

Effect of Pilot Hole Application on Screw Withdrawal Resistance and Full-Field Strain Distribution in Beech and Oak Wood Using Two-Dimensional Digital Image Correlation

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Effects of pilot-hole application and screw insertion surface were studied relative to the maximum screw withdrawal force and full-field strain distributions in beech (*Fagus orientalis*) and oak (*Quercus petraea*) wood using two-dimensional Digital Image Correlation (2D DIC). A total of 80 specimens were evaluated in a $2 \times 2 \times 2$ factorial experimental design, including two wood species, two anatomical surfaces (transverse and tangential), and two pilot-hole conditions (with and without pilot holes). Pilot-hole application increased the mean withdrawal force on transverse surfaces by approximately 30.0% in beech and 7.0% in oak. Conversely, it decreased the mean withdrawal force on tangential surfaces by approximately 15.7% in beech and 30.4% in oak. The factorial ANOVA indicated significant effects of anatomical surface and pilot-hole application, together with significant two-way interactions among the experimental factors. The DIC strain maps revealed spatial variations in normal and shear strain distributions around the screw withdrawal region. However, comparisons between experimental groups were interpreted qualitatively because the strain maps were obtained at different maximum load levels. The findings demonstrate that the influence of pilot-hole application depends on the anatomical surface and wood species, highlighting the importance of considering their interactions when evaluating screw withdrawal performance.

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INTRODUCTION

Wood screws are the most commonly used fastening elements in the furniture manufacturing and building industries. Screw withdrawal resistance (SWR) refers to the resistance of wood to the force required to withdraw an embedded screw. The SWR is a major factor affecting the reliability and mechanical strength of screwed joints (Eckelman 1978). Often, research in this area focuses on a comparison of the screw withdrawal resistance values that can be experimentally obtained (Rajak and Eckelman 1993). In addition to being an indicator for mechanical performance, wood screws can be used as semi-destructive probing tools to evaluate the structural degradation of wood due to natural aging and in-service deterioration (Kloiber *et al.* 2015). Moreover, previous research has demonstrated that wood screws can also be used as a reinforcing element for different design arrangements of structural timber products to improve their capacity and

performance under load (Andarini and Raftery 2023).

The main method for screw withdrawal resistance (SWR) estimation is based on experimental procedures and on subsequent prediction with empirical equations considering screw geometry and wood properties (Hoelz *et al.* 2022). Several wood-related investigations showed that SWR is affected by shaft and thread diameter, length of screw penetration into the wood, and thread geometry (Hoelz *et al.* 2021). It is also affected by wood anatomy (Brandner 2019); when the screw was inserted parallel or perpendicular to wood grain (Hoelz *et al.* 2020); by screw insertion procedures, such as the amount of driving torque (Gehloff 2011); the distance of the screw from the edge of the wood element (Li *et al.* 2021); and even by the sharpness of the drill bit employed to make pilot holes (Sydor *et al.* 2024). The size of the screw and the depth of embedment in withdrawal tests have a direct influence on the strength of the connection. For instance, Kaya and İmirzi (2023) used zinc-coated, Phillips-head, #8 screws of 4.2×38 mm dimension by embedding around 15 mm of the screw into the wood samples in the testing. Blaß and Bejtka (2004) considered the bending and compressive strength of timber beams and columns with analytical procedures established for timber engineering. They showed that the bending moments and compressive forces perpendicular to the grain can be transferred significantly by self-tapping screws. They also found that screws not only can be used as a means of fastening but also as a reinforcement element in the wood structures when these are fitted by this method. Mirdad *et al.* (2022) studied the withdrawal resistance of 9- and 11-mm-diameter screws at various penetration depths and installation angles. The study showed a linear increase of withdrawal resistance with increasing depth of screw penetration. They also reported that screw withdrawal resistance decreased as the angle between the screw axis and the wood grain increased from 0° to 90° . The deformations occurring during the mechanical tests were measured using two Linear Variable Differential Transformers (LVDTs). Gašparík *et al.* (2021) mechanically evaluated the screw withdrawal resistance of Norway spruce (*Picea abies*) and European larch (*Larix decidua*) under simulated seasonal temperature conditions ranging from -25°C to $+70^\circ\text{C}$. They reported no statistically significant difference in withdrawal resistance between the tangential and radial directions. Overall, European larch exhibited approximately 70% higher withdrawal resistance than Norway spruce, and increasing temperature resulted in an increase in screw withdrawal resistance. Hu *et al.* (2026) experimentally investigated the withdrawal performance of nuts and dowels embedded at different interference-fit depths in several wood-based materials, including particleboard, plywood, and blockboard. In addition to mechanical testing, stress distributions were analyzed using the Digital Image Correlation (DIC) technique. The authors found interference-fit depths of 0.7, 0.9, and 1.2 mm to be optimal for particleboard, plywood, and blockboard, respectively. They also stated that “DIC is a promising technique for the assessment and prediction of the mechanical behavior of multiple fastening systems in wood-based materials of various densities”. Bardak *et al.* (2017) demonstrated that 2D DIC is an effective technique for evaluating full-field strain distributions in solid wood and plywood under bending loads.

