commercial CLT by using finite element analysis.

This study aimed to predict the SWR of PW laminated MDF and PB panels. In doing so, the objectives were to (i) determine the screw withdrawal strength (SWS) of the PW, MDF, PB, and PW laminated panels and sandwich panels and (ii) predict the SWR of the PW laminated panels and sandwich panels.

2. Materials and methods

2.1. Materials

In this study, PW, MDF, and PB were used to determine screw withdrawal strength and predict the failure load of PW laminated panels and sandwich panels, respectively. For this purpose, the PW laminated MDF and PB panels and the sandwich panels were prepared by using PW with a thickness of 4 mm, MDF with a thickness of 12 mm, and PB with a thickness of 14 mm (Figure 1). Commercial PB, MDF and PW panels were obtained from local store in Bursa, Turkey. The nominal thickness of sandwich panels was different because of the core-materials. A DIN 7505 4.50 x 45 mm single threaded chipboard screw was used in the specimens (Figure 2). Polyurethane (PU) adhesive was used to glue layers.

(a) (b) (c)

Figure 1. Wood composite materials used in sandwich panels

Figure 2. Screws used in specimens

2.2. Specimen Construction

PW, MDF, and PB were cut into 600 mm by 600 mm dimensions. The panels were prepared with two and three layers, and 200 g/m^2 adhesive was used between layers. Cemil Usta SSP-180 T press was used with a temperature of 35 °C, a pressure of 4 atm, and a duration of 150 min.

According to TS EN 13446 (2002), all specimens (5 replications for each sample group) were cut into 50 mm by 50 mm nominal dimensions from all panels (Figure 3 and 4a). Pilot holes were drilled as of 80% of the major screw diameter, and specimens were constructed in which the entire tip of the screw protruded from the specimen (Figure 4b).

2.3. Density

According to TS EN 323 (1999), a total of 5 test specimens for each sample group with dimensions of *t* x 50x50 (*t* is the thickness of the panels in Figures 1 and 3) were prepared. All specimens were acclimatized at 20±2 °C and 65 ± 5% relative humidity according to TS-EN 326-1 (1999) and weighed with a 0.01 g precision scale. Their dimensions were measured with a 0.01 mm precision caliper. The density of the sandwich panels was calculated by using Equation 1.

$$\rho_{12} = \frac{m_{12}}{V_{12}} \quad (1)$$

where, ρ_{12} is the density (g/cm^3), m_{12} is the weight of the material (g), and V_{12} is the volume of the material (cm^3).

2.4. Screw withdrawal strength

All tests for the SWS were conducted on the SHIMADZU universal test machine according to TS EN 13446 (2002). Withdrawal load capacities were obtained by applying a withdrawal load parallel to the screw axis from the face of specimens with a rate of 2 mm/min and continued until the ultimate load reached (Figure 5). Equation 2 was used to calculate the SWS (σ, MPa) of panels.

$$\sigma = \frac{F_{max}}{2 \times \pi \times r \times d} \quad (2)$$

where, F_{max} is the ultimate withdrawal load (N), r is the radius of the screw (mm), and d is the penetration length (mm).

2.5. Statistical Analysis

Data collected for the presence of statistical significance among all sample groups through one-way ANOVA and Tukey pair-wise comparisons were examined in SPSS.

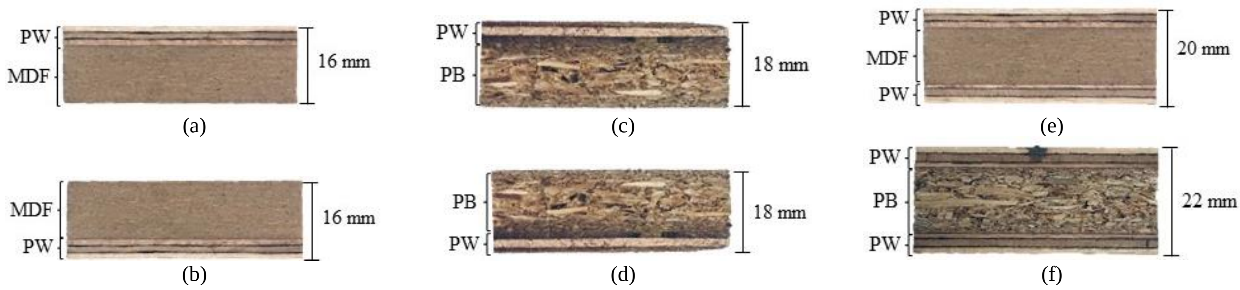

Figure 3. PW laminated panel; a) PW-MDF, b) MDF-PW, c) PW-PB and d) PB-PW, and sandwich panels; e) PW-MDF-PW and f) PW-PB-PW

