



Wood screw design: influence of thread parameters on the withdrawal capacity

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Abstract

Self-tapping wood screws are important fasteners in timber construction. A characteristic of these screws is their high axial load-bearing capacity, which also depends on their withdrawal capacity. This is used for structural design and is thus an important optimization parameter for wood screws. To increase the withdrawal capacity, knowledge of the influence of the thread parameters, such as outer diameter, pitch or flank angle, is required. The influences of pitch and flank angle on the withdrawal capacity have not yet been sufficiently subjected to research and are therefore investigated in this study. A total of ten specially developed screw prototypes with pitches in the range of 3.04 mm and 5.9 mm and flank angles in the range of 35° and 45° are used. The screw prototypes are flat ribbed bars with uncoiled screw thread. The effect on the withdrawal capacity is measured using an experimental setup based on test standard EN 1382:2016. The pitch showed a significant influence ($p=0.000$, $f=0.37$) whereas the influence of flank angle was not significant ($p=0.283$). A smaller pitch leads to a higher withdrawal capacity, irrespective of the flank angle. The experimental results are explained based on the theoretical models of bonding mechanisms and conical stress distribution. To optimize the withdrawal capacity of a \varnothing 8 mm screw, a smaller pitch is preferable. The determined influence of the pitch can also be used to improve the accuracies of calculation models for the withdrawal capacity.

1 Introduction

For joining elements made of wood, wood-based materials, and for metal-to-timber-connections, one of the preferred methods is using wood screws (Sydor 2019; Ringhofer and Schickhofer 2014). The use of wood screws, especially self-tapping ones, has increased in recent years (Frese and Blaß 2009). “Main reasons for their success are a flexible geometry enabling simple and economic installation without pre-drilling as well as a high load-bearing potential in terms of resistance and stiffness if stressed in axial direction” (Ringhofer et al. 2015b, p.79). When loaded in axial direction, a distinction is made between four failure mechanisms: (i) steel failure in tension and compression, (ii) pull-through failure of the screw head, (iii) withdrawal failure of the threaded part of the screw, and (iv) block shear failure of a group of screws (Ringhofer et al. 2015b). The failure mechanisms (i) and (ii) are rarely decisive for the design procedure

(Ringhofer and Schickhofer 2014). Joints with axially loaded screws are determined through withdrawal failure (iii) (Pirnbacher et al. 2009). This failure of the threaded part of the connection is a composite action between screw thread and timber (Ringhofer et al. 2015b).

The withdrawal capacity is limited by this failure. For use in load-bearing timber connections, self-tapping screws must fulfil the Construction Product Regulation (CPR) shown by CE-marking based on a European Technical Assessment (ETA) or EN 14592 (2012). The withdrawal capacity is an important parameter for this approval. It is used in the design of structural engineering and is therefore an essential optimization parameter for wood screws. According to Sydor (2019), the withdrawal capacity is usually analyzed for changing the constructive properties of wooden workpieces. Although it can be suspected that screw manufacturers have conducted tests on the influence of thread parameters on withdrawal capacity, there are no studies with significant results. The knowledge of these influences can be used to increase the single screw performance as well as to improve the overall structural capacity.

The present publication focuses on investigating the influence of thread parameters on the withdrawal capacity. For

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this purpose, details on thread parameters and the influence of wood are presented. Then, known influences of thread parameters on the withdrawal capacity are described.

1.1 Thread parameters of wood screws

Wood screws are composed of different design elements. According to Sydor (2019), for a partly threaded screw a distinction can be made between the five main elements shown in Fig. 1, left: head, unthreaded shank, shank profile, threaded shank, and tip. The screws can also have other possible elements, such as compressor after tip. Each element is relevant to different functions. The threaded shank is the element relevant to the failure mechanism (iii) and thus to the withdrawal capacity. The threaded shank is described by the parameters shown in Fig. 1 on the right. ISO 5408 (2009) defines the relevant parameters for threads. Threads are often described using the parameters outer diameter d , inner diameter $d1$, and pitch P . The pitch is the changed height of a screw flank during one turn. The flank distance is the axial distance between a thread flank and the immediately adjacent flank. For single-start threads, the pitch and flank distance are the same. In the case of multi-start threads, the thread flanks directly adjacent to each other do not belong to one pitch.

The thread height a also is an important parameter. It is defined by the radial distance between the crest and root of a thread ridge (ISO 5408:2009). Furthermore, there are the parameters flank angle α and lead angle φ . The lead angle is the result of the incline of the helical thread. It is the acute angle by the tangent of the helix and the plane perpendicular to the axis of the cylinder on which it lies (ISO 5408:2009). This angle can be calculated according to the uncoiled helix

using Eq. (1). Both the pitch P and the outside diameter d must be in mm.

$$\varphi = \arctan\left(\frac{P}{\pi \cdot d}\right). \quad (1)$$

Thus, single-start threads can be specified by the parameters of outer diameter d , inner diameter $d1$, thread height a , pitch, flank angle α , and lead angle φ .

1.2 Influence of wood

The material wood is a challenge in the analysis of the composite action of wood screws. Self-tapping wood screws are commonly used in softwood, such as spruce or fir (Blaß et al. 2006). These are anisotropic due to their naturally grown structure. Its mechanical behavior depends on its density, moisture, and natural characteristics (Franke and Quenneville 2011). Furthermore, the material properties change over time and temperature. Alternating early and late wood result in different main directions in the wood. The properties of the wood depend on these main directions (Pech et al. 2016). As shown in Fig. 2 left, a distinction is made between the main axes longitudinal (L), radial (R), and tangential (T).

The influence of these directions on the withdrawal capacity of screw joints is known. The withdrawal capacity depends on the angle between screw axis and fiber direction. The angle varies between 0° (parallel to the fiber) and 90° (normal to the fiber). This influence was shown by Blaß et al. (2006) and Ayoubi and Trautz (2015). It is also considered in design procedures such as EN 1995s-1-1 (2010).