Screw withdrawal resistance has typically been tested using traditional mechanical methods. For the analysis of deformation, instrumentation such as Linear Variable Differential Transformers (LVDTs) have been used. Such devices yield only single-axis displacement measurement data have been used predominantly. By contrast, a smaller number of studies have adopted the DIC technique, and its usage has been typically limited to some specific research fields. Therefore, the potential of DIC for application in other engineering fields as well as in wood joint research does not seem to have been explored

very deeply yet. This leaves much potential in terms of comprehensive full-field deformation and strain measurements. In contrast to prior work that was focused on conventional mechanical evaluation of withdrawal resistance of a screw, in this work full field strain results from 2D DIC are correlated with the screw withdrawal test to expose the effects of pilot-hole application on straining patterns of different wood sections, longitudinal and transverse. This method allows a deeper insight into the mechanical behavior of wood–screw connections.

EXPERIMENTAL

Materials

Beech (*Fagus orientalis* L.) and oak (*Quercus petraea* Liebl.) wood without visible defects such as knots, discoloration, degradation and other structural anomalies was received from a local saw mill in Bartın, Türkiye and utilized as solid wood material for the purpose of this study. For the sake of homogeneity of the test samples, only sapwood portions of each wood species were used. The cubes were prepared such that screw withdrawal tests could later be carried out on the transverse and tangential faces.

Zinc-coated wood screws with a nominal diameter of 3.5 mm and a nominal length of 50 mm were used in the withdrawal tests. Pilot holes with a diameter of 2.5 mm and a depth of 20 ± 0.5 mm were prepared for the corresponding experimental groups. Additional screw-thread geometry parameters, including root diameter, thread pitch, thread depth, and effective threaded embedment length, are relevant to the interpretation of screw withdrawal performance and should be reported based on direct measurements or verified manufacturer specifications. The nominal screw penetration depth was 20 mm. However, the nominal penetration depth should be distinguished from the effective threaded embedment length because the screw tip and any unthreaded portion within the wood may not contribute fully to thread engagement. Consequently, the effective threaded embedment length depends on the actual screw geometry. This distinction should be considered when interpreting withdrawal force and calculating normalized withdrawal resistance. Previous studies on screw withdrawal resistance in different wood species have also reported that the use of pilot holes significantly influences the behavior of screw connections and improves the repeatability of experimental results (Çavuş and Ayata 2018). The screws were fully driven into the pilot holes to the entire drilled depth. The screw used in the experimental tests is shown in Fig. 1.

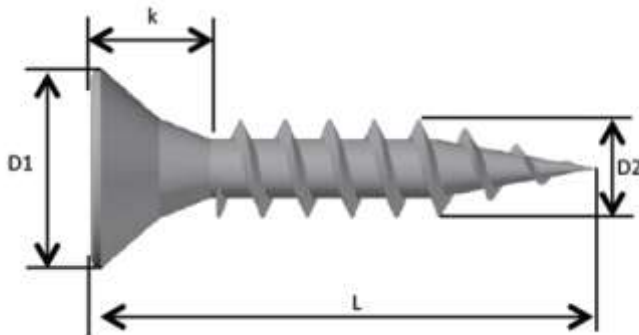


Fig. 1. Configuration of a wood screw (Yagmur Vida)

Table 1. Geometrical Dimensions of the Wood Screw Used in this Study

	D_1 (Head Diameter) (mm)	D_2 (Diameter) (mm)	K (Head Height) (mm)	L (Length) (mm)
Min.	6.64	3.2	-	48.8
Max.	7.5	3.55	3.6	51.2

Density and Moisture Content (MC)

The moisture content and density of the wood materials used in this study were determined in accordance with TS ISO 13061-1 (2021) and TS ISO 13061-2 (2021), respectively. For density determination, ten specimens from each wood species were oven-dried at 103 ± 2 °C until constant mass was achieved. The oven-dry densities of beech and oak were determined to be 0.63 g/cm³ and 0.66 g/cm³, respectively. The screw withdrawal tests were conducted under air-dry moisture conditions. To obtain the air-dry moisture content, seven specimens measuring $50 \times 50 \times 50$ mm were prepared from each wood species and conditioned at 20 ± 2 °C and $65 \pm 5\%$ relative humidity for three weeks. The equilibrium moisture contents of the beech and oak specimens were determined to be 10.1% and 10.4%, respectively.