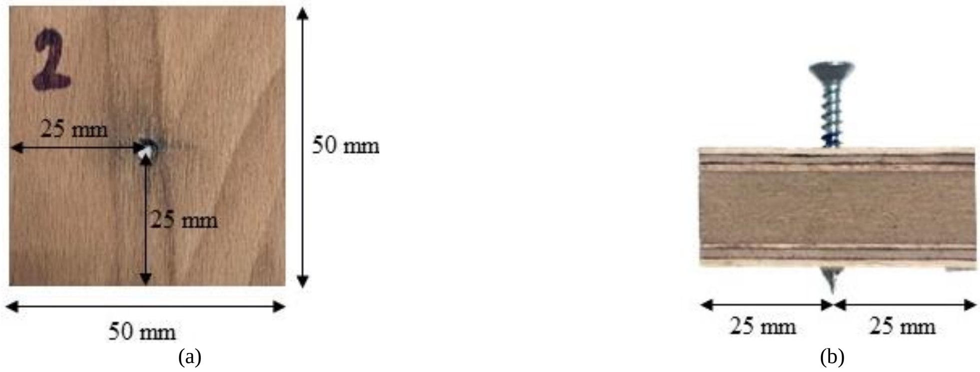

Figure 4. a) Pilot hole position on specimen and b) Specimens with tip protruding

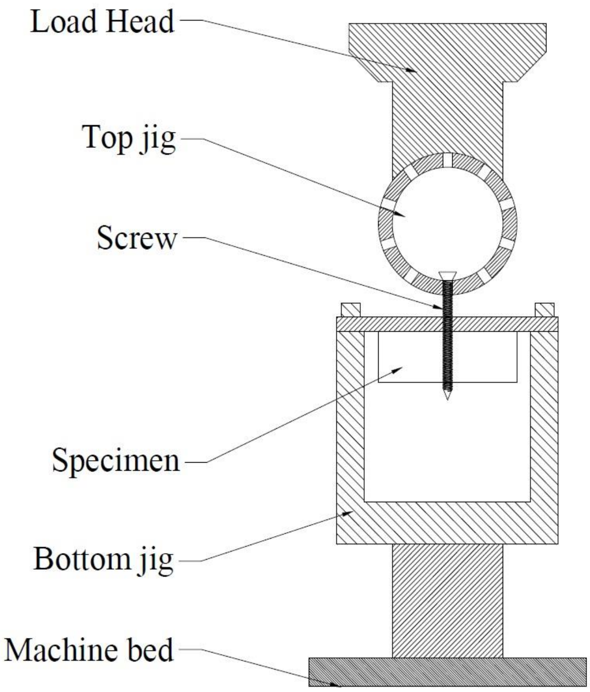

Figure 5. Test configuration for screw withdrawal strength from face

2.6. Prediction of screw withdrawal resistance

The screw withdrawal resistance of the sandwich panel was predicted by using Equation 3 (Pang et al., 2020). Although the equation was derived from hybrid CLT panels and screws were not protruded from specimens. However, screws were protruded from specimens, and sandwich panels consisted of two or three layers in this study. Therefore, the equation was revised by considering the total thickness of panels and the number of layers. Equations 4 and 5 were used for panels with two and three layers, respectively.

$$R_{predict} = min\left[\begin{matrix}\left(\frac{G_1 \times d_1}{G_2 \times d_2} + 1\right)\rho_2 \times 2 \times \pi \times r \times d_2\ , \\ \left(\frac{G_2 \times d_2}{G_1 \times d_1} + 1\right)\rho_1 \times 2 \times \pi \times r \times d_1\end{matrix}\right] \quad (3)$$

where $G_{1,2}$ are the withdrawal stiffness of the first and second layer materials used in panels (N/mm^3), $d_{1,2}$ are the depth of penetration for the first and second layer materials (mm), $\rho_{1,2}$ are the density of the material in the first and second layers (g/cm^3), r is the radius of the screw major diameter (mm - 4.5 mm).

