

## Evaluation of the relationship between pilot hole dimensions and screw holding strength in softwood furniture elements

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### Abstract:

The influence of pilot-hole geometry on screw holding strength in solid softwood furniture elements remains insufficiently understood, particularly when wood species, pilot-hole dimensions, and grain direction are considered simultaneously. This study aimed to investigate the effects of pilot-hole diameter and depth on the screw holding strength of selected softwood species commonly used in furniture manufacturing and to identify the best-performing pilot-hole configurations among the tested levels for different grain directions. The materials examined were *Larix decidua* Mill. (larch), *Pinus sylvestris* L. (Scotch pine), *Abies sp.* (fir), *Picea orientalis* L. (spruce) and *Cedrus libani* A.Rich (cedar). A total of 900 specimens were prepared, comprising 5 wood species, 9 pilot hole configurations (3 diameter by 3 depth), and 10 replications for each condition. Screw withdrawal tests were conducted under static tensile loading, with 450 specimens tested parallel to the grain and 450 perpendicular to the grain. The results indicated that, for the withdrawal tests parallel to the grain, the highest mean screw holding strength was obtained with a pilot-hole diameter corresponding to 50 % of the screw diameter, while pilot-hole depth had no significant main effect. In case of the withdrawal tests perpendicular to the grain, highest mean screw holding strength was obtained with a pilot-hole diameter corresponding to 75 % of the screw diameter, whereas pilot-hole depth again showed no significant main effect. Wood species and pilot-hole diameter significantly affected screw holding strength, and all two-way and three-way interactions were significant. Cedar exhibited the highest mean screw holding strength in both loading orientations. These findings highlight the importance of considering pilot-hole diameter in relation to wood species and grain direction for screw connections in solid softwoods.

**Keywords:** Screw holding strength, pilot hole diameter, pilot hole depth, softwood, grain direction.

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## Introduction

Various joining techniques are used in furniture joints. Traditional (glued) joints are currently being replaced by mechanical fastener (knock-down) joints. Developments in mass production machinery and the need to transport manufactured furniture over long distances have made it necessary for many pieces of furniture to be demountable (portable). Glue-less joints that are resistant to static and dynamic loads can be achieved by joining two or more elements using appropriate methods. Glue-less wood joining techniques are suitable for applications in which the use of glue is not suitable for various reasons, or in environments where a permanent bond is not desired. Wood screws are most frequently used for this purpose. However, the screw holding capacity of the wood screws to be used must be well understood. Previous studies have shown that screw holding performance is influenced by material characteristics, screw-related parameters, pilot-hole geometry, and grain orientation. However, the relative effects and interactions of these factors may vary depending on the wood species and loading direction.

Self-tapping screws have 6 - 15 % higher direct withdrawal strength compared to commonly used wood screws in the market. Lateral withdrawal strength, applicable to both types of screws, is directly proportional to the square of the screw diameter (Wilkinson and Laatsch 1970). The shear strength of wood material parallel to the grain is a better predictor of screw holding strength than density, and density is a distinctive feature in determining the screw holding strength of particleboard (Eckelman 1975). Relevant physical and mechanical properties of various solid wood and wood-based panels, which are necessary for furniture engineering design, have been determined according to relevant standards.

The screw holding strength of three different screw types, both parallel and perpendicular to the surface, was examined in beech wood, werzalit, particle board, and medium-density fiberboard materials. The research results showed that the highest screw holding strength was obtained in beech wood, and the lowest strength was obtained in particle board (Doğanay 1995).

An investigation into the effect of screw count and size on the moment performance of L-type glueless screwed corner joints for box furniture found that increasing diameter, length, and number of screws increased strength, but screw length was more effective than diameter. Furthermore, formulas were developed to predict average moment performance values (Kasal *et al.* 2006). These findings indicate that material-related characteristics, particularly wood density and anatomical structure, play an important role in screw holding performance.

In a study examining the effects of screw count and screw size on moment-carrying capacity in L-type glued screwed corner joints for box furniture, equations were developed to predict moment values under diagonal compression and tensile loads (Kasal 2008). In addition to material characteristics, previous research has demonstrated that screw-related parameters, including screw diameter, length, type, and number, can influence the strength of screwed joints and the holding strength of screws.

The nail and screw withdrawal strength of laminated veneer lumber consisting of hard and softwood layers was analyzed. Statistical analysis demonstrated that layer thickness had no significant effect on the withdrawal resistance perpendicular to the grain, but the resistance increased with increasing density in this direction. According to the cutting direction, the resistance in the radial direction was reported to exceed that in the tangential direction (Çelebi and Kılıç 2007).

In an investigation of the effects of screws on the withdrawal strength of laminated veneer lumber, the role of pilot hole parameters, screw type, and veneer layer thickness on withdrawal resistance were examined. The highest resistance was obtained in oak samples with a 4 mm veneer thickness, using a 3,5 mm x 16 mm screw and glued with phenol formaldehyde. The lowest resistance was obtained in Uludag fir samples with a 5 mm veneer thickness, using a 4 x 50 mm screw and glued with melamine formaldehyde adhesive. It was stated that pilot holes would increase the withdrawal resistance by preventing splitting (Özçiftçi 2009).

