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ORIGINAL ARTICLE

The influence of feed rate during pilot hole drilling on screw withdrawal resistance in particleboard

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Abstract
Screw withdrawal resistance (SWR) is a metric that assesses the strength of furniture joints made with wood screws. The SWR value is influenced by several factors, such as the size of the screw, the depth to which it is embedded, the diameter of the pilot hole, and the material properties of the furniture components that are being joined together. These factors have been widely studied in the scientific literature. The objective of the research was to investigate the previously unexplored factor of a feed rate during pilot hole drilling and its influence on SWR. This study used three particleboards composed of raw pine material and urea–formaldehyde resins; the boards varied in average density (633, 637, and 714 kg/m^3). Blind pilot holes with a diameter of 5 mm and depth of 25 mm were drilled in these boards using three significantly different feed rates (0.033, 0.33, and 3.33 mm/rev.). Subsequently, a confirmat-type furniture screw (7 mm major diameter, 4 mm minor diameter, 3 mm pitch) was screwed into these pilot holes. The ultimate SWR was measured with a universal testing machine. The results showed that the highest feed rate significantly decreases the SWR for all particleboards tested. This phenomenon can be attributed to the fact that a higher feed rate leads to a decreased precision in the internal surface of the pilot hole, consequently diminishing the screw's anchoring capacity within the hole. The high feed rate, used to increase production efficiency, may significantly reduce furniture durability and usability.

1 Introduction

Wood screws are widely used as fasteners in furniture and construction applications. Screw withdrawal resistance (SWR) is the ultimate pulling force that causes damage to the screw joint. A high SWR is advantageous as it provides greater bearing capacity and enhances the reliability of manufactured products. It is an important parameter in furniture strength design and architectural engineering. The experimentally determined SWR value can also serve for comparing different types of particleboards and other similar engineering materials, as well as to design and optimize the raw material composition and technology used to obtain an optimal material in various applications (Rajak and Eckelman 1993; Tankut 2011; Semple et al. 2014).

The primary method to determine the SWR is an experiment, but the value of SWR is also modeled empirically (Hoelz et al. 2022). Eckelman (1973, 1975) developed the first equations that estimate the ultimate SWR embedded in particleboards and fiberboards. Two proposed empirical equations predict the average ultimate SWR from the edge and face of particleboards:

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$$F_{\text{edge}} = 2055 \cdot D^{0.5} \cdot \left(L - \frac{D}{3}\right)^{1.125} \cdot G \quad (1)$$

$$F_{\text{face}} = 2655 \cdot D^{0.5} \cdot \left(L - \frac{D}{3}\right)^{1.125} \cdot G \quad (2)$$

where F = ultimate SWR (lb., at 65% RH), D = shank diameter of the screw (in.), L = depth of embedment of the threaded portion of the screw, G = specific gravity of the material based on oven-dry weight and volume at test.

Equations 1 and 2 consider the main factors that can affect the strength of the joint. These factors include the density of the wood-based material, the direction of screw mounting (on the edge or the face of the board – an edge SWR is only 77% of the face withdrawal resistance), the moisture content of the material, and its overall density.

Board density is an essential factor influencing the value of the SWR, as confirmed by the scientific literature (Poblete et al. 1994). Eckelman (1975) noted that his equations (Eqs. 1 and 2) could be applied only to boards air-conditioned to 10% moisture content (MC). Barnes and Lyon (1978) compared Eckelman's models with their experimental data for particleboard with two varied MCs. Eckelman's models described only ultimate screw withdrawal resistance from air-dry boards, as expected. Eckelman's model for face SWR (Eq. 2) agreed well with data from unweathered boards tested by Barnes and Lyon (1978), with an average error of only 2%. Eckelman's model for edge SWR (Eq. 1) overestimates values for unweathered boards by approximately 5%. In the case of weathered boards, the predicted edge SWR values exceeded actual values by approximately 22%, suggesting that weathering and exposure to water contributed to the deterioration of adhesive bonds and internal bond strength (IBS), which reduced SWR. In other studies, SWR in particleboard has been linked to particleboard IBS. Findings by Fujimoto and Mori (1983) suggest that the bending failure load of L-type joints of particleboard connected by screws is strongly affected by the particleboard density and the IBS of the particleboard (Fujimoto and Mori 1983).