$$R_{predict} = min\left[\begin{matrix}\left(\frac{G_{PW} \times d_{PW}}{G_{MDF,PB} \times d_{MDF,PB}} + 1\right)\rho_{MDF,PB} \times 2 \times \pi \times r \times d_{SP}\ , \\ \left(\frac{G_{MDF,PW} \times d_{MDF,PB}}{G_{PW} \times d_{PW}} + 1\right)\rho_{PW} \times 2 \times \pi \times r \times d_{SP}\end{matrix}\right] \quad (4)$$

$$\sigma R_{predict} = min\left[\begin{matrix}\left(\frac{2 \times G_{PW} \times d_{PW}}{G_{MDF,PB} \times d_{MDF,PB}} + 1\right)\rho_{MDF,PB} \times 2 \times \pi \times r \times d_{SP}\ , \\ \left(\frac{G_{MDF,PW} \times d_{MDF,PB}}{2 \times G_{PW} \times d_{PW}} + 2\right)\rho_{PW} \times 2 \times \pi \times r \times d_{SP}\end{matrix}\right] \quad (5)$$

where, d_{SP} is the screw penetration for the sandwich panels.

The withdrawal stiffness of the material was calculated by using the following equation;

$$G = \frac{F_{0.4} - F_{0.1}}{2 \times \pi \times r \times d \times (a_{0.4} - a_{0.1})} \quad (6)$$

where, $F_{0.4}$ is 40% of the ultimate failure load (N), $F_{0.1}$ is 10% of the ultimate failure load (N), $a_{0.4}$ is the deformation at the 40% of the ultimate failure load (mm), and $a_{0.1}$ is the deformation at the 10% of the ultimate failure load (mm).

3. Results and discussion

3.1. The screw withdrawal strength and the density

The results of the SWS and the density of the specimens were given in Figure 6. Results showed a correlation between SWS and density of materials but except MDF. Even though its SWS decreased compared to the SWS of the PW, it is denser compared to PW.

The highest average SWS was 12.51 MPa for the PW-MDF-PW panel with a standard deviation of 1.03 MPa. Then, the average SWS of the panels with top-face laminated MDF (PW-MDF) was 10.53 MPa with a standard deviation of 0.57 MPa. Those of PW-PB-PW were 9.36 MPa and 1.41 MPa, respectively.

Moreover, in the case of the top-face laminated MDF and PB for panels with two layers, SWS was 19.93% and 9.88% higher compared to those of the bottom-face, respectively. SWS of the panels with MDF and PB laminated PW on the top-face increased by 45.64% and 104.35% compared to MDF and PB, respectively. The increase in those of the bottom face was 21.44% and 71.18%, respectively. Regarding panels for both laminated faces (sandwich panels), SWSs for PW-MDF-PW and PW-PB-PW were 73.03% and 139.39% greater compared to MDF and PB, respectively. Screws penetrate each of the plywood layers and core layer of MDF/PB in screwing in face orientation, so screw treads held in each layer in the panel, and SWS was enhanced by an increase in the number of layers (Birinci and Kaymakci, 2023). Besides, failure on specimens in the screw withdrawal test occurred on the top-face of the panels, so the top-face laminated specimens had higher SWS compared to those of the bottom face.

One-way ANOVA was performed to examine the significant effect of the panel types on SWS (α=0.05). Besides, Tukey pair-wise comparison analysis was conducted to examine whether there was a significant difference among sample groups at the confidence level of 95%. According to statistical analysis, panel types (p-value = 0.000) significantly influenced the SWS of panels (Table 1). According to Tukey pair-wise analysis, there is no evidence to prove that the SWS of the PW-MDF-PW and PW-MDF were statistically different as shown in Table 2. Furthermore, the SWS of the PW-MDF, PW, PW-PB-PW, and MDF-PW cannot be proved to be statistically different. Moreover, the top face of MDF and PB laminated with PW and those of the bottom-face were not statistically different, respectively.