The screw withdrawal resistance in heat-treated wood material was investigated. The screw withdrawal resistance obtained in the tangential section exceeded that in the cross-section. The highest screw withdrawal resistance in the tangential and cross-sections was found in sessile oak (*Quercus petraea* (Matt.) Liebl.) samples, and the lowest in black poplar (*Populus nigra* L.) samples. Accordingly, it was determined that heat-treated wood species with high density and tangential surfaces could be preferred in furniture construction design in the terms of screw holding performance (Perçin and Ayan 2012).

The effect of screw diameter, pilot hole diameter, screw type, and loading speed on the screw holding performance in reconstructed bamboo lumber was evaluated. The results indicated no statistically significant differences in withdrawal resistance depending on screw diameter, screw type, and loading speed. It was determined that the screw withdrawal resistance exhibited an inverse relationship with pilot hole diameter. The withdrawal resistance of screws applied to the face and edges of reconstructed bamboo lumber exceeded that of medium-density fiberboard (MDF) and particleboard (PB) (Chen *et al.* 2016).

Pilot-hole geometry is another important factor because it determines the amount of wood engaged by the screw threads and can influence mechanical interlocking and local wood damage. Previous studies have shown that pilot-hole diameter affects screw withdrawal performance; however, the magnitude and direction of this effect vary with material type, screw characteristics, and loading conditions.

In plywood, the screw holding strength of screws of different diameters glued and screwed into different pilot holes was investigated. The study revealed that samples without pilot holes exhibited higher screw withdrawal strength, and that the withdrawal strength of screws driven from the face was higher than that of screws driven from the edge. Furthermore, the withdrawal strength of screws glued with polyvinyl acetate (PVAc) was determined. It was also determined that screw withdrawal strength increased with increasing screw diameter (Yörür *et al.* 2017).

The screw withdrawal strength in medium-density fiberboard (MDF) and particleboard (PB) was investigated. The results showed that the highest screw withdrawal strength was obtained in test blocks treated with polyurethane (PU), whereas the lowest pull-out resistance was observed in test blocks without pilot holes for both materials. In addition, medium-density fiberboard MDF generally exhibited better performance than PB (Yörür *et al.* 2020).

When the screw withdrawal strength of laminated medium-density fiberboard (MDF) and particleboard (PB) panels was investigated, a linear relationship between the screw holding strength and the density of the panels was determined. It was also reported that the highest screw holding strength was obtained in panels using plywood and MDF (Uysal and Güntekin 2024).

The reviewed studies therefore suggest that screw holding performance is governed by multiple interacting factors rather than by a single material or screw parameter. However, most available studies have focused on individual factors or wood-based composite materials, while comparatively limited evidence is available on the combined effects of pilot-hole dimensions in solid softwoods.

Although previous studies have established that screw holding performance is affected by wood properties, screw characteristics, pilot-hole geometry, and grain orientation, important uncertainties remain regarding the combined effects of these factors in solid softwoods. In particular, it remains unclear whether the effects of pilot-hole diameter and depth are consistent across different wood species and loading directions or whether they depend on interactions among these factors. This uncertainty is relevant to furniture manufacturing because pilot holes are commonly used in solid-wood components to facilitate screw insertion and reduce the risk of wood damage, while their dimensions may influence the load-carrying capacity of the resulting screw connection. The available literature provides limited evidence on the combined effects of pilot-hole diameter and depth across multiple solid softwood species and grain

directions. More importantly, it remains unclear whether pilot-hole dimensions exert independent effects on screw holding strength or whether their effects depend on wood species and grain direction. Addressing this uncertainty is important for understanding the screw–wood interaction and for selecting appropriate pilot-hole dimensions in screwed solid-softwood connections. Therefore, this study aimed to evaluate the effects of pilot-hole diameter and depth on screw holding strength in five solid softwood species under loading parallel and perpendicular to the grain. A factorial experimental design was used to examine the main effects and interactions of wood species, pilot-hole diameter, and pilot-hole depth. The study provides comparative experimental evidence on how these factors jointly influence screw holding strength and identifies pilot-hole configurations associated with higher holding strength under the experimental conditions investigated.

## **Material and methods**

### **Wood materials**

In the experiments, softwood materials commonly used in the Turkish furniture industry were used: larch (*Larix decidua* Mill.), scotch pine (*Pinus sylvestris* L.), fir (*Abies sp.*), spruce (*Picea orientalis* L.), and cedar (*Cedrus libani* A.Rich.) species were utilized. The selection of materials was influenced by the natural distribution of these wood species in Turkey, and their use in Turkish furniture industry. The materials were randomly obtained from commercial suppliers. The materials were selected from commercial suppliers as visually graded first-class structural timber in accordance with supplier classification, with particular attention given to obtaining defect-free samples with straight grain, and free from knots, cracks, or other visible defects.

### **Moisture content and density**

Wood density and moisture content were determined in accordance with the TS ISO 13061-1 (2021) and TS ISO 13061-2 (2021), respectively. All specimens were conditioned and tested

following these standards to ensure consistency and comparability of the results. The moisture content and density of the test samples at the time of testing are given below. Average moisture content (MC) values were 9,5; 8,8; 8,5; 8,9; and 8,1 % and, density values were 0,54; 0,40; 0,44; 0,41; and 0,61 g/cm<sup>3</sup> for larch, scotch pine, fir, spruce, and cedar, respectively.