$$\delta_{12} = M_{12} / V_{12} \text{ (g/cm}^3\text{)} \quad (1)$$

Preparation of Experimental Samples

The maximum screw withdrawal force ($F_{\max}$, N) was determined as the peak load recorded during the withdrawal test. The term maximum withdrawal force is used throughout the manuscript when referring to the experimentally measured values expressed in newtons (N). Normalized screw withdrawal resistance (f , N/mm²), when reported, is distinguished from the measured withdrawal force and calculated using the specified normalization equation and the relevant screw dimensions. Accordingly, the results presented in Table 4 refer to maximum screw withdrawal force ($F_{\max}$), rather than normalized withdrawal resistance.

$$f = \frac{F_{\max}}{d * l_p} \quad (2)$$

where $F_{\max}$ is the maximum load at failure (N), d is the screw diameter (mm), and l_p is the screw embedment depth (mm).

To evaluate screw withdrawal resistance, specimens were prepared using two anatomical sections: transverse and tangential. Gašparík *et al.* (2021) investigated the screw withdrawal resistance of radial and tangential sections and reported no statistically significant difference between these two anatomical directions. Therefore, screw withdrawal tests were conducted on transverse and tangential sections to examine the influence of wood anatomical orientation on withdrawal behavior. The specimen design and experimental groups prepared for this study are presented in Table 2. A total of 80 specimens were prepared for the screw withdrawal tests. The experimental design consisted of two wood species (beech and oak), two anatomical sections (transverse and tangential), and two screw installation conditions (with and without pilot holes). Ten replicate specimens ($n = 10$) were tested for each of the eight experimental combinations. This balanced factorial design allowed the evaluation of the individual and interaction effects of wood species, anatomical section, and pilot-hole application on screw withdrawal performance.

Table 2. Sample Pattern

Wood Species	Section	Application
Beech wood	Transverse	with pilot hole
		without pilot hole
	Tangential	with pilot hole
		without pilot hole
Oak wood	Transverse	with pilot hole
		without pilot hole
	Tangential	with pilot hole
		without pilot hole

Digital Image Correlation (2D DIC)

The anatomical surface and screw insertion direction were considered separately. For specimens prepared with screws inserted perpendicular to the transverse surface, the screw axis was aligned with the longitudinal (L) direction of the wood. For specimens prepared with screws inserted perpendicular to the tangential surface, the screw axis was aligned with the radial (R) direction. The terms “transverse surface” and “tangential surface” refer to the screw insertion surfaces, whereas “longitudinal” and “radial” describe the corresponding screw-axis orientations. The transverse surface is sometimes also called the cross-sectional surface or the end-grain. The strain fields developed at the maximum load ($F_{\max}$) during the screw withdrawal tests were analyzed using the Digital Image Correlation (DIC) technique. Strain measurements were performed using the NCORR software, an open-source, MATLAB-based DIC package that enables two-dimensional full-field strain analysis.

A random black-and-white speckle pattern was applied to the specimen surfaces to enable displacement tracking during the DIC analysis. The pattern was designed to provide sufficient contrast between the speckles and the specimen background. The speckle size and spatial density should be reported based on the original specimen images and the image calibration parameters, since these characteristics can affect correlation quality and spatial measurement resolution (Fig. 2).



Fig. 2. View of the test specimen with a random speckle pattern applied for Digital Image Correlation (DIC) analysis and a wood screw installed

For each test specimen, the maximum load ($F_{\max}$) was recorded as the maximum screw withdrawal force. If normalized withdrawal resistance is calculated, the appropriate normalization equation and screw dimensions must be used. A representative image of the

screw withdrawal test setup and the specimen surface used for the DIC analysis is presented in Fig. 3.

The DIC strain maps presented in Figs. 4 to 6 illustrate the deformation patterns observed in individual screw withdrawal tests. These maps are used to provide qualitative insight into the spatial distribution of normal and shear strains. Since the figures do not represent averaged strain fields across all ten replicates, they should not be interpreted as direct evidence of the variability within each experimental group. The selection criteria for the displayed specimens and the consistency of their strain patterns with those of the remaining replicates should be established from the original image records.