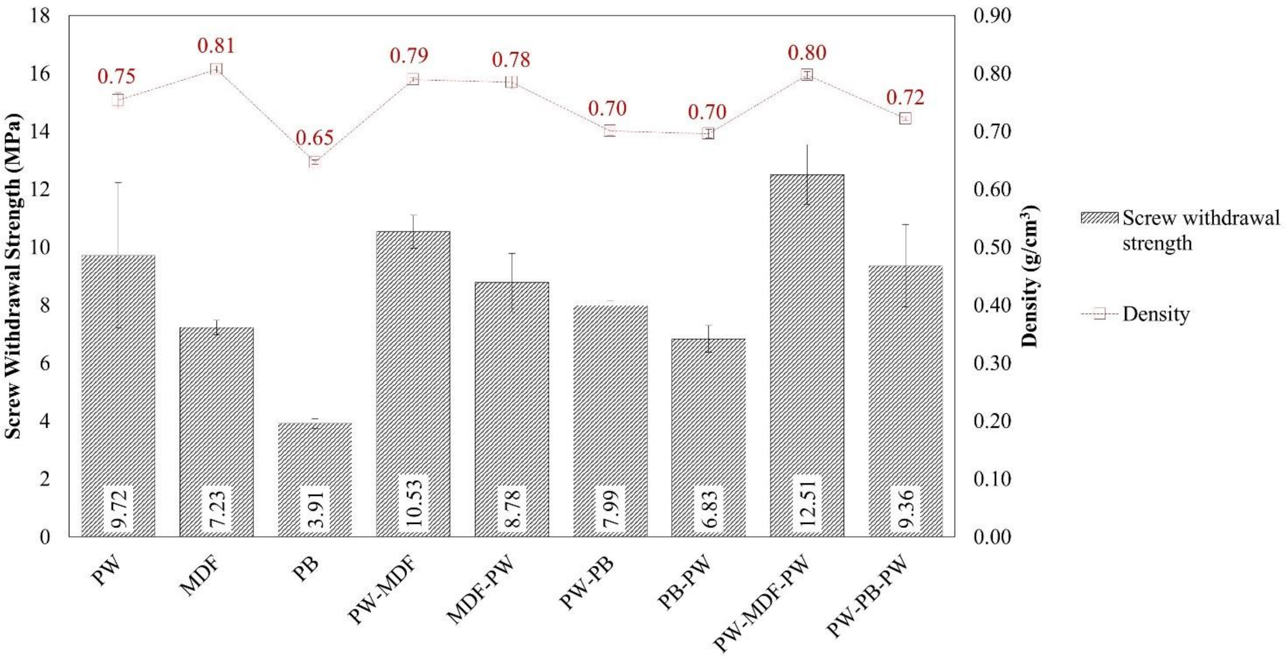

Figure 6. Screw withdrawal strength and density of the sandwich panels (PW: Plywood, MDF: Medium density fiberboard, PB: Particleboard, PW-MDF: Top face PW laminated MDF panel, MDF-PW: Bottom face PW laminated MDF panel, PW-PB: Top face PW laminated PB panel, PB-PW: Bottom face PW laminated PB panel, PW-MDF-PW: Sandwich panel with MDF core and PW-PB-PW: Sandwich panel with PB core

Table 1. One-way ANOVA for SWS of the sandwich panels

	Sum of squares	Degre of freedom	Mean square	F	Sig.
Between Groups	240.82	8	30.10	24.50	0.000
Within groups	44.23	36	1.23		
Total	285.05	44			

Table 2. Tukey mean comparison for SWS of the sandwich panels

Material	n	Mean	Grouping					
PW-MDF-PW	5	12.51	A					
PW-MDF	5	10.53	A	B				
PW	5	9.72		B	C			
PW-PB-PW	5	9.36		B	C	D		
MDF-PW	5	8.78		B	C	D	E	
PW-PB	5	7.99			C	D	E	
MDF	5	7.23				D	E	
PB-PW	5	6.83					E	
PB	5	3.81						F

3.2. Prediction of the screw withdrawal resistance

Table 3 shows the average and standard deviation of the ultimate screw withdrawal load and the withdrawal stiffness for PW, MDF, and PB. The load-deformation curves of PW, MDF, and PB were given in Figure 7 and used to calculate the withdrawal stiffness (G, MPa) of the specimens (Table 3).

By using equations 4 and 5, the SWR of the panels with two layers and three layers were predicted in columns a and b (Table 4). In column c (Table 4), the minimum predicted SWRs of the panels in either column a or b were compared with the experimental values of the SWR. According to the results, the ratios between predicted and experimental values varied from 0.20% to 24.86%. It does not matter which face was laminated for MDF and PB because the predicted SWR for panels with two layers was obtained by using the experimental SWR and the density of the materials with a single layer (Pang et al., 2020). Hence, the predicted SWR of the PW-MDF and MDF-PW (2163.62 N) and PW-PB and PB-PW (1515.77 N) were identical. The highest predicted SWS was 3303.64 N for PW-MDF-PW and differentiated from 1.66% to 14.74% from the experimental values.