### **Screw**

In the experiments, Phillips-head low-carbon steel screws commonly used in the furniture industry, with a diameter of 4 mm ( $\pm 0,3$ ) and a length of 50 mm, were selected in accordance with TS ISO 965-4 (2005) and TS ISO 965-5 (2005). The screws had a root diameter of 2,4 mm ( $\pm 0,25$ ) and a thread pitch of 1,8 mm (Figure 1).



**Figure 1:** 4 x 50 mm screws used in the experiments.

### **Preparation of test samples**

The specimens were carefully cut from the first-class, defect-free timber obtained from commercial suppliers, and 10 replicate specimens were prepared for each experimental condition. All specimens were prepared to dimensions of 75 mm x 75 mm x 18 mm and conditioned under controlled climatic conditions ( $20 \pm 2$  °C,  $65 \pm 3$  % RH) until constant mass was reached. After moisture stabilization, pilot holes were drilled as follows: parallel to the grain, with diameters of 2, 3, and 3.5 mm and depths of 10, 20, and 32 mm; perpendicular to the grain, with diameters of 2, 3, and 3.5 mm and depths of 7, 10, and 13 mm. The tests were conducted in two orientations, parallel and perpendicular to the grain, defined according to the

direction of screw insertion relative to the wood grain. In addition, different depths were used for each grain direction due to specimen geometry and practical constraints. For perpendicular-to-grain conditions, shorter depths were required because the screws were driven through the thickness of the member, which limited the maximum depth. In contrast, longer depths could be used for parallel-to-grain conditions. Therefore, embedment depth varied depending on the grain direction. Subsequently, 4 x 50 mm screws were driven perpendicular to the grain into the test samples to a depth of 19 mm, leaving 1 mm of the screw protruding from the bottom face of the material. In case of the parallel to the wood grain direction, screws were driven into the test samples to a depth of 32 mm. Specimens were prepared with consideration of grain and annual ring orientation in order to minimize the influence of anatomical variability on screw holding strength. All samples were selected from radial or near-radial sections where possible, and care was taken to maintain a consistent and comparable annual ring orientation among specimens. In addition, the grain direction was kept uniform across all test samples to ensure that any variations in screw holding strength could be attributed to the experimental variables rather than differences in wood anatomy. The screw withdrawal test specimens are provided in Figure 2.

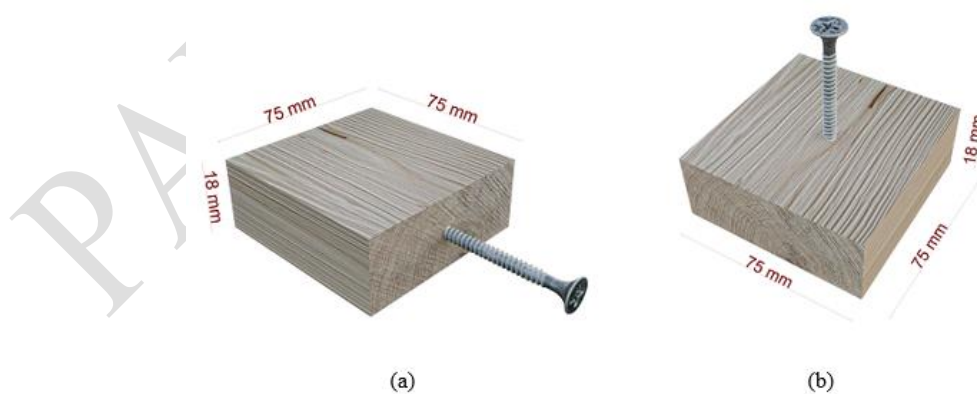


**Figure 2:** Screw withdrawal test specimens (a) parallel and (b) perpendicular to the grain.

A total of 900 test specimens were prepared, with 10 samples from each material: 450 for withdrawal parallel to the grain and 450 for withdrawal perpendicular to the grain (Table 1).

### Performing screw withdrawal tests

Screw holding strength was evaluated using an axial screw withdrawal test in accordance with TS EN 1382 (2016) and following procedures commonly reported in previous studies ASTM-D 1037 (2001) (Eckelman 1978). The screw withdrawal test specimen and setup are provided in Figure 3. The mechanical tests were conducted using a 5-ton capacity Universal Testing Machine. The loading rate was set at 2 mm/min. The screw holding strength was defined as the maximum withdrawal force recorded during screw extraction. The average screw holding strength values were calculated by averaging the maximum force values obtained from all specimens within each experimental group.