Semple and Smith (2006) noted that Eckelman's density-based models for face and edge SWR with terms for screw dimensions and embedment depth had significant limitations. Only samples with relatively high IBS to density values matched these models. The measured face and edge SWR of boards with a low IBS-to-density ratio was markedly lower than the density-based model predictions. There was also little correlation between face and edge SWR and density, suggesting that SWR is more closely linked to IBS. The results of more recent studies confirmed that IBS is an essential material parameter determining the pull-out force of screws from particleboards (Fujimoto and Mori 1983; Semple and Smith 2006; Kurt 2022). Face SWR can be predicted as a function of particleboard density, while edge SWR can be estimated based on IBS. The particle sizes influence the board density and IBS and affect SWR prediction models' accuracy (Arabi et al. 2012).

A technical standard EN 320:2011 provides a method for evaluating the SWR of particleboards and fiberboards. This standard uses a screw with a standardized major diameter of 4.2 mm and a pitch of 1.4 mm. The screw is screwed into pre-bored pilot holes with a diameter of 2.7 ± 0.1 mm and a depth of 19 ± 1 mm. The technical standard aims to compare the screw withdrawal resistance of boards and evaluate the performance of different particleboards. The screw described in this standard is "a laboratory" screw and is not commonly used to produce furniture made of particleboards nor commonly used in construction applications.

In general, the scientific literature indicates that the SWR of particleboards is influenced by various factors, including:

- Material properties of the particleboard, such as density (Eckelman 1973, 1975) and the IBS parameter (Fujimoto and Mori 1983). Variations in material properties of the particleboard include changes in moisture content (Máchová et al. 2019), ambient temperature induced changes and local nonuniformity of density due to technological limitations during particleboards production (Wang and Salenikovich 2007).
- The age of the board, the board may lose strength during long-term use, decreasing the SWR (Abu and Ahmad 2011).
- Screw size, including diameters that characterize threads, the thread angle, pith, cross-sectional shape of a thread (thread-form), and other screw design factors (Park et al. 2006; Sydor 2019; Hoelz et al. 2021).
- Screw insertion technique (Abu and Ahmad 2014), including the pilot hole size ratio to the screw size (Rajak and Eckelman 1993), the torque used to tighten the screw (over-tightening the screw can cause it to strip the threads in the material, reducing the maximum pull-out force (Tor et al. 2015; Yu et al. 2015)).
- Nature of the load, whether static or cyclic (Wang and Salenikovich 2009), and load direction (a withdrawal force applied along the screw axis results in a lower maximum SWR than a force applied not strictly parallel to the screw axis (Sydor 2004)).

While many factors affecting the SWR value of screws screwed into particleboards have been studied, to our knowledge, no one has specifically examined the relationship between the feed rate during drilling pilot holes in particleboard and the resistance to axial withdrawal of screws screwed in these holes (SWR). Therefore, this experimental