A study by Hoelz et al. (2020) investigated the failure behavior of wood screws in spruce at an angle of 90° to the fiber direction. It was found that the observable failure behavior depends on the observation plane. The main directions (L, R, T) are used to define these observation planes (RT, TL, LR). Depending on the observation plane, other failure mechanisms of the composite action of thread and wood become visible. This effect was explained by the varying fiber directions depending on the observation plane (see Fig. 2, right). The withdrawal capacity is influenced by different failure mechanisms depending on the fiber direction. Further, fiber deviations appear globally over the whole length or more locally over a limited length and reduce the strength of timber (Denzler and Weidenhiller 2014). The fiber direction can, therefore, be regarded as a disturbance variable, which should be reduced or controlled to identify influences between screw parameters and withdrawal capacity (Hoelz et al. 2020).

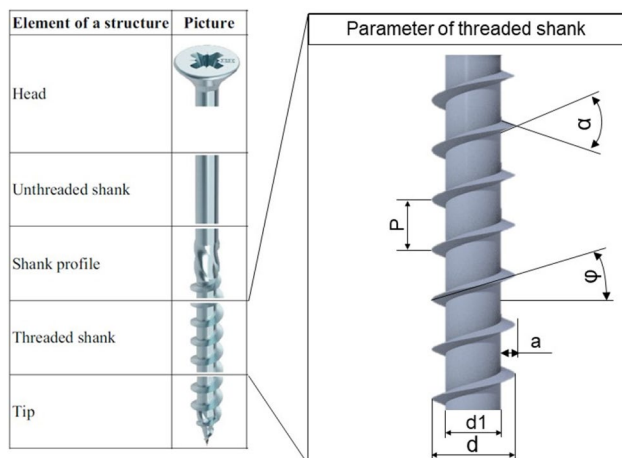


Fig. 1 On the left, elements of wood screws (Sydor 2019), and on the right, parameters of the threaded shank

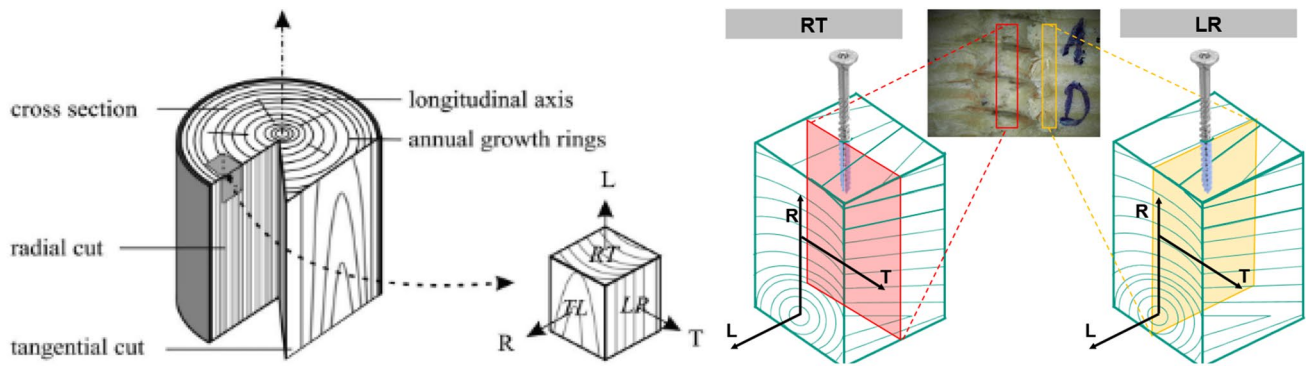


Fig. 2 Main directions of wood (Franke and Quenneville 2011), and different observation planes (Hoelz et al. 2020)

1.3 Influences of thread parameters on the withdrawal capacity

In the following, the known influences of thread parameters on the withdrawal capacity are presented based on experimental tests. The withdrawal capacity of self-tapping screws is described in different calculation models. However, calculation models like those provided by Frese et al. (2010), Zarnani and Quenneville (2014), or Ringhofer et al. (2015a) do not have the goal of determining the influences between screw parameters and withdrawal capacity to optimize the screw. The aim is to improve the prediction quality of design procedures. For calculation of the withdrawal capacity, the regression model by Frese et al. (2010) uses the parameters screw-in depth, the outer diameter, and the density of wood. Thus, the outer diameter and embedded thread length are the only thread parameters representing thread geometry in the design of withdrawal capacity.

The influence of the outer diameter on the withdrawal capacity was also investigated by Pirnbacher et al. (2009). Increasing the outer diameter is often not suitable for increasing the single screw performance. The maximum possible screw diameter is often limited by the application itself. For example, for metal-to-timber connections, the diameter is predetermined. To avoid the splitting behavior, or fit a group of screws with spacings and minimal distances in a given geometry of a member, the smallest possible screw diameter should be used.

Gaunt (1997) investigated the withdrawal capacity of five types of screws, that were screwed into radiata pine parallel to the grain. The thread profiles used differed in thread pitch, thread height, and flank angle. No significant difference in the thread profiles on the withdrawal capacity could be shown.

Pirnbacher and Schickhofer (2007) investigated the influence of screw parameters on the withdrawal capacity. For this investigation, they used commercially available self-tapping screws. These differ in head, shank profile, and

tip, as well as in thread parameters such as thread height, inner diameter, and flank angle. Pirnbacher and Schickhofer (2007) showed an influence of the different screws on the withdrawal capacity in spruce, but concluded that it is not relevant to their investigation purpose. Because the screws differed in many parameters and only the difference between screw clusters was investigated, it could not be shown which thread parameters cause this influence. Hübner (2013) also investigated the influence of thread pitches of commercially available screws. The screws varied in a few parameters such as pitch, flank angle and inner diameter. The result of the investigation was that the medians of the withdrawal capacity for the pitches differ. However, a statistical significance for the influence of the thread pitch on the withdrawal capacity could not be shown for spruce.