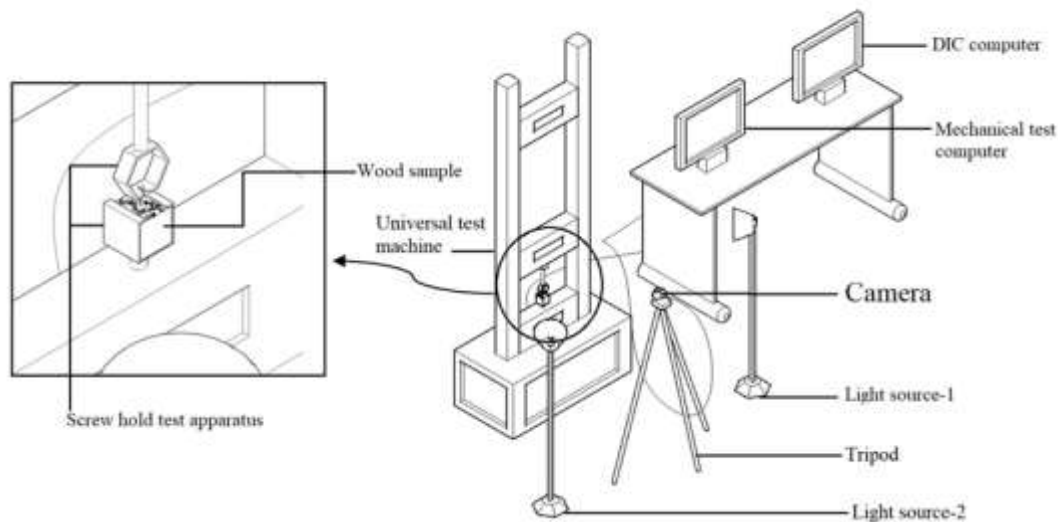


Fig. 3. Integration of 2D DIC method with universal testing machine

Statistical Analysis

A three-way factorial analysis of variance (ANOVA) was performed to evaluate the effects of wood species (beech and oak), anatomical section (transverse and tangential), and pilot-hole application (with and without pilot holes) on maximum screw withdrawal force. The experimental design comprised eight treatment combinations, with ten replicate specimens per combination ($N = 80$). The analysis included the three main effects, all two-way interactions, and the three-way interaction. The ANOVA calculations were based on the reported group means, standard deviations, and sample sizes. Statistical significance was evaluated at $p < 0.05$. Because individual specimen measurements were unavailable for reanalysis, residual normality and outlier diagnostics could not be performed.

RESULTS AND DISCUSSION

Density and Moisture Content

The oven-dry density and air-dry moisture content of the beech and oak specimens used in this study are presented in Table 3. These physical properties were determined prior to the mechanical tests because they have a direct influence on the mechanical behavior and screw withdrawal resistance of wood. They provide an important basis for interpreting the experimental results presented in the following sections.

Table 3. Densities and Moisture Content (MC) of Oak and Beech Wood (g/cm³)

Wood Species	Density (g/cm ³) (Mean $\pm$ SD)	Moisture Content (%) (Mean $\pm$ SD)
Oak	0.66 $\pm$ 0.024	10.40 $\pm$ 0.24
Beech	0.63 $\pm$ 0.026	10.10 $\pm$ 0.26

Mechanical Test Results

The screw withdrawal tests were performed on the transverse and tangential sections of both beech and oak specimens. For each anatomical section, specimens were tested under two installation conditions, namely with and without pilot holes. The screw withdrawal resistance values obtained from the mechanical tests are shown in Table 4.

Differences in the anatomical structure of beech and oak may contribute to the observed variation in screw withdrawal behavior. However, the present study did not directly quantify growth-ring orientation, vessel distribution, ray characteristics, or local wood damage surrounding the screw threads. Consequently, the influence of these anatomical features should be considered a possible explanation rather than a demonstrated mechanism. Further investigations incorporating anatomical imaging and localized damage assessment are required to establish their contributions to screw withdrawal performance.

Table 4. Maximum Screw Withdrawal Force of Beech and Oak Specimens under Different Anatomical Sections and Pilot-Hole Conditions

Wood species	Section	Pilot Hole	Mean $\pm$ SD (N)	Statistical Group*
Beech	Transverse	With	1865 $\pm$ 145	C
	Transverse	Without	1435 $\pm$ 118	D
	Tangential	With	2585 $\pm$ 155	B
	Tangential	Without	3065 $\pm$ 320	A
Oak	Transverse	With	2050 $\pm$ 175	C
	Transverse	Without	1915 $\pm$ 160	C
	Tangential	With	1970 $\pm$ 135	C
	Tangential	Without	2830 $\pm$ 165	AB

*Different letters indicate statistically significant differences ($p < 0.05$).

For beech specimens, pilot-hole application increased the mean withdrawal force from 1435 to 1865 N on transverse surfaces, corresponding to an increase of approximately 30.0%. In contrast, the mean withdrawal force decreased from 3065 N to 2585 N on tangential surfaces, representing a reduction of approximately 15.7%. A similar directional pattern was observed in oak specimens. Pilot-hole application increased the mean withdrawal force from 1915 to 2050 N on transverse surfaces (approximately 7.0%), whereas it decreased the force from 2830 to 1970 N on tangential surfaces (approximately 30.4%). These results demonstrate that the influence of pilot-hole preparation cannot be generalized independently of the screw insertion surface.