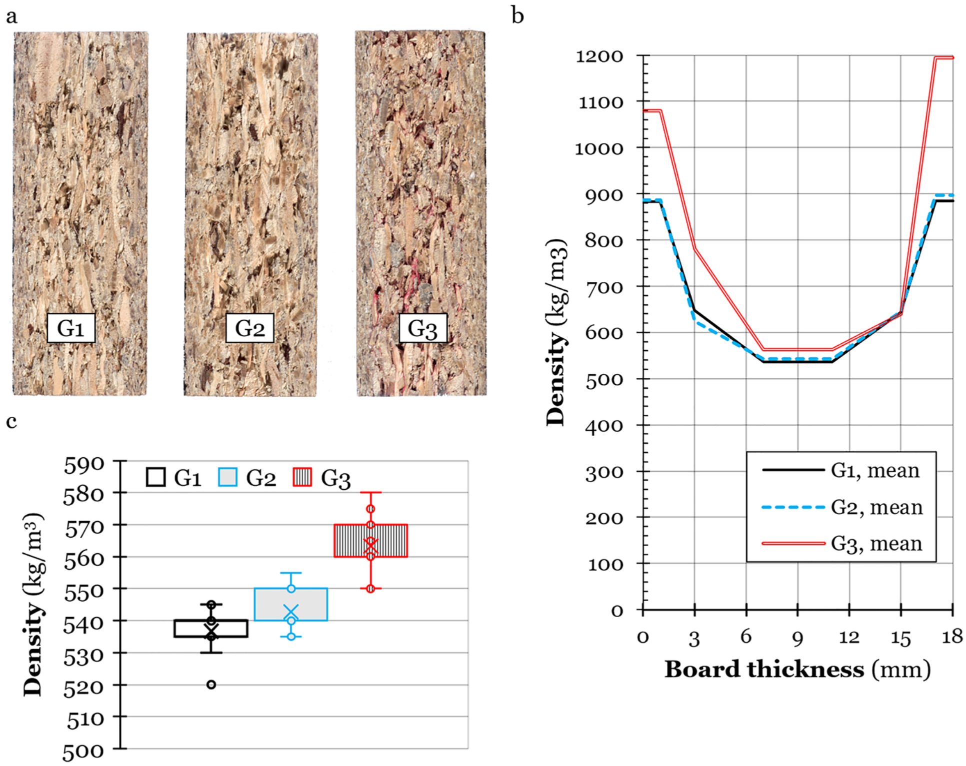

Fig. 1 Particleboards used in the study: **a** a three-layer structure (two surface layers and a core layer with a lower density), **b** density profiles, **c** core layer density comparison ($n=9$)

study aims to verify the hypothesis that the feed rate when drilling pilot holes in particleboard directly affects the SWR.

2 Material and methods

2.1 Materials

2.1.1 Particleboards

The particleboards used in the study were produced from pine wood particles with urea–formaldehyde resin as a three-layer, flat-pressed, with a sanded surface. The boards are labeled as G1, G2, and G3. The G1 board represented a standard particleboard, the G2 board has reduced formaldehyde emission, and the G3 board was a non-flammable STOP-FIRE particleboard (Swiss Krono, Żary, Poland). According to EN 312:2010, the particleboards tested are classified as type P2, intended for interior use (including furniture) in dry indoor conditions. The particleboards differed in their average density. Figure 1 summarizes the material properties of these particleboards. Figure 1a illustrates the three-layer structure of the particleboards, Fig. 1b shows the density profiles, and Fig. 1c presents the average densities of the middle layers of the boards (pilot holes were drilled in these layers). Particleboards' density profiles were tested using an X-ray density profiler (DAX, Fagus-GreCon Greten GmbH & Co. KG, Alfeld (Leine), Germany) with a resolution of measurement of 0.01 kg/m^3 for $50 \times 50 \times 18$ mm samples.

The moisture content (MC) of the boards was determined using the oven-dry method specified in EN 322:1993a and calculated as:

$$MC = \frac{m_m - m_o}{m_o} \cdot 100 \tag{3}$$

where m_m was the sample mass, and m_o was the oven-dry mass of a sample.

The weight of the samples was measured using an electronic laboratory balance (OHAUS, Parsippany, NJ, USA) of type PA 213/1, with a measurement uncertainty of $\Delta m = \pm 0.001$ g. Three measurements were obtained to calculate the MC values, which were then averaged. Table 1 shows the results of MC and average density measurements.

The tested particleboards exhibited varying strength properties, which were evaluated using the technical standards EN 310:1993b and EN 319:1993c (three-point bending, universal testing machine, Z005, Zwick Roell Group, Ulm, Germany). Table 2 provides a summary of the measurements obtained from these tests.

2.1.2 Screw

Confirmat-type screws are widely used in the furniture industry for assembling particleboard and medium-density

Table 1 Moisture content (MC) and average densities of particleboards

Sample series	Average moisture content (%) ($n=3$) standard deviation in parentheses	Average particleboard density (kg/m^3) ($n=9$) standard deviation in parentheses	Average core layer density (kg/m^3) ($n=9$) standard deviation in parentheses
Particleboard G1	12.3 (0.05)	637 (3.65)	537 (7.91)
Particleboard G2	11.8 (0.13)	633 (4.75)	543 (7.12)
Particleboard G3	12.0 (0.08)	714 (3.43)	563 (10.31)