Hoelz et al. (2020) assume that the pitch has an influence on the withdrawal capacity. In the study, the failure behavior of wood screws in spruce during the pull-out process was investigated for different screws. For the investigation, two analysis techniques allowing failure process observation are presented. Based on the observations, the hypothesis was made that pitches smaller than 3.6 mm lead to higher withdrawal capacities than larger pitches. This hypothesis was based on the argument that the contact surface of the flanks is increased by the smaller pitch and the stress is distributed more evenly in the wood environment. Hoelz et al. (2020) could not confirm the hypothesis but suggested to test it with wood screws, which vary in these parameters.

2 Aim

Knowledge of the influence of the thread parameters is required to be able to optimize wood screws with regard to their withdrawal capacities. Whereas the influence of the thread parameter outer diameter is already known, the influence of other thread parameters has not yet been sufficiently investigated. Although the influence of thread parameters

has been suspected in many studies, no significant result could be shown so far. In this study, the influence of the pitch and the flank angle on the withdrawal capacities of wood screws will be investigated. The disturbance variable fiber direction must be reduced because it constitutes a difficulty in the determination of the influences. This knowledge enables to increase the withdrawal capacity of single screws while keeping the outer diameter constant. This is important because it allows for the structural capacity of the overall construction to be increased and design procedures to be improved by taking the examined parameters into account.

3 Materials and methods

To investigate the influence of thread parameters on the withdrawal capacity, this chapter presents the used screw prototypes and wood specimens as well as the experimental procedure and sample preparation. Finally, the study design and models to explain the experimental results are described.

3.1 Materials: screw prototypes and test pieces

Screw prototypes are required for investigation of the thread parameters pitch and flank angle. According to Hoelz et al. (2020), the fiber direction is a disturbance variable that should be reduced. According to ISO 5408 (2009), the thread is a continuous and projecting helical ridge of uniform section on a cylindrical surface. The flanks of the screw thread interact in timber with timber in observation planes RT and LR with different mechanical properties. To reduce this mixed influence and analyze the influence of observation planes RT and LR, it is recommended to uncoil the thread from the cylinder to a plane. To determine the influence of the thread parameters pitch and flank angle,

the uncoiled thread is not applied to a round but to a flat base body. For the present investigation, ribbed bars with uncoiled screw thread were used. This so-called screw prototype is shown in Fig. 3.

In Fig. 3, the pitch P corresponds to the flank distance. The lead angle φ was calculated using Eq. (1) assuming an outer diameter of 8 mm. For screws, the parameters pitch, outer diameter, and lead angle are geometrically dependent. For these screw prototypes, the parameters could also be selected independently. The thread height a was chosen to be constant at 1.48 mm. The T-profile at the upper end of the screw prototype was used for coupling to the pull-out machine. The values for the parameters pitch P and flank angle α are varied according to the values of the study design from Table 1. The values lead angle φ and thread length $lg1$, which are adjusted accordingly, depend on this. Care is taken to represent only whole flanks that span the entire width of the prototype. To avoid lateral forces during the pull-out process, the thread flanks on the front and back were arranged in opposite directions to each other. Two different variants of the manufactured prototypes (GP04 and GP10) are shown in Fig. 3 on the right. The screw prototypes were made from 90MnCrV8 (No. 1.2842). They were hardened at 840 °C and tempered at a temperature of 420 °C for 50 min with subsequent furnace cooling.

Spruce (*Picea abies* (L.)) was used for the test pieces. The specimens were conditioned to a humidity content of 15% according to EN 1382 (2016). The strength class of the spruce was C24 according to EN 338 (2016). The wood was screened, so that all tests could be carried out in tangential direction. Only wood was used that had no natural defects such as knotholes, resin pockets, or fissures. According to EN 1382 (2016), the test pieces used have a minimum width and thickness in screw-in direction of the sum of the screw length and five times the screw diameter. For the screw