This indicates that load transfer was greatly affected by the wood anatomical direction and that in the tangential direction, the mechanical interlocking of the wood fibers with the screw threads, in the unthreaded portion of the screw, was more significant when the screw is driven without pre-drilling. In the case of oak wood, the effect of pilot-hole drilling on screw withdrawal resistance was very low in the radial direction, and the

result did not show any statistical significant difference between the two conditions of installation. However, without pre-drilling, an approximately 43.7% increase in screw withdrawal resistance was obtained in the tangential direction. This can be explained by the ring-porous oak anatomical structure, which gives the screw a better mechanical bonding when the screw is joined with the wood fibers in the tangential direction. One of the most salient aspects of the screw withdrawal tests was that the influence of pilot-hole application varied between the radial and tangential section of the wood. In the present study, pilot-hole application decreased withdrawal force on tangential surfaces in both species, whereas it increased withdrawal force on transverse surfaces. This behavior is likely associated with the anatomical characteristics of wood cells and their orientation relative to the direction of loading. Similarly, previous studies conducted on different wood species have reported that screw withdrawal resistance generally reaches higher values on tangential surfaces than on other anatomical sections (Çavuş *et al.* 2025). No statistically significant difference in screw withdrawal resistance was observed between beech and oak. This finding is likely attributable to the similar densities of the two wood species, which were determined to be 0.63 g/cm³ and 0.66 g/cm³ for beech and oak, respectively. This observation is consistent with previous studies demonstrating that screw withdrawal resistance is closely related to wood density and the integrity of the internal wood structure. Kaya and İmirzi (2023) reported that reductions in wood density resulted in significant decreases in screw withdrawal resistance.

No statistically significant difference was found between the pilot-hole and non-pilot-hole applications in the transverse section of oak. This may be explained by the anatomical characteristics of *Quercus petraea*, a ring-porous hardwood with relatively narrow annual growth rings (Bardarov and Nistorova 2012). These anatomical characteristics could lead to a more even distribution of stresses around the threads of the screw and lessen the impact of using the pilot hole on the withdrawal resistance.

To extend the study on the influence of wood species, section orientation, and pilot hole use on screw withdrawal resistance, statistical analyses were carried out. The results of these analyses are presented in Table 5. The statistical analysis was conducted to determine whether the observed differences among the experimental groups were statistically significant ($p < 0.05$).

Table 5. Three-way Factorial ANOVA Results for Maximum Screw Withdrawal Force

Source of Variation	df	F-value	p-value
Wood species (A)	1	1.301	0.258
Anatomical section (B)	1	385.640	<0.001
Pilot-hole application (C)	1	22.833	<0.001
AxB	1	87.255	<0.001
AxC	1	17.321	<0.001
BxC	1	137.960	<0.001
AxBxC	1	0.275	0.602
Error	72	-	-

The ANOVA was calculated from the reported group means, standard deviations, and sample sizes ($n = 10$ per group). Statistical significance was evaluated at $p < 0.05$. The three-way factorial ANOVA results are presented in Table 5. Anatomical section had a statistically significant effect on maximum screw withdrawal force ($F = 385.640$, $p < 0.001$). Pilot-hole application also showed a significant main effect ($F = 22.833$, $p < 0.001$),

whereas the main effect of wood species was not statistically significant ($F = 1.301$, $p = 0.258$). Significant two-way interactions were observed between wood species and anatomical section ($F = 87.255$, $p < 0.001$), wood species and pilot-hole application ($F = 17.321$, $p < 0.001$), and anatomical section and pilot-hole application ($F = 137.960$, $p < 0.001$). However, the three-way interaction was not statistically significant ($F = 0.275$, $p = 0.602$). These findings indicate that the effect of pilot-hole application on screw withdrawal force depends on the anatomical section and wood species. Therefore, the influence of pilot holes should be interpreted in relation to the specific experimental combinations rather than solely on the basis of overall main effects.

2D DIC Analysis

The full-field strain maps obtained from the Digital Image Correlation (DIC) analysis are presented in detail in Figs. 4 through 6, providing a comprehensive visualization of the deformation behavior under the maximum applied load. The full-field strain distributions presented in Figs. 4 through 6 were obtained at the maximum withdrawal force ($F_{\max}$) of the corresponding specimens. Because the maximum force differed among experimental groups, the strain maps represent different absolute loading conditions and potentially different stages of local damage development. Therefore, direct comparisons of strain magnitude or spatial extent between groups should be interpreted cautiously. The presented DIC maps provide qualitative information about deformation localization and distribution rather than a controlled comparison at an identical applied load.