Table 2 Particleboard mechanical properties specifications

Property	Test method	Particleboard		
		G1	G2	G3
Bending strength (lengthwise)	EN 310:1993b	13.19 (1.12)	13.60 (1.33)	14.03 (0.63)
Bending strength (crosswise)		13.25 (0.85)	12.55 (0.60)	13.84 (0.50)
Modulus of elasticity in bending (lengthwise)		2736 (244)	2818 (358)	3541 (163)
Modulus of elasticity in bending (crosswise)		2559 (64.7)	2489 (73.1)	3242 (85.0)
Internal bond strength (IBS)	EN 319:1993c	0.41 (0.03)	0.42 (0.03)	0.50 (0.05)
Surface soundness	EN 311:2002	1.08 (0.10)	1.24 (0.09)	1.30 (0.13)

$n=12$, the standard deviation in parentheses, all values in N/mm^2

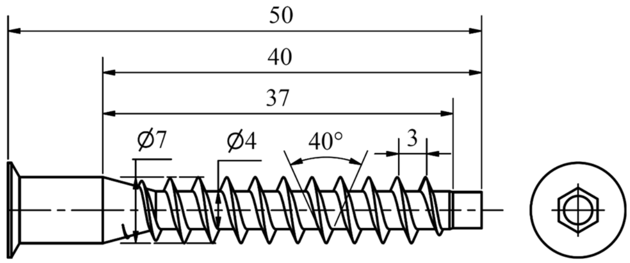

Fig. 2 Screw used in the SWR measurements

fiberboard (MDF). These screws have a coarse and deep thread that can compress the soft, layered structure of the particleboard, creating an internal thread in the pilot hole without cutting. The screws are designed with a minor diameter of 4 mm and a major diameter of 7 mm, while the pilot hole diameter is 5 mm. This design ensures convenient assembly for the end customer of ready-to-assemble furniture. Additionally, the 5 mm pilot hole and 8 mm clearance hole are compatible with the widely used industrial "system 32" in furniture made of wood-based boards, making it a versatile option for various applications. Figure 2 ilustrates the screw's dimensions, including a total length of 50 mm, major diameter of 7 mm, a minor diameter of 4 mm, a pitch of 3 mm, and a thread angle of 40°.

Confirmat-type furniture screws are widespread for their strength, stability, and ease of installation.

2.2 Methods

Blind pilot holes were prepared using a fully sharp, new high-performance industrial twist drill (the GL77 HW/D5/NL44/S10 × 25/RE model from Leitz GmbH & Co. KG, Oberkochen, Germany) with a nominal diameter of 5 mm and a length of 77 mm. The drill was equipped with cemented carbide blades renowned for their durability and cutting efficiency. The drilling was conducted using an automated machine (the CNC Creator 950, manufactured by Felder Group in Hall in Tirol, Austria). The spindle speed was 6000 rpm and three different feed rates were employed: 0.2, 2.0, and 20 m/min, resulting in feed per revolution values of 0.033, 0.33, and 3.33 mm/rev, respectively.

The SWR was measured using a laboratory universal testing machine (Z005, Zwick Roell Group, Ulm, Germany). The test samples used in this study consisted of particleboard panels and screws, as shown in Fig. 2. Each particleboard panel measured 50 × 50 × 18 mm and had a pilot hole with a diameter of 5 mm and a depth of 25 mm drilled into its edge. The screws used in the test had a penetration depth of 20 mm. The tested samples were fixed using the jig and the screws were withdrawn at an initial force of 5 N and a speed of 5 mm/min. Figure 3 shows the sample size and the SWR measurements. The experimental setup included 180 research samples.