Fig. 3 Screw prototype with the parameters pitch P and flank angle α

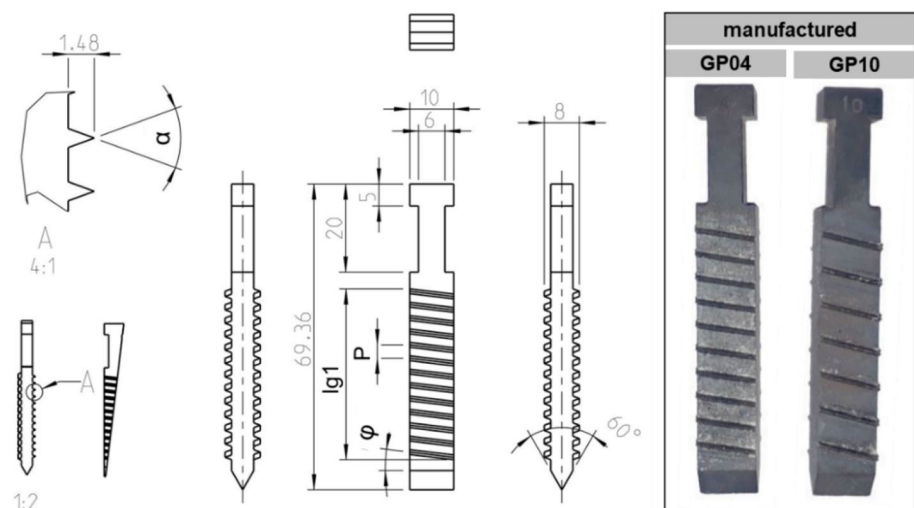


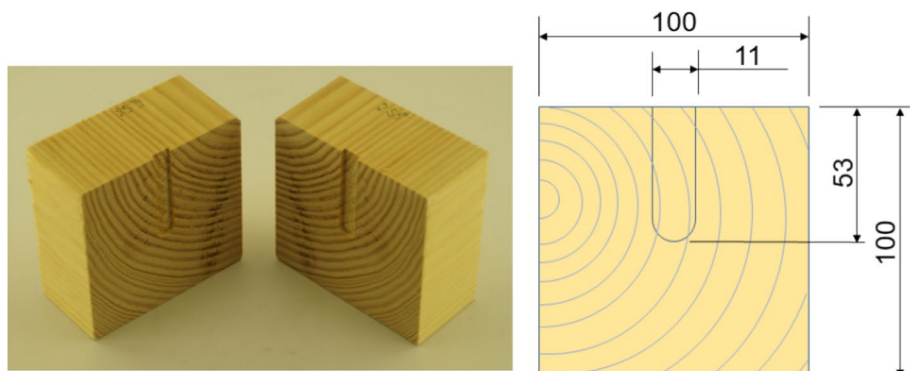
Table 1 Factor levels and dependent parameters of the manufactured screw prototypes used for this investigation

Screw prototype	Factors		Dependent parameters		Comment
	P	α	φ	lg1	
GP01	3.04	40	6.8	38.76	
GP03	3.64	40	8.1	38.91	
GP04	4.03	40	8.9	38.93	
GP05	4.5	35	10	38.71	
GP06	4.5	40	10	38.86	
GP07	4.5	45	10	39.01	
GP08	5.11	40	11.3	38.87	
(GP09)	5.9	35	13	38.67	not used
GP10	5.9	40	13	38.81	
GP11	5.9	45	13	38.97	

diameter, the largest side of the screw prototype is considered to be 10 mm. Therefore, wood with a cross-section of 100×100 mm was used.

3.2 Experimental procedure

The withdrawal capacity was measured with pull-out tests according to EN 1382 (2016). It corresponds to the maximum force in the tests and is shown in kilonewtons. The pull-out tests were carried out at a uniform speed, which was determined in accordance with EN 1382 (2016). The force was measured with a load cell (manufacturer: HBM, product: U2B/50 kN, Darmstadt, Germany). The displacement was measured with a potentiometric displacement transducer (manufacturer: novotechnik, product: TE1-0050-102-411-101, Ostfildern, Germany). Both force and displacement were recorded continuously. A mounting was used to connect the test pieces to the pull-out machine. EN 1382 (2016) defines that for the mounting, at least a distance of three times the screw diameter is required. The distance was therefore 80 mm for the width of the screw prototype of 10 mm and 62 mm for the thickness of 8 mm.

Fig. 4 Test piece halves and their dimensions

3.3 Experimental setup

To measure the withdrawal capacity, a specially developed experimental setup is presented for the screw prototypes. Because of the geometry changes, which enable a disturbance-reduced investigation, the screw prototypes cannot be screwed in anymore. They were therefore inserted into the test piece halves shown in Fig. 4 and braced. To be able to insert the screw, a groove was milled into the test piece.

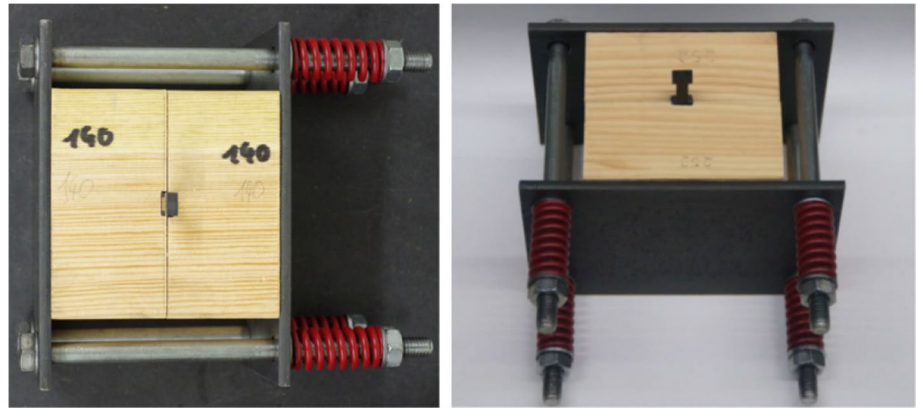
According to Brandner et al. (2019), it is state-of-the-art to pre-drill with a maximum diameter equal to the inner diameter of screws and does not lead to a loss in withdrawal capacity. The groove of the test piece corresponds to the pre-drilling for screws. The depth of the groove was 2.5 mm. The groove width of both halves, therefore, was 5 mm. With a width of the screw prototype of 5.04 mm, which can be compared to the inner diameter of screws, this condition is fulfilled. Hoelz et al. (2020) have presented a similar experimental setup in which two test piece halves were clamped with bolts. It was found that bracing leads to a failure behavior comparable to that of screwed-in screws in solid wood. However, the absolute withdrawal capacity will be changed by the setup.

EN 1382 (2016) defines that the axis of the fastener must be perpendicular to the wood surface. The groove was arranged accordingly. With 11 mm, the groove was wider than the screw prototypes with 10 mm to avoid friction at the sides of the screw prototype. The groove length of 53 mm ensures that the groove is longer than the thread length and tip of the screw prototypes.

To determine the withdrawal capacity in pull-out tests, the two halves of the test piece were clamped with the screw prototype inserted. Figure 5 shows the clamping consisting of two 5 mm thick sheets of S235JR, which were connected by four hexagon head bolts M10×170 (ISO 4014:2011) of strength class 8.8.