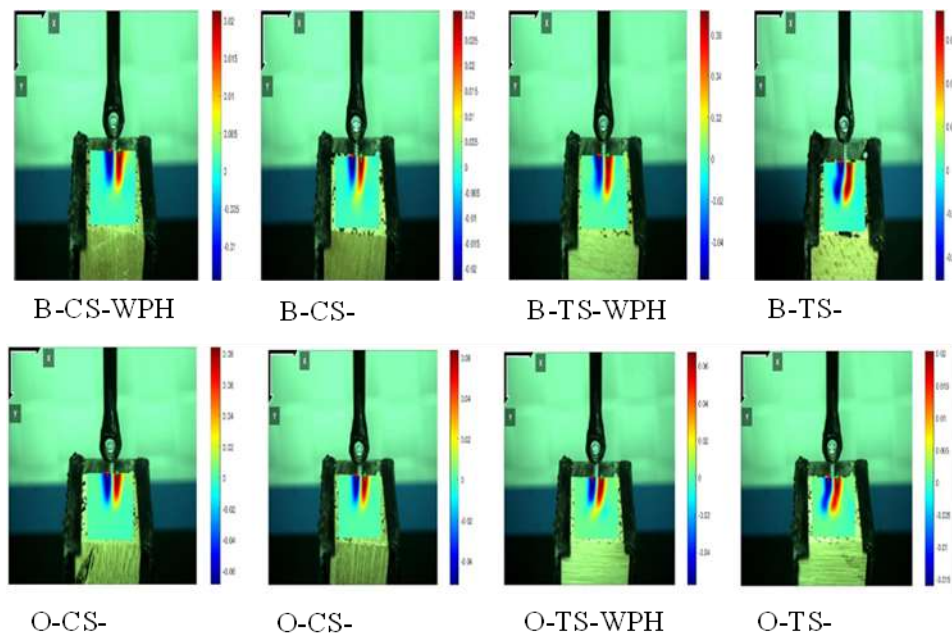


Fig. 4. Strain distributions in the XX direction (B: Beech, O: Oak, CS: Transverse, TS: Tangential Section, WPH: With Pilot Hole, WoPH: Without Pilot Hole)

Figure 4 illustrates the distribution of the normal strain component (ϵ_{xx}) around the screw withdrawal region. The observed strain concentrations indicate nonuniform deformation of the specimen surface during loading. Differences in the spatial distribution of ϵ_{xx} may be associated with the screw insertion condition, wood anatomical structure, and

local deformation mechanisms. However, because the strain maps were obtained at different maximum withdrawal forces, direct comparisons of strain magnitude and affected area should be interpreted cautiously. The sign and magnitude of ϵ_{xx} should be evaluated according to the coordinate system and color scale used in each map.

The ϵ_{xx} strain maps reported in Fig. 4 show that the maximum tensile strain magnitudes occurred immediately at the tip of the screw for both test methods, where load was transferred from the screw to the surrounding wood. In the samples without pilot hole, the strain field was spread on a much wider area, especially in the tangential sample. This suggests that a larger region of the surrounding wood underwent surface deformation. However, these strain maps were obtained at different maximum loads, and they do not independently establish the underlying mechanical interlocking mechanism.

The strain pattern for the samples with pilot holes was more concentrated and radially symmetric. The pilot hole eliminated the difference in densification of wood around the screw threads, resulting in a more even stress distribution and less strain on the neighboring fibers. Similar results were obtained by Hu *et al.* (2026) who demonstrated that DIC-based measurements can sensitively detect strain concentrations in the vicinity of mechanical fasteners and offer insights associated with stress redistribution under withdrawal loading. Figure 5 presents the in-plane shear strain component ϵ_{xy} . The adjacent regions with opposite strain signs indicate local variations in the direction of shear deformation around the screw withdrawal zone. Such patterns may arise from nonuniform displacement and local rotation of the surrounding wood material during loading. The red and blue regions correspond to positive and negative shear strain values according to the plotted color scale. These observations describe the measured surface deformation field and do not, by themselves, establish the underlying internal failure mechanism.