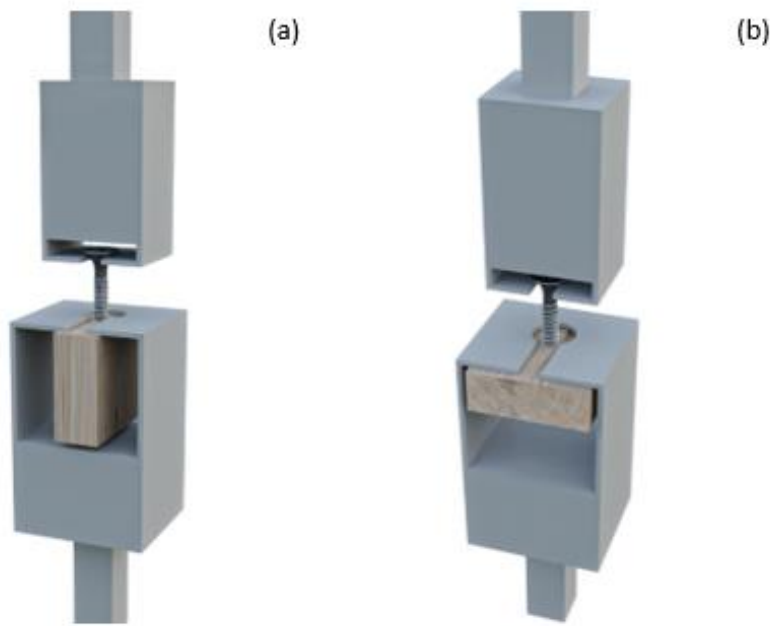


**Figure 3:** Screw withdrawal test setup (a) parallel and (b) perpendicular to the grain.

### Experimental design and statistical evaluation

In the experiments, a total of 900 samples were prepared separately for screw holding strength tests parallel and perpendicular to the grain. 5 wood species, 3 pilot hole diameters, and 3 pilot hole depths were used. It should be noted that the parallel- and perpendicular-to-grain

withdrawal tests were evaluated independently. Since different thread embedment lengths were required by the specimen geometry, no direct statistical comparison was made between the two grain directions. For each condition, 10 samples were prepared for the parallel to the grain tests and 10 samples for the perpendicular to the grain tests ( $5 \times 3 \times 3 \times 10 = 450$  for each direction). The experimental design for the wood materials is given in Table 1.

**Table 1:** Experimental design used for the study.

| Wood Species            | Pilot Hole Diameter (PHDT) (mm) | Screw Holding Strength |     |     |                            |     |     |
|-------------------------|---------------------------------|------------------------|-----|-----|----------------------------|-----|-----|
|                         |                                 | Parallel to the grain  |     |     | Perpendicular to the grain |     |     |
|                         |                                 | Pilot hole depth (mm)  |     |     | Pilot hole depth (mm)      |     |     |
|                         |                                 | 10                     | 20  | 32  | 7                          | 10  | 13  |
| <i>Larix decidua</i>    | 2                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3,5                             | 10                     | 10  | 10  | 10                         | 10  | 10  |
| <i>Pinus sylvestris</i> | 2                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3,5                             | 10                     | 10  | 10  | 10                         | 10  | 10  |
| <i>Abies sp.</i>        | 2                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3,5                             | 10                     | 10  | 10  | 10                         | 10  | 10  |
| <i>Picea orientalis</i> | 2                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3,5                             | 10                     | 10  | 10  | 10                         | 10  | 10  |
| <i>Cedrus libani</i>    | 2                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3                               | 10                     | 10  | 10  | 10                         | 10  | 10  |
|                         | 3,5                             | 10                     | 10  | 10  | 10                         | 10  | 10  |
| Total                   |                                 | 150                    | 150 | 150 | 150                        | 150 | 150 |
| Grand total             |                                 | 900 test samples       |     |     |                            |     |     |

In the statistical evaluation of the data, two separate three-factor analyses of variance (ANOVA) were conducted for screw holding strength parallel and perpendicular to the grain. For each grain direction, wood species (WS), pilot-hole diameter (PHDT), and pilot-hole depth (PHDE) were included as fixed factors, together with all two-way and three-way interactions among these factors. The least significant difference (LSD) test at the 5% significance level was applied for post-hoc comparisons when statistically significant effects were detected. The analyses were performed using the General Linear Model procedure in Minitab Statistical Software (Version 17, 2023).

## Result and discussion

### Experimental results of screw holding strength

The screw withdrawal tests lasted approximately 60 - 90 seconds, and deformation in the test specimens occurred as the screw was withdrawn from the material. Each test specimen was subjected to an axial screw withdrawal test in one of two orientations: parallel or perpendicular to the grain. The average screw holding strength values of the wood materials are given in Table 2. The results of variance analyses for the effects of pilot hole dimensions on screw holding strength in parallel and perpendicular to the grain are given in Table 3.