The wood piece was pretensioned by helical compression springs (Sodemann Industrifjedre A/S, product: R205-408, 94.2 N/mm, Hinnerup, Denmark). As a result of the preload, the thread of the screw prototype was pressed into the groove

Fig. 5 Experimental setup for bracing the piece halves

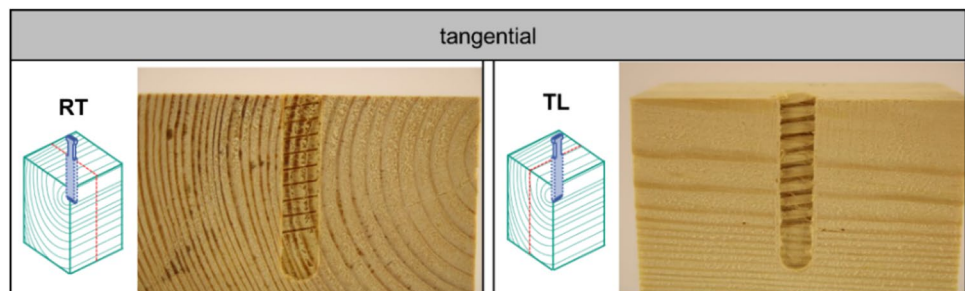


base. The preload was 3.2 kN. This was determined in preliminary tests. Criteria for a minimum preload were the gap-free contact of the test halves over the entire surface and the complete penetration of the thread into the wood. In individual cases, a higher force was applied until there was gap-free contact and then the spring was unloaded to the nominal force. The preload must be lower than the permitted force, which leads to failure of the wood. According to EN 338 (2016), strength class C24 of the wood corresponds to a compressive strength in the direction of the grain of 21 N/mm² and 2.5 N/mm² across the grain. EN 338 (2016) is for structural timber and the values are to be seen as very conservative estimates for small clear wood test pieces. However, for a cross-section of 100 × 100 mm, a maximum compressive force of 25 kN for compression across the grain is therefore permissible.

3.4 Study design: parameters and factor levels

For this investigation, the thread parameters pitch and flank angle were varied. The factor levels used are listed in Table 1. Non-linear correlations were assumed. Therefore, the pitch was examined in six steps, the flank angle in three steps. For practical relevance, the parameters were varied in the range of those used for commercial screws. The dependent parameters lead angle φ and thread length lgI , for the selected factor levels, are also shown in Table 1. To reduce the test effort, a test plan with D-optimality design was used.

Fig. 6 The fiber directions RT and TL to be examined, with the same tangential screw-in direction of the screw prototype



Screw prototypes were produced for the mentioned factor levels. Due to manufacturing problems, GP09 could not be used for the tests.

The straight screw flanks reduce the disturbance variable fiber direction. With the same screw-in direction, different fiber orientations can be investigated by axial rotation of the screw prototype. In Fig. 6, the screw prototype is shown schematically for the tangential screw-in direction in two different fiber directions. In the present investigation, the fiber direction was therefore included as an additional factor. Both fiber directions RT and TL were examined for the tangential screw-in direction.

To reduce the influence of the wood, the experimental design was randomized. The experiments were divided into blocks on the wooden beams to be able to calculate the influence of the wood strength in the evaluation.

3.5 Theoretical models for explanation

The experimental results will be discussed based on theoretical models. These models will be presented in the following. The load-bearing capacity can be explained with bonding mechanisms. According to Ayoubi and Trautz (2015), three different bonding mechanisms can be distinguished in the contact area between thread and wood. The first bonding mechanism is the adhesive and interlocking bond due to the self-locking of the thread. The second mechanism is the shear bond, which is the result of the mechanical

interlocking of the thread with the wood located in the areas between the flanks. The wood in the thread area is stressed to shear off. The friction bond is the third mechanism that occurs due to the displacement of the threaded surface and the wood but also in the contact area between the separated wood fibers. (Ayoubi and Trautz 2015) The load-bearing capacity depends on the bonding mechanisms and the bond quality. The shear bond and the friction bond can occur simultaneously. However, the influence of the thread parameters on the bond quality is unknown.

In other research areas, where fasteners are used, a model by Tefpers (1973) explains the bond behavior. Ayoubi (2014) transferred this model to wood screws. During the pull-out process, the screw is braced against the wood via the flanks. This results in conical stress distributions on the flanks. The stresses cause crack formation and crack growth, hence the failure process starts. This model is used, for example, in investigations on crack formation in concrete bonds (Pedziwiatr 2008) or anchored deformed reinforcing bars (Tefpers 1979). With these two models, the experimental results are explained in Sect. 5.

4 Results

The statistical analysis was done using the program SPSS Statistics Version 25.0.0.1. A multifactorial ANOVA was performed to show the influence of the factors pitch, flank angle, and fiber direction. The lead angle is not a factor because it is geometrically dependent on the pitch. For this contribution, the influences of the wood should be as constant as possible. Despite the great care taken in the selection of the wood, it is assumed that the properties of the wood vary from beam to beam. To consider the variation of the wood properties between the wooden beams, blocking was applied. Blocking is a procedure in statistics to reduce the influence of known but uncontrollable factors in the evaluation. Therefore, each wooden beam represents one block. This allows the different wood properties, for example wood strength, of the wooden beams to be considered in ANOVA without measuring them. Table 2 shows the number of evaluable tests by screw prototype and fiber direction. A total of 313 experiments could be evaluated.