2.3 Statistical analysis

The two-way ANOVA was utilized to analyze the effects of two independent variables (particleboard type and feed rate)

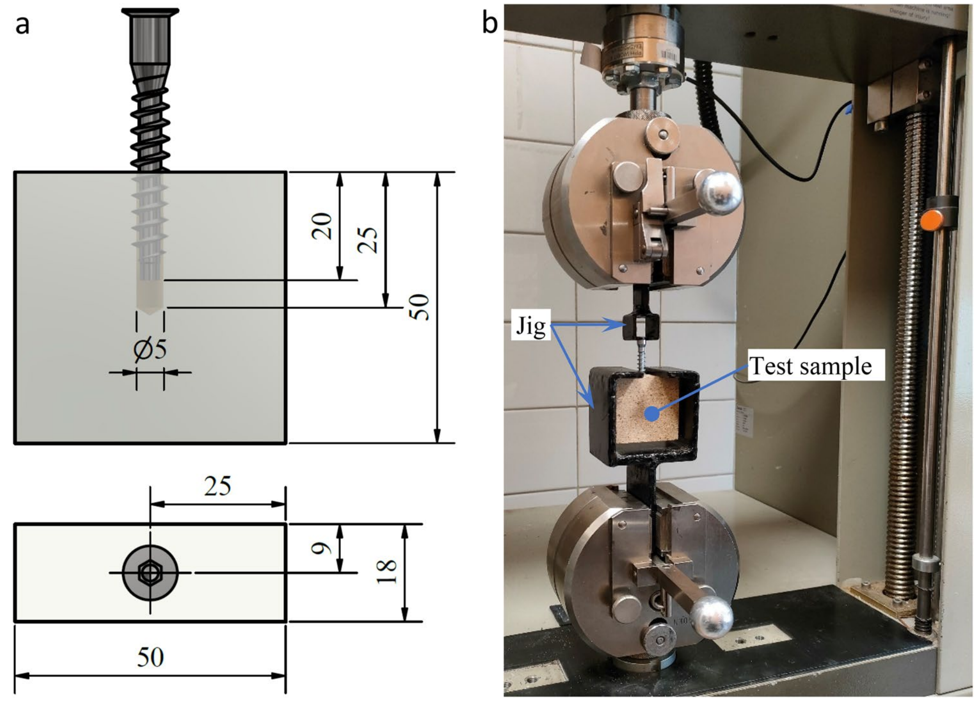

Fig. 3 Experimental setup: **a** test sample size, **b** withdrawal measurements

on a dependent variable (SWR). Post hoc tests using a Bonferroni correction were also conducted to identify significant differences between groups. Additionally, Tukey Fence was employed to detect potential outliers, and the Shapiro–Wilk test was applied to assess the normality assumption. Statistical calculations and data visualization were performed using Microsoft Excel.

3 Results

Table 3 shows the results of the screw withdrawal resistance (SWR) measurements. The SWR was calculated as mean values of 20 repetitions in each variant tested.

The results summarized in Table 3 indicate that the mean SWR decreases with increasing feed rate. This trend is evident across all three types of tested particleboard. The most significant decrease in mean SWR was observed for particleboard G3, which had the highest mean density of 714 kg/m^3. The G3 board also showed the highest mean SWR value (1775 N) at a feed speed of 0.033 mm/rev., 1715 N at 0.33 mm/rev., and a decrease of almost 17% at the fastest feed speed to 1419 N. Similar trends were observed for G1 boards (with a mean board density of 637 kg/m^3) and G2 boards (with a mean board density of 633 kg/m^3 at different moisture contents of 12.3% and 11.8%, respectively), but with the medium variant of feed speed. The mean SWR values for G1 and G2 boards were 1394 N and 1458 N, respectively. The results presented in Table 3 are shown in more detail in Fig. 4, which provides a more detailed comparison of the tested particleboards.

Notably, a feed rate of 0.033 mm/rev. (0.2 m/min) is considered too slow from a practical perspective as it is significantly extending drilling time in industrial conditions. Such feed rates are not typically used in industrial settings. On the other hand, a feed rate of 0.33 mm/rev. is found to be optimal, providing efficient drilling without exerting undue stress on the drill. Conversely, a feed rate of 3.3 mm/rev. is considered too fast and places a heavy load on the drill (these feed rates were 0.2, 2.0, and 20 m/min, respectively).