**Table 2:** Mean values of screw holding strength of wood species.

| Wood Species            | Pilot hole diameter (mm) | Parallel to the grain (N) |                |                | Perpendicular to the grain (N) |                |                |
|-------------------------|--------------------------|---------------------------|----------------|----------------|--------------------------------|----------------|----------------|
|                         |                          | Pilot hole depth (mm)     |                |                |                                |                |                |
|                         |                          | 10                        | 20             | 32             | 7                              | 10             | 13             |
|                         |                          | Mean                      | Mean           | Mean           | Mean                           | Mean           | Mean           |
| <i>Larix decidua</i>    | 2                        | 2022<br>(15,2)            | 2239<br>(16,9) | 2090<br>(8,7)  | 1352<br>(23,3)                 | 1393<br>(13,3) | 1331<br>(14,8) |
|                         | 3                        | 2171<br>(12,8)            | 2449<br>(11,4) | 2248<br>(9,3)  | 1328<br>(22,7)                 | 1381<br>(32,8) | 1480<br>(34)   |
|                         | 3,5                      | 1891<br>(21,7)            | 2034<br>(16,6) | 1617<br>(13,1) | 1391<br>(28,5)                 | 1435<br>(10,2) | 1268<br>(13,1) |
| <i>Pinus sylvestris</i> | 2                        | 1996<br>(10,3)            | 220<br>7 (8,9) | 2101<br>(9,9)  | 1002<br>(14,2)                 | 1094<br>(49,4) | 1224<br>(50,3) |
|                         | 3                        | 2193<br>(11,4)            | 1920<br>(19,5) | 1513<br>(5,4)  | 1428<br>(28,3)                 | 1323<br>(11,4) | 1212<br>(7,6)  |
|                         | 3,5                      | 1961<br>(15,4)            | 1423<br>(20,3) | 986<br>(36,9)  | 1216<br>(18,3)                 | 975<br>(19,3)  | 963<br>(9,7)   |
| <i>Abies sp.</i>        | 2                        | 2249<br>(11,6)            | 2461<br>(12)   | 2873<br>(11,9) | 1257<br>(17,8)                 | 1224<br>(37,8) | 1329<br>(17)   |
|                         | 3                        | 249<br>7 (7)              | 1844<br>(15,6) | 2030<br>(20,6) | 1390<br>(29,2)                 | 1391<br>(3,5)  | 1411<br>(13,7) |
|                         | 3,5                      | 2397<br>(9,6)             | 2384<br>(9,5)  | 2150<br>(10,6) | 1124<br>(11,7)                 | 1331<br>(4,5)  | 1072<br>(20)   |
| <i>Picea orientalis</i> | 2                        | 1726<br>(25,7)            | 1935<br>(9)    | 2041<br>(7,8)  | 1076<br>(23,7)                 | 987<br>(26)    | 1140<br>(32)   |
|                         | 3                        | 1533<br>(8,9)             | 1505<br>(14,3) | 2105<br>(18,1) | 1129<br>(23,7)                 | 1122<br>(14,6) | 1161<br>(44,5) |
|                         | 3,5                      | 1621<br>(11,6)            | 1669<br>(18,2) | 1989<br>(11,4) | 1038<br>(6,3)                  | 913<br>(7,4)   | 876<br>(28,3)  |
| <i>Cedrus libani</i>    | 2                        | 2876<br>(9,8)             | 3355<br>(9)    | 3346<br>(20)   | 1326<br>(15,5)                 | 1295<br>(56,8) | 1776<br>(25,3) |
|                         | 3                        | 2936<br>(24,6)            | 2703<br>(14,2) | 2991<br>(15,1) | 1712<br>(55,1)                 | 2029<br>(12,1) | 1768<br>(52,5) |
|                         | 3,5                      | 3740<br>(9,5)             | 3739<br>(10,2) | 3053<br>(11,8) | 1459<br>(49,6)                 | 1789<br>(24,4) | 1604<br>(22,9) |

\*: The values in parentheses are coefficients of variation

**Table 3:** Results of three-factor variance analyses regarding the effect of pilot hole on screw holding strength in parallel and perpendicular to the grain.

| Experiment                 | Sources of variance | Degrees of freedom | Sum of squares | Mean squares | F Value | Probability of error (p < 0,05) |
|----------------------------|---------------------|--------------------|----------------|--------------|---------|---------------------------------|
| Parallel to the Grain      | WS                  | 4                  | 1192024067     | 298006017    | 3101182 | 0,0000                          |
|                            | PHDT                | 2                  | 36686351       | 18343176     | 190887  | 0,0000                          |
|                            | WS x PHDT           | 8                  | 147612560      | 18451570     | 192015  | 0,0000                          |
|                            | PHDE                | 2                  | 2235524        | 1117762      | 11632   | NS                              |
|                            | WS x PHDE           | 8                  | 86190320       | 10773790     | 112117  | 0,0000                          |
|                            | PHDT x PHDE         | 4                  | 71843129       | 17960782     | 186908  | 0,0000                          |
|                            | WS x PHDT x PHDE    | 16                 | 62454893       | 3903431      | 40621   | 0,0000                          |
|                            | Error               | 405                | 389182100      | 960943       | -       | -                               |
|                            | Total               | 449                | 1988228944     | -            | -       | -                               |
| Perpendicular to the Grain | WS                  | 4                  | 183427711      | 45856928     | 801541  | 0,0000                          |
|                            | PHDT                | 2                  | 31271791       | 15635896     | 273302  | 0,0000                          |
|                            | WS x PHDT           | 8                  | 15265342       | 1908168      | 33353   | 0,0010                          |
|                            | PHDE                | 2                  | 800831         | 400416       | 06999   | NS                              |
|                            | WS x PHDE           | 8                  | 11349702       | 1418713      | 24798   | 0,0124                          |
|                            | PHDT x PHDE         | 4                  | 12970969       | 3242742      | 56680   | 0,0002                          |
|                            | WS x PHDT x PHDE    | 16                 | 19420764       | 1213798      | 21216   | 0,0070                          |
|                            | Error               | 405                | 231704500      | 572110       | -       | -                               |
|                            | Total               | 449                | 506211611      | -            | -       | -                               |

WS: Wood Species; PHDT: Pilot Hole Diameter; PHDE: Pilot Hole Depth;

NS: Statistically Insignificant

According to the ANOVA results, wood species and pilot-hole diameter had significant main effects on screw holding strength parallel to the grain, whereas pilot-hole depth had no significant main effect ( $p > 0.05$ ). All two-way and three-way interactions among the factors were statistically significant ( $p < 0.05$ ). For screw holding strength perpendicular to the grain, wood species and pilot-hole diameter had significant main effects, whereas pilot-hole depth had no significant main effect. All two-way and three-way interactions were also statistically significant. Therefore, the LSD multiple comparison test was applied to significant main effects and interaction terms to determine differences among the corresponding groups. Examination of the F-values obtained from the ANOVA revealed that wood species had a stronger effect on screw holding strength than pilot-hole diameter and depth.