In a first step, a Kolmogorov–Smirnov test and a Shapiro–Wilk test were performed for all screw prototypes in fiber direction TL to check for normal distribution ($\alpha=0.05$). The significance in the Kolmogorov–Smirnov test is greater than $p>0.05$ for all factor groups (GP01 $p=0.2$, GP03 $p=0.2$, GP04 $p=0.171$, GP05 $p=0.114$, GP06 $p=0.097$, GP07 $p=0.2$, GP08 $p=0.2$, GP10 $p=0.2$, GP11 $p=0.123$). The significance values of the Shapiro–Wilk test are GP01 $p=0.272$, GP03 $p=0.294$, GP04 $p=0.186$, GP05 $p=0.144$, GP06 $p=0.048$, GP07 $p=0.172$, GP08

Table 2 Number of pull-out tests according to screw prototype and fiber direction

Screw prototype	Fiber direction		Total
	RT	TL	
GP01	17	16	33
GP03	15	17	32
GP04	15	17	32
GP05	17	16	33
GP06	26	26	52
GP07	16	17	33
GP08	17	16	33
GP10	16	17	33
GP11	17	15	32
Total	156	157	313

$p=0.953$, GP10 $p=0.916$, GP11 $p=0.826$. The screw prototype GP06 is barely below the significance limit in the Shapiro–Wilk test, but shows a normal distribution in the Kolmogorov–Smirnov test. Therefore, it can be assumed that all factor groups within fiber direction TL are normally distributed. In the next step, the normal distribution is also checked in fiber direction RT. In the Kolmogorov–Smirnov test, all factor groups (GP01 $p=0.065$, GP03 $p=0.173$, GP04 $p=0.2$, GP05 $p=0.2$, GP07 $p=0.2$, GP08 $p=0.2$, GP10 $p=0.157$, GP11 $p=0.116$) show a significance greater than $p=0.05$. The significance values of the Shapiro–Wilk test are GP01 $p=0.021$, GP03 $p=0.447$, GP04 $p=0.836$, GP05 $p=0.599$, GP06 $p=0.736$, GP07 $p=0.601$, GP08 $p=0.781$, GP10 $p=0.214$, GP11 $p=0.230$. An exception is the screw prototype GP01 which is above the significance limit in the Shapiro–Wilk test, but shows a normal distribution in the Kolmogorov–Smirnov test. Therefore, all factor groups in fiber direction RT can be considered as normally distributed. The homogeneity of variances is asserted using Levene’s test ($\alpha=0.05$). The Levene’s test is not significant ($F(225,87)=0.707$, $p=0.978$), hence variance homogeneity can be assumed. Thus, the conditions for multifactorial ANOVA are fulfilled.

Table 3 shows the results of the multifactorial ANOVA. It is shown that the overall model is significant ($F(37,275)=85.52$, $p=0.000$, adjusted $R^2=0.909$, $n=313$). As shown in Table 3, there are three main effects on the withdrawal capacity. The fiber direction ($F(1,275)=361.85$, $p=0.000$), the parameter wooden beam ($F(22,275)=61.09$, $p=0.000$), and the pitch ($F(5,275)=7.64$, $p=0.000$) have a significant effect. No significant correlation can be shown for the flank angle ($F(2,275)=1.27$, $p=0.283$). Furthermore, there is no significant interaction of both pitch with fiber direction ($F(5,275)=1.51$, $p=0.187$) and flank angle with fiber direction ($F(2,275)=1.382$, $p=0.252$).

Table 3 Results of the multifactorial ANOVA

Tests of between-subjects effects						
Dependent variable: withdrawal capacity						
Source	Type III sum of squares	df	Meansquare	F	Sig	Partial eta squared
Corrected model	896.450 ^a	37	24.228	85.519	0.000	0.920
Intercept	3537.663	1	3537.663	12,486.954	0.000	0.978
Pitch	10.826	5	2.165	7.643	0.000	0.122
Flank angle	0.719	2	0.360	1.269	0.283	0.009
Fiber direction	102.515	1	102.515	361.851	0.000	0.568
Wooden beam	380.758	22	17.307	61.090	0.000	0.830
Pitch * fiber direction	2.139	5	0.428	1.510	0.187	0.027
Flank angle * fiber direction	0.784	2	0.392	1.384	0.252	0.010
Error	77.910	275	0.283			
Total	14,992.525	313				
Corrected total	974.360	312				

^aR squared = .920 (Adjusted R squared = .909)

Table 4 Withdrawal capacities of fiber directions TL and RT in kilonewtons

Descriptive statistics						
Fiber direction		N	Minimum	Maximum	Mean	Std. deviation
TL	Withdrawal capacity	157	2.960	8.571	5.447	1.119
	Valid N (listwise)	157				
RT	Withdrawal capacity	156	5.535	11.804	7.945	1.370
	Valid N (listwise)	156				

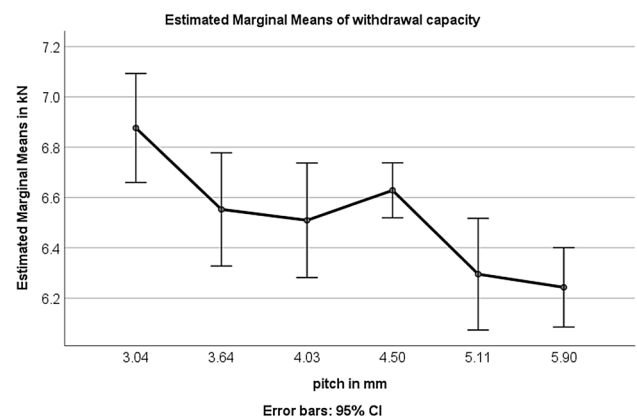
Cohen's *d* is calculated to determine the effect size (Cohen 1992). According to Cohen (1988), the size of the effect is assessed. The effect sizes can be rated as strong for the fiber direction ($f = 1.15$) and for the factor wooden beam ($f = 2.21$). The pitch has a medium effect size ($f = 0.37$).

Table 4 shows the withdrawal capacities for the two fiber directions. It can be seen that fiber direction TL has a significantly lower withdrawal capacity compared to direction RT.