The density of the material is a characteristic of wood and wood-based products. Therefore, it is quite significant to predict SWR of the panels. In addition, difference in density profile for materials may causes higher differentiation in the prediction of SWR of panels. Besides, withdrawal stiffness of the material used in layers obviously affected predicted SWR of panels. In the case of that the number of layers penetrated by the screws in single- or both face laminated panels decreased (from 3-7 layers to single layer), test values in SWRs were higher than predicted values (Pang et al., 2020). In this study, specimens were screwed with tip protruding, so predicted values were mostly higher than test values. Furthermore, if the density and the withdrawal stiffness of material in the top layer was higher than those of core or bottom layers, differences between test and predicted values were higher (PW-PB, PB-PW and PW-PB-PW sample groups in Table 4). It was resulted that the estimation of the SWR panels made of core material with a low-density and withdrawal stiffness would be higher than test values. On the other hand, it would provide a sight to estimate SWR of panel with high-withdrawal stiffness utilizing for structural purposes.

The SWRs of PW, PB and MDF in Table 3 were benchmarked those SWRs in various studies (Table 5). The SWR increase with an increase in penetration depth and screw diameter. SWR of the materials used in this study compensate results in literature. Moreover, results of the SWS for the veneer laminated panels (Popovska et al., 2019) and those of PW-MDF-PB and PW-PB-PW sandwich panels (Figure 6) were close to each other.

Table 3. Sample statistics for the SWR and the withdrawal stiffness of PW, MDF, and PB

Material	Ultimate screw withdrawal load (N)			Withdrawal stiffness (N/mm^3)		
	Average	SD	CoV	Average	SD	CoV
PW	602.19	165.21	27.43%	10.09	1.38	13.73%
MDF	1248.75	42.29	3.39%	13.87	1.84	13.29%
PB	708.13	28.59	4.04%	6.26	0.40	6.40%