The comparison results of screw holding strength parallel and perpendicular to the grain according to wood species are given in Table 4.

**Table 4:** Mean comparison of screw holding strength by wood species.

| Wood Species            | Parallel to the Grain |    | Perpendicular to the Grain |    |
|-------------------------|-----------------------|----|----------------------------|----|
|                         | Mean (N)              | HG | Mean (N)                   | HG |
| <i>Larix decidua</i>    | 2084                  | C  | 1373                       | B  |
| <i>Pinus sylvestris</i> | 1811                  | D  | 1160                       | D  |
| <i>Abies sp.</i>        | 2321                  | B  | 1281                       | C  |
| <i>Picea orientalis</i> | 1792                  | D  | 1049                       | E  |
| <i>Cedrus libani</i>    | 3193                  | A  | 1640                       | A  |

HG: Homogeneity group; LSD  $\pm$  9,084 N; LSD  $\pm$  7,009 N

Although no direct statistical comparison was performed between the two grain directions, the mean values indicate that screw holding strength was higher parallel to the grain than perpendicular to the grain under the experimental conditions investigated. The mean values were approximately 25–50% higher parallel to the grain than perpendicular to the grain, depending on the wood species. This difference may be associated with the anisotropic structure of wood and the different mechanisms of interaction between the screw threads and wood fibers in the two orientations. In contrast, in the perpendicular-to-grain direction, the screw cuts across the grain, which reduces mechanical interlocking and results in comparatively lower holding strength. Cedar samples showed the highest strength in both directions, followed by fir and larch; scotch pine and spruce exhibited lower performance. The observed differences among wood species may be related to variations in density and anatomical characteristics, as suggested by previous studies (Eckelman 1975; Doğanay 1995). In particular, differences in grain structure, fiber length, and the arrangement of anatomical elements such as vessels and growth rings can influence the mechanical interlocking between the screw threads and the wood matrix. In addition, microstructural features such as microfibril angle and the proportion of earlywood and latewood may also contribute to the observed variations in screw holding performance. These factors are likely to affect the resistance of wood to screw withdrawal by altering the local strength and deformation behaviour of the material.

The findings are consistent with previous studies highlighting the effect of grain direction and wood species on screw holding strength (Eckelman 1975, Çelebi and Kılıç 2007, Perçin and Ayan 2012). Although the literature mainly focuses on panel-based materials, this study reveals the critical role of species selection and grain direction on the load-bearing capacity of screw connections in solid coniferous woods. The comparison results for the screw holding strength value parallel and perpendicular to the grain according to the pilot hole diameter of the wood species are given in Table 5.

**Table 5:** Mean comparisons of screw holding strength values according to the pilot hole diameter.

| Pilot Hole Diameter<br>(mm) | Parallel to the Grain |    | Perpendicular to the Grain |    |
|-----------------------------|-----------------------|----|----------------------------|----|
|                             | Mean (N)              | HG | Mean (N)                   | HG |
| 2                           | 2368                  | A  | 1254                       | B  |
| 3                           | 2176                  | B  | 1418                       | A  |
| 3,5                         | 2177                  | B  | 1230                       | B  |

HG: Homogeneity group; LSD  $\pm$  7,037 N; LSD  $\pm$  5,429 N

Analysis of the data from the sample shows that the effect of pilot hole diameter on screw holding strength varies depending on the grain direction. Within the pilot-hole diameters evaluated in this study, the highest mean screw holding strength parallel to the grain was obtained with the 2 mm pilot-hole diameter while lower mean values were observed at larger diameters. Within the pilot-hole diameters evaluated in this study, the highest mean screw holding strength perpendicular to the grain was obtained with the 3 mm pilot-hole diameter.

This directional difference reveals that the pilot hole-screw interaction is controlled by the anisotropic structure of the wood. The obtained results are consistent with the literature reporting that small pilot holes increase mechanical locking, but excessively small diameters perpendicular to the fibers can lead to local damage (Özçiftçi 2009, Chen *et al.* 2016). These results indicate that pilot-hole diameter should be selected considering grain direction, as the

highest mean screw holding strength was obtained at different tested diameter levels for the two orientations. The comparison results of screw holding strength in wood materials, parallel and perpendicular to the grain, according to the interaction between pilot hole diameter and pilot hole depth, are presented in Table 6.