Post-hoc tests were applied to determine which of the factor levels of the pitch have a significant influence on the dependent variable. Bonferroni corrected tests ($\alpha = 0.05$) show that the withdrawal capacity at a pitch of 5.9 mm ($M = 6.300$, $SD = 1.776$) is significantly lower compared to that at pitches of 3.04 mm ($M = 6.923$, $SD = 1.593$), 3.64 mm ($M = 6.686$, $SD = 1.742$), 4.03 mm ($M = 6.754$, $SD = 1.830$), and 4.5 mm ($M = 6.848$, $SD = 1.775$). No difference in withdrawal capacity was found between the other pitches.

The profile diagram for the different pitch levels is shown in Fig. 7. Error bars indicate 95% confidence interval.

As the interaction between thread pitch and fiber direction is not significant, no distinction is made between the direction RT and TL. The estimated marginal means predicted from the model and the corresponding standard errors are

**Fig. 7** Profile diagram showing the influence of the pitch

used. Table 5 shows the estimated marginal means of the withdrawal capacity for the six thread pitches.

5 Discussion

In a study by Hoelz et al. (2020), it was stated that the fiber direction is a disturbance variable in the investigation of the withdrawal capacity. For this reason, screw prototypes with

Table 5 Estimated marginal means of withdrawal capacity in kN for the investigated pitches in mm

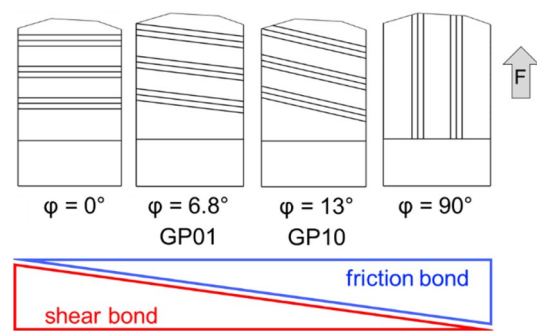
Dependent variable: withdrawal capacity				
Pitch	Mean	Std. Error	95% Confidence Interval (CI)	
			Lower Bound	Upper Bound
3.04	6.876	0.110	6.660	7.093
3.64	6.553	0.114	6.328	6.778
4.03	6.509	0.116	6.282	6.737
4.50	6.629	0.056	6.519	6.738
5.11	6.295	0.113	6.073	6.517
5.90	6.243	0.080	6.085	6.401

straight thread flanks were used in this study to control fiber direction as a factor. The influence of fiber direction was investigated in this study and could be quantified. In the RT plane, higher withdrawal capacities are achieved than in the TL plane. This is supported by Hübner (2013), who describes that due to the material properties of wood, higher forces are transmitted in longitudinal direction via the thread flanks. In this study, the longitudinal direction corresponds to the RT plane. Ayoubi (2016) also describes the force distribution of the screw normal to the axis not as round but as elliptical. The results support this description and the ellipse can be parameterized with the data of this investigation.

The pitch has a significant influence on the withdrawal capacity in the range from 3.04 to 5.9 mm for ϕ 8 mm screws. A smaller pitch results in higher withdrawal capacity. However, an optimum in the chosen limits could not be found. This corresponds to the investigation by Hoelz et al. (2020), in which it was assumed that a pitch smaller than 3.6 mm leads to a higher withdrawal capacity. To optimize the withdrawal capacity of a ϕ 8 mm screw, a smaller pitch is preferable. It can be guessed that smaller pitches lead to further increases.

With this knowledge, screw design procedures can also be improved. The pitch and lead angle should be part of the product description in EN 14592 (2012) and EADs to ensure that the models are valid for withdrawal strength. If manufacturers develop screws with different pitches or lead angles, which significantly influence the withdrawal strength, then these parameters should be added in these design models.

In the following, the results of the investigation will be explained. For this purpose, the known model of bonding mechanisms according to Ayoubi and Trautz (2015) and cone-shaped stress (Ayoubi 2014) will be used. In the case of multi-start threads, the thread flanks directly adjacent to each other do not belong to one pitch. Hence, it has to be considered that the change of the pitch results in a change of the lead angle as well as of the flank distance. Due to the geometric independence of the screw prototypes and

**Fig. 8** Proportions of shear bond and friction bond action on the withdrawal capacity for different lead angles ϕ

in the case of multi-start threads, the more specific term flank distance is used instead of pitch. The determined effect should, therefore, be explained in terms of lead angle and flank distance. The explanations only apply to an insertion angle of 90° .

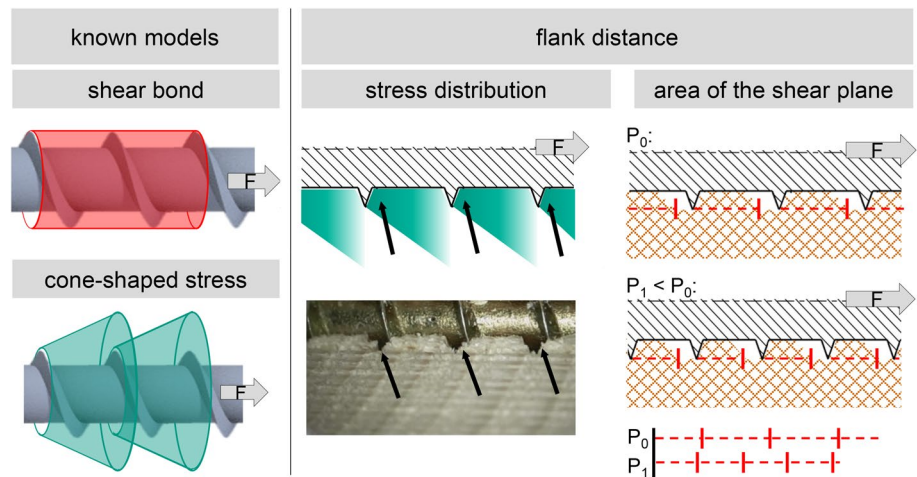
Lead Angle Until the withdrawal capacity is reached, both the shear bond and the friction bond are acting (Ayoubi and Trautz 2015). As shown in Fig. 8, it can be concluded that a change in the lead angle results in opposing proportions of the acting bonding mechanisms. In the extreme values at $\phi = 0^\circ$ only the shear bond is effective due to the mechanical interlocking, whereas at $\phi = 90^\circ$, only the friction bond is effective.