Table 3 Measured screw withdrawal resistances

Board type	G1			G2			G3		
Feed rate (mm/rev.)	0.033	0.33	3.33	0.033	0.33	3.33	0.033	0.33	3.33
Mean (N)	1476	1394	1364	1479	1458	1376	1775	1715	1419
SD	197	177	132	108	192	186	183	145	312
Ratio G1/G3, G2/G3 and G3/G3 (%)	83.2%	81.3%	96.1%	83.3%	85.0%	97.0%	100%	100%	100%
n (pcs.)	20	20	20	20	20	20	20	20	20

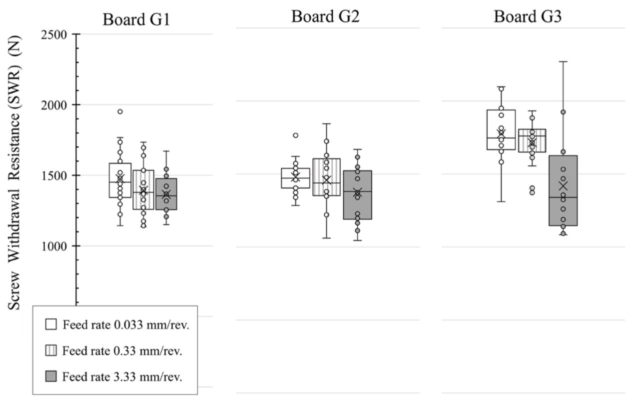

Fig. 4 A box plot comparing screw withdrawal resistances for board types and feed rates used

To illustrate, drilling a hole with a feed rate of 0.2 m/min took 7.5 s, drilling at 2 m/min lasted only 0.75 s, and drilling with a feed rate of 20 m/min took merely 0.075 s. The highest used feed rate is feasible for relatively soft material like particleboard, it may potentially overload the machine and cause damage to the drill, especially when working with denser wood materials.

Table 4 summarizes the results of the statistical analysis of the SWR measurement results.

A significant main effect of particleboard density was found, $F(2, 42) = 23.68$, $p < 0.001$, $\eta^2 = 0.21$. Post hoc tests using a Bonferroni correction revealed that the average score for board G1 ($M = 84.0$, $SD = 8.8$) was significantly different from both board G1 ($M = 73.0$, $SD = 7.9$) and board G3 ($M = 71.4$, $SD = 9.4$), $ps < 0.001$. The average score for board G2 also significantly differed from board G3, $p = 0.009$.

A significant main effect of feed rate was also found, $F(2, 42) = 15.15$, $p < 0.001$, $\eta^2 = 0.15$. Post hoc tests using a Bonferroni correction revealed that the average score for feed rate FR1 ($M = 75.2$, $SD = 7.6$) was significantly different from both feed rate FR2 ($M = 79.0$, $SD = 8.5$) and Feed Rate FR3 ($M = 86.0$, $SD = 8.8$), $ps < 0.001$. The average score for Feed Rate FR2 was also significantly different from Feed Rate FR3, $p = 0.008$.

No significant interaction effect was found, $F(4, 84) = 1.80$, $p = 0.14$, $\eta^2 = 0.08$.

The residuals contained one potential outlier (0.56% of observations) identified using the Tukey Fence method. The ANOVA results were robust to the presence of this outlier. The normality assumption was checked using the Shapiro–Wilk Test and was not violated, $W(48) = 0.97$, $p = 0.22$. The test priori power was strong for both factors (power = 1). However, the test power for the interaction effect was low and undefined, indicating that the observed effect size may be exaggerated or even in the wrong direction. The design was balanced, with equal sample sizes for all groups.

4 Discussion

As mentioned in the methodology, the screw used in screw withdrawal resistance (SWR) measurements typically connects panel elements made of wood-based materials commonly used in the furniture industry. Many previous studies show that the mean SWR is higher for MDF than for particleboard. Due to the manufacturing technology and raw material properties, MDF has a more uniform vertical density profile than particleboard. The natural adhesive properties of wood fibers certainly affect the boards' SWR and density profile, directly affecting SWR. The material used and its properties translate into the quality of particleboards (Pędzik et al. 2021). Particle size and geometry are essential factors that affect the properties of particleboards made from them, including IBS (Karlinasari et al. 2021). Numerous authors point to the value of the IBS parameter as crucial to interpreting SWR results. A study by Wronka and Kowaluk (2022) on the contribution of pine branch particles in particleboards to their properties found that SWR was highest for a particleboard made with 100% pine branch particles in the core layer and 100% industrial particles in the surface layers. The study of Pędzik et al. (2022) states that pine branches are denser than pine wood from the girdle section. These results affect the mechanical properties of the boards, especially the internal bond strength (IBS), which was 0.72 N/mm^2 for the boards from the higher-density raw material, and only 0.46 N/mm^2 for the lower-density particles.