**Table 6:** Mean comparison results of screw holding strength according to the two-way interaction between pilot hole diameter and pilot hole depth.

| Pilot hole Diameter (mm) | Parallel to the Grain |          |    | Perpendicular to the Grain |          |    |
|--------------------------|-----------------------|----------|----|----------------------------|----------|----|
|                          | Pilot Hole Depth (mm) | Mean (N) | HG | Pilot Hole Depth (mm)      | Mean (N) | HG |
| 2                        | 10                    | 2174     | DE | 7                          | 1203     | CD |
|                          | 20                    | 2439     | AB | 10                         | 1199     | CD |
|                          | 32                    | 2490     | A  | 13                         | 1360     | AB |
| 3                        | 10                    | 2266     | CD | 7                          | 1397     | A  |
|                          | 20                    | 2084     | E  | 10                         | 1449     | A  |
|                          | 32                    | 2177     | DE | 13                         | 1406     | A  |
| 3.5                      | 10                    | 2322     | BC | 7                          | 1246     | CD |
|                          | 20                    | 2250     | CD | 10                         | 1289     | BC |
|                          | 32                    | 1959     | F  | 13                         | 1157     | D  |

HG: Homogeneity group; LSD  $\pm$  12,19 N; LSD  $\pm$  9,404 N

Table 6 shows that the effect of pilot hole diameter and depth on screw holding strength varies significantly depending on the fiber direction. The highest strength in the direction parallel to the grains was obtained with a combination of a 2 mm pilot hole and 32 mm hole depth, while the strength decreased at larger diameters and depths. In the direction perpendicular to the grain, the highest mean screw holding strength was obtained at a 3 mm pilot hole diameter. These findings are consistent with previous studies reporting that small pilot holes increase mechanical locking, but excessive diameters and depths can cause weakening in the fibers (Özçiftçi 2009, Chen *et al.* 2016). The results indicate that pilot-hole geometry should be evaluated in relation to grain direction and the specific combinations of the experimental factors

considered. The comparison of the three-way interactions between wood species, pilot hole diameter, and pilot hole depth on screw holding strength is presented in Table 7 and Table 8.

**Table 7:** Mean screw holding strength: three-way interactions (parallel to grain).

| Wood Species            | PHDT (mm) | Parallel to the Grain (N) |        |      |        |      |        |
|-------------------------|-----------|---------------------------|--------|------|--------|------|--------|
|                         |           | Pilot Hole Depth (mm)     |        |      |        |      |        |
|                         |           | 10                        |        | 20   |        | 32   |        |
|                         |           | Mean                      | HG     | Mean | HG     | Mean | HG     |
| <i>Larix decidua</i>    | 2         | 2022                      | IJKLM  | 2239 | FGHI   | 2090 | IJKLM  |
|                         | 3         | 2171                      | HIJK   | 2449 | EFG    | 2248 | FGHI   |
|                         | 3,5       | 1891                      | LMNOP  | 2034 | IJKLM  | 1617 | QRS    |
| <i>Pinus sylvestris</i> | 2         | 1996                      | IJKLMN | 2207 | GHIJ   | 2101 | IJKLM  |
|                         | 3         | 2193                      | GHIJ   | 1920 | KLMNO  | 1513 | RS     |
|                         | 3,5       | 1961                      | JKLMN  | 1423 | S      | 986  | T      |
| <i>Abies sp.</i>        | 2         | 2249                      | FGHI   | 2461 | EFG    | 2873 | CD     |
|                         | 3         | 2497                      | EF     | 1844 | MNOPQ  | 2030 | IJKLM  |
|                         | 3,5       | 2397                      | FGH    | 2384 | FGH    | 2150 | HIJKL  |
| <i>Picea orientalis</i> | 2         | 1726                      | NOPQR  | 1935 | JKLMNO | 2041 | IJKLM  |
|                         | 3         | 1533                      | RS     | 1505 | RS     | 2105 | IJKLM  |
|                         | 3,5       | 1621                      | PQRS   | 1669 | OPQRS  | 1989 | IJKLMN |
| <i>Cedrus libani</i>    | 2         | 2876                      | CD     | 3355 | B      | 3346 | B      |
|                         | 3         | 2936                      | CD     | 2703 | DE     | 2991 | C      |
|                         | 3,5       | 3740                      | A      | 3739 | A      | 3053 | C      |

HG: Homogeneity group; LSD  $\pm$  27,25 N

Table 7 shows that the effects of pilot-hole diameter and pilot-hole depth on screw holding strength parallel to the grain varied among wood species, as indicated by the significant three-way interaction among wood species, pilot-hole diameter, and pilot-hole depth. The effect of pilot-hole depth varied among wood species and pilot-hole diameters, indicating that the response should be interpreted in terms of the specific factor combinations rather than as an independent depth effect.

Cedar samples showed the highest values in all combinations; this may be associated with differences in density and anatomical structure (Eckelman 1975, Doğanay 1995). These findings are consistent with previous studies reporting that pilot hole geometry strongly

influences screw-wood interaction and that the best-performing hole sizes among the tested levels should be evaluated in conjunction with species characteristics (Özçiftçi 2009, Chen *et al.* 2016).

The results indicate that the effects of pilot-hole diameter and depth should be considered in relation to wood species, as the highest-performing combinations varied among the species evaluated.