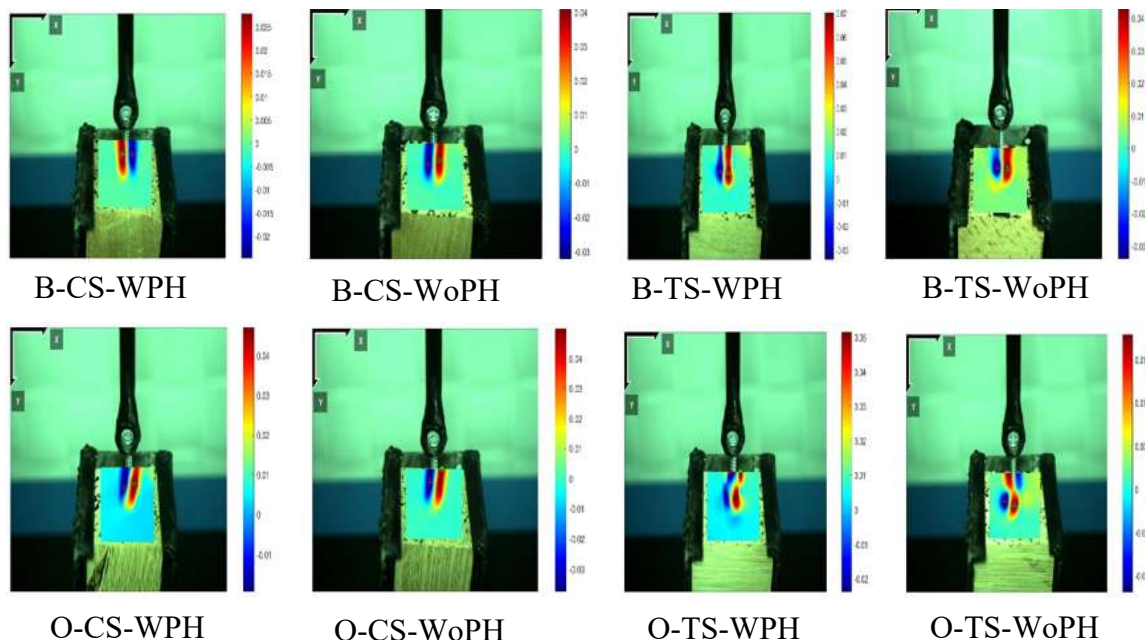


Fig. 5. Strain distributions in the XY direction (B:Beech, O: Oak, CS:Transverse Section, TS: Tangential Section, WPH: With Pilot Hole, WoPH: Without Pilot Hole)

The maps of ϵ_{xy} strain show that shear strains were produced asymmetrically around the screw under withdrawal loading. This was particularly pronounced in tangential samples without pilot holes, as the engagement between screw threads and longitudinal

wood fibers created larger shear deformation fields. Due to the highly anisotropic nature of wood, the shear strain was biased along the fiber direction, rather than radially around the screw.

The shear strain field was significantly diminished by the use of a pilot hole. The reduction of compression in the wood surrounding the screw threads allowed for a reduction in the local shear stresses and an even more balanced deformation. Similar results have been demonstrated by Hoelz *et al.* (2020), showing that screw thread geometry exploitation of wood structure has a great impact on failure initiation and deformation under withdrawal loading.

The distributions of ϵ_{yy} strain in Fig. 6 illustrate that the compressive strain was concentrated under the screw head and round the screw axis in the direction of the withdrawal load. Samples with pilot holes showed significantly more localized strain concentrations which means that the pretension load was borne on a relatively small area around the screw. Conversely, general tests without pilot holes revealed wider compressive strain fields in the surrounding wood matrix. This suggests that more wood was deformed prior to screw withdrawal, which agrees with the higher withdrawal resistance observed in the tangential samples without pilot holes. The strain localization patterns observed here are consistent with prior work showing that full-field DIC measurements can be used to gain insight into how deformation nucleates and evolves about mechanical fasteners (Mirdad *et al.* 2022; Hu *et al.* 2026).

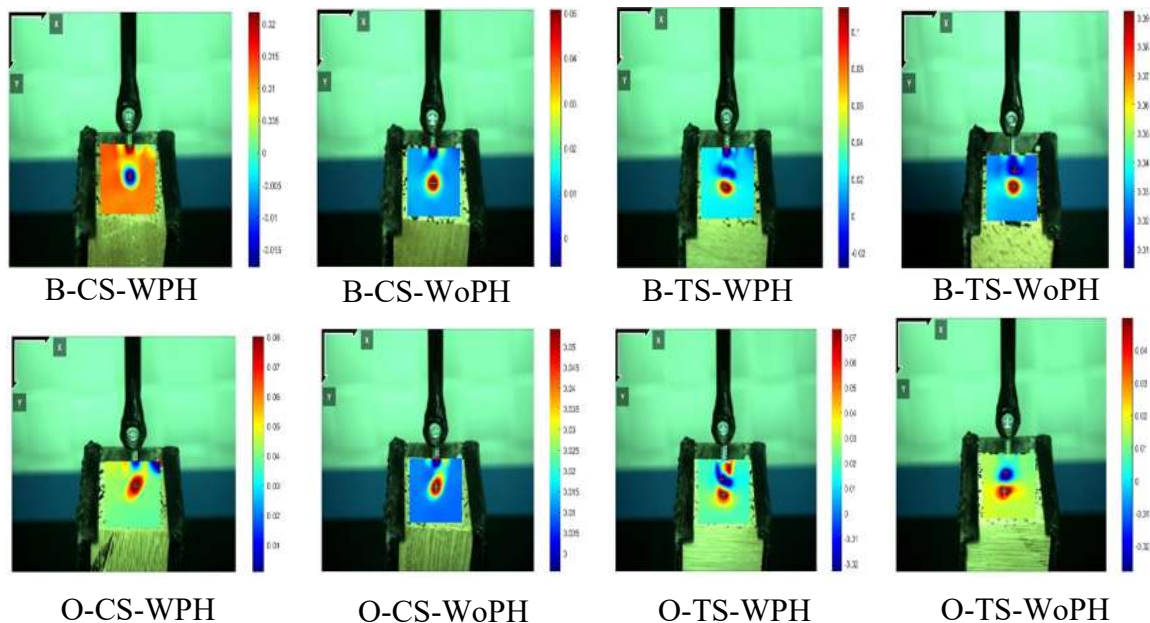


Fig. 6. Strain distributions in the YY direction (B: Beech, O: Oak, CS: Transverse Section, TS: Tangential Section, WPH: With Pilot Hole, WoPH: Without Pilot Hole)