Table 3 shows that the IBS of the G1 and G2 particleboards was only 82–84% of the IBS of the G3 board IBS; at the same time, the density of the G1 and G2 boards was approximately 89–90% of the density of the G3 board. For small feeds ranging from 0.033 to 033 value of the G3 board,

Table 4 Statistical analysis

Source	DF	Sum of square (SS)	Mean square (MS)	F statistic (d_{f1}, d_{f2})	P-value
Board type (factor A–rows)	2	1,812,132.133	906,066.0667	23.68315 (2,175)	0.000
Feed-rate (factor B–columns)	2	1,158,943.333	579,471.6667	15.14649 (2,175)	0.000
A × B	4	555,214	138,803	3,87	0.004921
Error	171	6,695,120.333	38,257.83048		

the mean SWR value of these boards was 83–85% of the mean SWR value of the G3 board (suggesting an association between SWR and IBS as well as an association between SWR and board density). However, at a faster feed rate of 3.33 mm/rev., the SWR value approached 96–97% of the G3 plate (Table 3). This suggests that the SWR value does not correlate with the IBS and density value at very high feed rates. Consequently, Eckelman,s formulas (1 and 2) cited in the Introduction are no longer applicable.

The Forest Products Laboratory conducted a study investigating the factors that affect the SWR in solid wood or plywood blocks. Despite controlling for variables such as screw size and specimen material characteristics, the study found that the primary factor affecting SWR was the characteristics of the pilot hole. Specifically, pilot holes with smooth sidewalls demonstrated significantly higher SWR than those with rough sidewalls. The study found that a well-sharpened drill bit and a low feed speed are necessary to achieve a smooth hole. The study also revealed that a twist drill produced a smoother hole than a machine drill in the tested materials (Douglas fir plywood and Sitka spruce). Pilot holes with visibly scratched or torn walls outside the cut line of the drill underwent more severe deformation at lower loads and exhibited lower proportional and end loads than holes with smooth walls (Goodell and Phillips 1944).

Rajak and Eckelman (1993) investigated the edge and face withdrawal strength of large screws in particleboard and medium-density fiberboard (MDF). The study explored the effects of various parameters, including screw diameter, length, type, and pilot hole diameter. Regarding the pilot hole diameter, the authors found that the optimal size depends on the screw's thread major diameter (external diameter of the screw). For screws with an external diameter of 6 mm or less, a pilot hole diameter of 70–75% of the screw's thread major diameter provided the highest SWR. For screws with a diameter greater than 6 mm, a pilot hole diameter of 80–85% of the major diameter of the screw thread was optimal. The cited authors also noted that a pilot hole diameter smaller than optimal results in lower withdrawal strength and increased risk of splitting. On the contrary, the use of a pilot hole diameter larger than optimal reduced the screw anchoring ability, resulting in a lower SWR. Yorur et al. (2020) drilled pilot holes of 80% of the external diameter of the screw, i.e., pilot hole diameters were 2.8 mm and 3.2 mm for external screw diameters of 3.5 mm and 4.0 mm. Using 18.0 mm thick particleboards, they obtained SWRs of 1042 N and 948 N, respectively. The same study proved that soaking the samples in water reduces the SWR by up to 50%. In our experiment, the 5 mm pilot holes were used, while the confirmat type screw had a minor diameter of 4 mm. The diameter of the pilot hole was 1 mm larger than the minor diameter of the screw and corresponded to 71% of the external diameter of the screw (7 mm). Although this diameter is slightly smaller than the optimal diameter suggested by Eckelman, it is commonly used in the furniture industry's "system 32".