**Table 8:** Mean screw holding strength: Three-way interactions (perpendicular to grain).

| Wood Species            | PHDT (mm) | Perpendicular to the Grain (N) |          |      |         |      |          |
|-------------------------|-----------|--------------------------------|----------|------|---------|------|----------|
|                         |           | Pilot Hole Depth (mm)          |          |      |         |      |          |
|                         |           | 7                              |          | 10   |         | 13   |          |
|                         |           | Mean                           | HG       | Mean | HG      | Mean | HG       |
| <i>Larix decidua</i>    | 2         | 1352                           | DEFGH    | 1393 | DEFG    | 1331 | DEFGHI   |
|                         | 3         | 1328                           | DEFGHI   | 1381 | DEFG    | 1480 | CD       |
|                         | 3.5       | 1391                           | DEFG     | 1435 | CDE     | 1268 | EFGHIJK  |
| <i>Pinus sylvestris</i> | 2         | 1002                           | MNOP     | 1094 | JKLMNO  | 1224 | FGHIJKL  |
|                         | 3         | 1428                           | CDEF     | 1323 | DEFGHI  | 1212 | GHIJKLM  |
|                         | 3.5       | 1216                           | GHIJKL   | 975  | NOP     | 963  | NOP      |
| <i>Abies sp.</i>        | 2         | 1257                           | EFGHIJK  | 1224 | FGHIJKL | 1329 | DEFGHI   |
|                         | 3         | 1390                           | DEFG     | 1391 | DEFG    | 1411 | CDEFG    |
|                         | 3.5       | 1124                           | IJKLMNOP | 1331 | DEFGHI  | 1072 | KLMNOP   |
| <i>Picea orientalis</i> | 2         | 1076                           | KLMNOP   | 987  | NOP     | 1140 | IJKLMNOP |
|                         | 3         | 1129                           | IJKLMNOP | 1122 | IJKLMNO | 1161 | HIJKLMN  |
|                         | 3.5       | 1038                           | LMNOP    | 913  | OP      | 876  | P        |
| <i>Cedrus libani</i>    | 2         | 1326                           | DEFGHI   | 1295 | DEFGHIJ | 1776 | B        |
|                         | 3         | 1712                           | B        | 2029 | A       | 1768 | B        |
|                         | 3.5       | 1459                           | CDE      | 1789 | B       | 1604 | BC       |

HG: Homogeneity group; LSD  $\pm$  27,25 N

According to Table 8, screw holding strength perpendicular to the grain varied significantly among the combinations of wood species, pilot-hole diameter, and pilot-hole depth, as reflected by the significant interaction effects reported in Table 3. Within the experimental combinations evaluated, a 3 mm pilot-hole diameter generally resulted in higher mean screw holding strength values for several species, whereas the 3.5 mm diameter was associated with lower values in some species. This is consistent with the literature reporting that large pilot holes disrupt fiber

continuity and weaken mechanical locking (Eckelman 1975, Özçiftçi 2009). Among the wood species, cedar exhibited the highest screw holding strength in all combinations; followed by fir. In contrast, increasing the hole depth had a limited effect on strength in low-density spruce and scotch pine species. The observed differences may be associated with differences in wood density and anatomical characteristics, consistent with previous studies (Wilkinson and Laatsch 1970; Chen et al. 2016).

## Conclusions

In this study, the relationship between screw holding strength and pilot hole diameter, and depth in different softwood species was experimentally investigated in parallel and perpendicular to grain direction. The results clearly showed that screw holding strength was higher in the direction parallel to the grain than in the direction perpendicular to the grain in all species.

When the effect of wood species was examined, cedar wood exhibited the highest screw holding strength under all test conditions, while fir and larch showed intermediate-to-high strength, and spruce and scotch pine showed relatively low strength values. The observed differences among wood species may be related to differences in density and anatomical characteristics, as reported in previous studies (Eckelman 1975; Doğanay 1995). This relationship should be considered as a possible explanation rather than a directly established relationship in the present study.

Although no statistical analysis was conducted for direct comparison, the experimental data allow certain observations to be made regarding the effect of grain direction. The effects of pilot-hole diameter and depth varied depending on wood species and grain direction, as indicated by the significant interaction effects. Within the experimental conditions evaluated, smaller pilot-hole diameters generally resulted in higher screw holding strength parallel to the grain, whereas a 3 mm pilot-hole diameter generally provided higher mean values perpendicular to the grain. The effects of pilot-hole diameter and depth therefore should be interpreted in

relation to the specific wood species and grain direction rather than as independent effects. In contrast, a 3,5 mm pilot hole diameter resulted in lower strength values in some species. This finding may be related to differences in the amount of wood engaged by the screw threads and the resulting mechanical interlocking. Such mechanisms are proposed as possible explanations and were not directly evaluated in the present study. In conclusion, under the experimental conditions investigated, screw holding strength was influenced by wood species and the interaction of pilot-hole geometry with wood species and grain direction. The study findings provide experimentally based evidence for considering pilot-hole diameter in relation to wood species and grain direction when evaluating screw connections in solid softwoods.

The findings address the identified knowledge gap by providing systematic experimental evidence on the effects of pilot-hole diameter and depth on screw holding strength in five solid softwood species under both parallel- and perpendicular-to-grain conditions. The results demonstrate that the effect of pilot-hole geometry is dependent on wood species and grain direction, providing a basis for more condition-specific evaluation of screw connections in solid wood. The findings are limited to the investigated wood species, 4 × 50 mm screws, pilot-hole dimensions, and test conditions; therefore, their applicability to other screw types, sizes, wood species, and connection conditions should be evaluated separately.

#### **Authorship contributions**

S. D.: Conceptualization, data curation, funding acquisition, investigation, methodology, resources, software, validation, visualization, writing – original draft. S. D.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, resources, supervision, visualization, writing – original draft, writing – review and editing. A. K.: Conceptualization, data curation, funding acquisition, formal analysis, investigation,

methodology, project administration, resources, supervision, software, validation, writing – original draft, writing – review and editing.

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### Declaration of interest

The authors declare no conflict of interest.

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