The broader strain distributions observed in some specimens without pilot holes may be associated with several interacting mechanisms. In addition to mechanical engagement between the screw threads and surrounding wood, screw insertion without a pilot hole may produce localized fiber crushing, plastic deformation, microcracking, splitting, and residual stresses. These insertion-related effects could influence the subsequent deformation response during withdrawal. Since the present study did not directly characterize damage induced during screw installation, the observed strain patterns

cannot be attributed exclusively to stronger mechanical interlocking. The DIC analysis in the present study primarily focuses on the qualitative comparison of full-field strain distributions. Although the strain maps provide information about deformation localization and the spatial extent of strain development, quantitative comparisons of maximum strain values or region-of-interest (ROI) averages were not performed across all replicate specimens. Therefore, the findings should be interpreted as descriptive observations rather than statistically validated differences in strain magnitude. Future analyses incorporating consistent ROI definitions and replicate-based strain measurements would enable a more comprehensive quantitative comparison of deformation behavior. The strain concentrations observed near the screw insertion region may reflect local interactions between the screw threads and surrounding wood. However, the surface strain maps obtained using 2D DIC do not directly reveal the positions of individual screw threads within the specimen. Therefore, a direct spatial correspondence between specific thread locations and the observed strain concentrations cannot be established from the present measurements. Additional imaging or sectioning techniques would be required to investigate these localized interactions in greater detail. The findings of this study are specific to the screw geometry, pilot-hole dimensions, wood species, and experimental conditions investigated. Different screw designs, including self-tapping screws and screws with alternative thread profiles or tip geometries, may produce different withdrawal responses and local deformation patterns. Therefore, the observed effects of pilot-hole application should not be generalized to all screw types without additional experimental validation.

CONCLUSIONS

1. Pilot-hole application influenced maximum screw withdrawal force differently depending on the anatomical surface. On transverse surfaces, the mean withdrawal force increased by approximately 30.0% in beech and 7.0% in oak following pilot-hole application. In contrast, reductions of approximately 15.7% and 30.4% were observed on tangential surfaces in beech and oak, respectively.
2. The factorial ANOVA indicated statistically significant main effects of anatomical surface and pilot-hole application. Significant two-way interactions were also identified between wood species and anatomical surface, wood species and pilot-hole application, and anatomical surface and pilot-hole application. These findings suggest that the effects of the experimental factors should be evaluated in combination rather than independently.
3. The highest mean withdrawal force (3065 N) was recorded in beech specimens without pilot holes on tangential surfaces, whereas the lowest mean value (1435 N) was obtained in beech specimens without pilot holes on transverse surfaces. These differences demonstrate the substantial influence of screw insertion surface and installation conditions on withdrawal performance.
4. The 2D DIC analysis provided qualitative information about the spatial distribution of normal strains (ϵ_{xx} and ϵ_{yy}) and shear strain (ϵ_{xy}) around the screw withdrawal region. Differences in strain localization were observed among experimental configurations. However, because the strain maps were obtained at different maximum loads, direct quantitative comparisons between groups require further investigation.

5. The broader strain distributions observed in some specimens without pilot holes may be associated with multiple mechanisms, including screw-thread engagement, localized fiber crushing, plastic deformation, microcracking, and residual stresses. The present measurements do not permit these mechanisms to be distinguished conclusively.
6. The findings are specific to the investigated wood species, screw geometry, and experimental conditions. Further studies incorporating quantitative DIC measurements, detailed anatomical characterization, and alternative screw designs are recommended to better understand the mechanisms governing screw withdrawal behavior.

The application of two-dimensional Digital Image Correlation provided additional qualitative information about surface strain localization and deformation patterns during screw withdrawal testing. The technique complemented conventional force measurements by visualizing spatial variations in normal and shear strains. However, the present study did not independently quantify DIC measurement uncertainty or establish repeatability through a dedicated validation procedure. Therefore, conclusions regarding measurement accuracy and reproducibility require further experimental verification.

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ChatGPT (OpenAI) was used solely to improve the grammar, readability, and language of this manuscript. The authors take full responsibility for all scientific content, including the study design, data analysis, interpretation of the results, and final conclusions.

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