Abu and Ahmad (2015) state that the durability issues commonly observed in furniture joints can be attributed to the interplay between screw withdrawal force and damage on the board surface, such as spalling or surface damage within the screw holes. These factors lead to a reduction in the SWR and adversely affect the load-bearing capacity of the furniture joints. The roughness of the surface of holes drilled in wood materials depends on the material type and tool used. When drilling with a thorough drill, the roughness parameters are lower than for a blind drill. Surface roughness parameters decrease with increasing spindle speed and decreasing feed per tooth rate. The roughness parameters for particleboards are higher than solid wood, regardless of the processing condition (Joshi 2000; Czarniak et al. 2009). To effectively increase the SWR, it's critical to ensure the accuracy of the pilot hole diameter (Nad' et al. 2019; Sydor et al. 2020), including minimizing edge-chipping (Buckner 1986), and reducing surface defects in the inner cylindrical surface of the pilot hole (Sydor et al. 2021, 2023).

The presented study results have some potential limitations:

1. The study only focused on one way of mounting the screw in the board. This study did not analyze other potentially influential factors related to furniture screws, such as screw size, screw design variants, and others. The study results may not be applicable to all types of wood screws.
2. The study was conducted on particleboards made of raw pine material and urea–formaldehyde resins with three different densities. The results may not be applicable to other types of wood or composite materials used in furniture manufacturing.
3. The study used idealized conditions for pilot hole drilling. The SWR measurement was carried out laboratory, which may not fully represent all the conditions encountered in furniture manufacturing operations. As a result, caution should be exercised when applying the findings to practical situations.

Regardless of these limitations, the study results have evident practical implications:

1. The study highlights the importance of controlling the feed rate during pilot hole drilling to achieve optimal screw withdrawal resistance (SWR). The study demonstrates that excessive feed rates can significantly decrease the SWR of furniture joints. This could lead to improved manufacturing processes and higher-quality

furniture products. By avoiding excessively high feed rates, manufacturers can prevent a decrease in furniture usability due to weak joints.

2. The study used different variants of particleboards composed of raw pine material and urea–formaldehyde resins. Manufacturers can use this information to select materials most suitable for achieving optimal SWR and increasing the longevity of furniture products.

5 Conclusion

The type and size of the screw, the screw in-depth, the diameter of the pilot hole, and the material properties of the particleboard are well-known factors affecting the screw withdrawal resistance (SWR). However, the novelty of our study lies in pointing out that the feed rate during drilling the pilot hole also impacts SWR. The effect observed is comparable to the impact of the feed mentioned earlier in terms of enhancing the quality of the holes drilled in particleboards with different feed rates. A favorable increase in the SWR can be achieved by maintaining the pilot hole diameter accuracy, reducing edge cracking, and minimizing defects on the inner cylindrical surface of the pilot hole. The mean SWR is lower when drilling at very high feeds.

The results analysis confirms the research hypothesis. It can be concluded that the feed rate when drilling pilot holes in the particleboard affects the SWR because it affects the quality of the hole. A slow feed rate produces a clean round hole with smooth walls, which provides a good grip for the screw. On the other hand, a fast feed rate can cause the drill to wander and produce a rough, oblong hole, which reduces the grip and screw-holding strength.

The SWR decreases with an increase in the feed rate because the high feed rate causes increased roughness of the internal surface of the pilot hole. If the internal cylindrical surface of the pilot hole is too rough, it can cause the particles to split or break, reducing the material's overall strength and making it more difficult for the screw to grip onto the wood material.

A low to moderate feed rate is recommended to produce good hole quality without damaging the drill tool and material. However, in industrial conditions, the feeds are increased to boost efficiency. Our research shows that the price related to the high feed rate is also the force that holds the screws in the holes. Therefore, a slower feed rate is recommended to drill pilot holes in the particleboard to increase the SWR.

Author contributions MS conceived and designed the study. ZP and MP conducted the experiments and collected the data. All authors (MS, MP, ZP, MH, and TR) contributed equally to the discussion and collaborated on formulating the conclusions. MS wrote the manuscript. MS reviewed and edited the manuscript during the peer review process. All authors have read and approved the final version of the manuscript.

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Data availability The authors confirm that the data analyzed during this study are included in this published article.

Declarations

Conflict of interest On behalf of all authors, the corresponding author declares that the authors have no competing interests as defined by Springer or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Ethical approval Ethical approval was not required for this study as it did not involve human subjects, animals, or the collection of living plant material. Additionally, the research did not involve any sensitive data.

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