SD: Standard Deviation and CoV: Coefficient of Variation

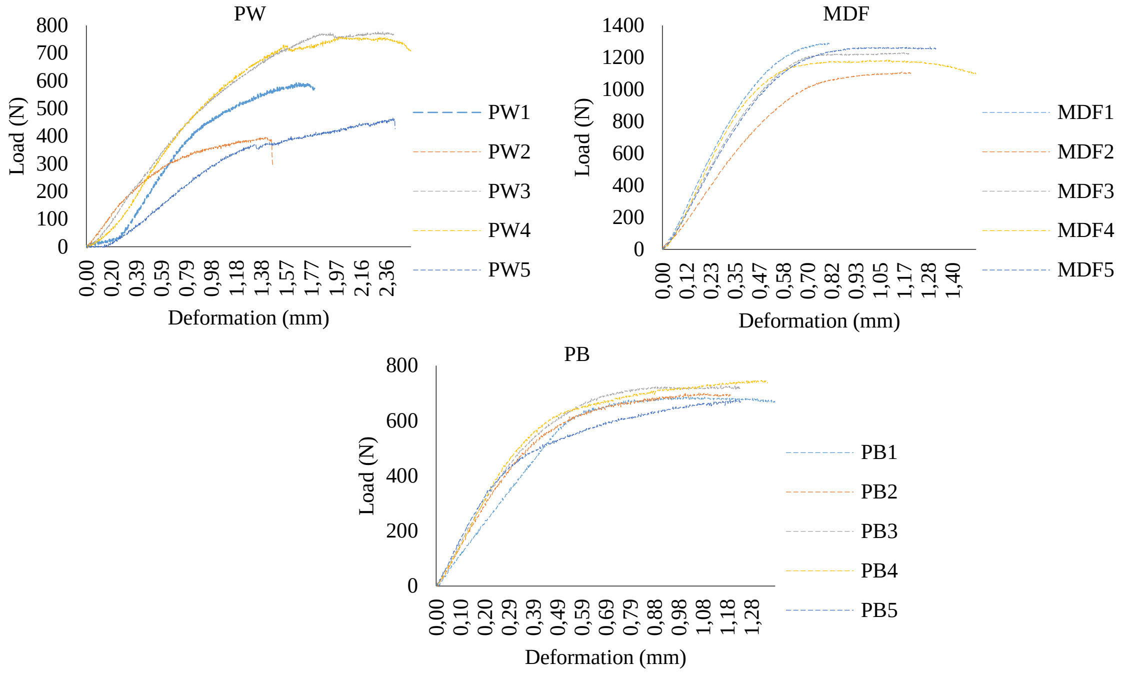

Figure 7. Load-deformation curves

Table 4. Results of the experimental and predicted SWR of panels

Material	Sample No	Ultimate SWR (N)	Predicted SWR (N)			Difference
			a*	b*	c*	
PW-MDF	1	2434.38	11061.56	2163.62	2163.62	11.12%
	2	2264.06				4.44%
	3	2353.13				8.05%
	4	2298.44				5.87%
	5	2492.19				13.18%
MDF-PW	1	2200.00	2163.62	11061.56	2163.62	1.65%
	2	1732.81				-24.86%
	3	1864.06				-16.07%
	4	2153.13				-0.49%
	5	2300.00				5.93%
PW-PB	1	1860.94	7019.60	1515.77	1515.77	18.55%
	2	1987.50				23.73%
	3	1939.06				21.83%
	4	1998.44				24.15%
	5	1904.69				20.42%
PB-PW	1	1518.75	1515.77	7019.60	1515.77	0.20%
	2	1782.81				14.98%
	3	1706.25				11.16%
	4	1498.44				-1.16%
	5	1778.13				14.75%
PW-MDF-PW	1	3562.50	8444.95	3303.64	3303.64	7.27%
	2	3359.38				1.66%
	3	3875.00				14.74%
	4	3812.50				13.35%
	5	3454.69				4.37%
PW-PB-PW	1	3084.38	5908.84	2551.83	2551.83	17.27%
	2	2673.44				4.55%
	3	2239.06				-13.97%
	4	2939.06				13.18%
	5	3206.25				20.41%

*a: First calculation in equations 4 and 5, b: Second calculation in equations 4 and 5, and c: Minimum of the a and b.

Table 5. SWRs of the materials in the various studies

Material		Penetration depth (mm)	Screw Diameter (mm)	SWR (N) Face	SWR (N) Edge	Test Standard	Reference
PW	Beech	12	3.5	1279	943	EN 13446	Birinci and Kaymakci (2023)
	Ozigo			726	563		
	Okoume			691	487		
	Larch	24	6.5	5430	-	KS F ISO 9087	Pang et al. (2020)
			8.5	6100	-		
	Larch	24	6.5	5426	-	KS F ISO 9087	Ahn et al. (2021)
			8	6100	-		
	Beech	10-	3.5	2265	1573	TS EN 13446	Yorur et al. (2017)
			4	2993	2096		
MDF		-	3.5	1048	335	TS EN 320	Yorur et al. (2020)
			4	1167	401		
			4	1149	1066	Undefined	Wolpiuk and Sydor (2016)
		15	6.3	1651	1620		
		15/19	3.8	1037	865	EN 320	Pour et al. (2022)
			4	1191	1106		
		16/28	3.5	658	893	TS EN 13446	Uysal et al. (2023)
		16/30	4.5	681	1052		
PB		10	4	548	254	EN 320	Guo et al. (2018)
			5	488	324		
			6	452	208		
		-	3.5	1007	476	TS EN 320	Yorur et al. (2020)
			4	1053	620		
			4	675	462	Undefined	Wolpiuk and Sydor (2016)
		15	6.3	964	724		
		16/28	3.5	495	675	TS EN 13446	Uysal et al. (2023)
		16/30	4.5	511	830		
Veneer Laminated Wood based panel (Core:PB)	Beech-Pine			12.81*	2.04*	Undefined	Popovska et al. (2019)
	Poplar-Pine			11.31*	2.65*		
	Poplar-Beech			13.24*	3.24*		

** Values in N/mm² for SWS of materials*

4. Conclusion

In this study, the SWS of the PW laminated panels and sandwich panels were determined, and their SWR was estimated by using the SWR, the withdrawal stiffness, and the density of the material used in each layer.

- The results showed that laminated panels and sandwich panels could be designed for screw-based joints by considering the SWR of the material used in panels as core and face layers.
- The highest average density was obtained for MDF. However, PW-MDF-PW had the highest SWS. It showed that sandwich panels could be lighter due to a higher strength/density ratio. Besides, there is no statistically significant difference in which face of MDF or PB laminated, but top face laminated panels had a higher strength.
- In the prediction of the SWR of laminated panels and sandwich panels, experimental values and predicted values were differentiated between 0.20% and 24.86%. It was around from 1.66% to 20.41% for sandwich panels, which roughly satisfied the predicted values in literature, around 13-14% (Pang et al., 2020).
- The procedure gives better prediction for panels with bottom- or core-layers having higher withdrawal stiffness compared to those of top layers.

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