Mainly the shear bond is decisive for the withdrawal capacity. The relevant proportion of the shear bond is higher at low lead angles. Therefore, at constant flank distance, a smaller lead angle results in a higher withdrawal capacity. For screw prototype GP01 ($p = 3.04$ mm), the lead angle is lower with $\phi = 6.8^\circ$ compared to screw prototype GP10 ($p = 5.6$ mm, $\phi = 13^\circ$). Therefore, the higher withdrawal capacity at $p = 3.04$ mm can be explained by the smaller lead angle caused by the higher proportion of shear bond. Based on this explanation, the smallest possible angle should be designed to increase the screw performance.

Flank Distance The shear bond fails due to shearing of the wood (Ayoubi and Trautz 2015). The area of this shearing plane is relevant to shearing. As shown in Fig. 9 on the left, the shearing plane can be seen as the shell surface of the screw. However, for different flank distances, the area of the shear plane is unchanged. Hence, the shear bond cannot be used to explain the influence of the flank distance on the withdrawal capacity. Therefore, the model of conical stress distribution by Tepfers (1973) is used (Fig. 9 left). This model explains the influence of the flank distance. Two explanations are presented: stress distribution and area of the shear plane.

Stress distribution The flanks transmit the force into the wood. This creates cone-shaped compressive stress (Ayoubi

Fig. 9 Left: Shear bond and cone-shaped stress according to Ayoubi (2014), Middle: Failure of force introduction due to conical stress distribution, Right: Area of the shear plane on the failure of force introduction for different pitches



2014). The stress decreases continuously with the distance to the screw flank due to the increasing cone diameter. Therefore, the bond stress is highest near the flanks and the wood fails first at that point. A smaller flank distance increases the number of flanks at constant screw-in depth. A higher number of flanks represents a larger number of points of load transmission. The stress on the individual flanks is thus reduced and the wood fails later. This failure of the wood near the flanks was described by Hoelz et al. (2020). The failure causes a relative displacement of the screw and the failed areas are thus on the bottom of the flank. This is shown by arrows in the photograph in Fig. 9. A smaller flank distance thus results in a higher withdrawal capacity.

Area of the shear plane If the wood deforms at the point of load introduction, the screw will be displaced. This shortens the part of the wood in the area between the flanks for the transmission of force. The shear plane of the screw becomes smaller. Figure 9 (on the right) shows the shear plane for two different pitches (P_0 , P_1) as dashed lines. For the same screw-in depth, a smaller pitch results in a larger number of flanks. With the same screw displacement in the pull-out, the shear plane is reduced according to the number of flanks (comparison of dashed lines for P_0 and P_1). Therefore, with a larger pitch, a higher pull-out distance can be reached before the shear surface falls below the critical level and the shear bond fails. Consequently, a larger flank distance results in a higher withdrawal capacity. This theoretical effect can only be valid if the effect of the lead angle is stronger than the effect of the flank distance.

To verify the different explanations, further studies should be carried out to investigate the influence of the thread parameters lead angle and flank distance independently of each other. So-called design hypotheses (Grauberger et al. 2020) can be applied to support verification. The failure mechanisms need further research on the shear mechanisms at failure and force distribution in the close proximity of the thread. For a better understanding of the

failure process, it is useful to transfer existing research methods from other research areas to wood screws. For example, investigations similar to those carried out by Goszczyńska (2014) could help to better understand crack initiation and crack growth.

The influence of the flank angle could not be shown between 35° and 45° . In practice, this is relevant to manufacturers of wood screws. The tolerances of the flank angle can be specified within a range of $\pm 5^\circ$ without influencing the withdrawal capacity. Based on the conical stress distribution, it can nevertheless be justified that the flank angle has an influence. According to Tepfers (1973), the angle of the cone depends on the flanks. An assumption is that a larger flank angle results in a larger cone. In accordance with the stress in the cones, the bond stress is lower for a larger flank angle. Whereby the angle of the cone depends on the insertion angle and the rotation angle around the screw axis. The influence of the flank angle should therefore be analyzed outside the investigated range.

Limitations resulting from the tested prototypes. The pitch and the lead angle are correlated. Without having tested the explanations on the physical processes, the effects of the pitch are only valid for the specific lead angles shown in Table 1. The parameter wooden beam exerts a significant effect. Reasons for this are on the one hand varying wood strengths and, on the other hand a varying block length of the wooden beams used.

Further limitations result from the new experimental setup. To reduce the disturbance variable fiber direction, a straight screw flank was suggested. A comparable experimental setup using a plane thread was used by Adachi et al. (2010). The influence of different thread parameters of bolt-nut connections on the thread strength was investigated. However, the results are not comparable to the present study. Adachi et al. (2010) used a wooden thread and both the screw thread and the nut thread were manufactured. In the case of wood screws, only the screw thread

is manufactured, the counterpart in the wood is formed by the screw.

If the absolute values of the withdrawal capacity should be compared with screws, then the screw prototypes must consider the perimeter size of a usual insertion length to avoid size effects. Usually, the tested thread length is $8d$ and the perimeter is πd . A further challenge is the balancing of the withdrawal capacity of the two fiber directions.

6 Conclusion

An experimental setup based on EN 1382:2016 was presented for investigation of the influence of the parameters pitch and flank angle of \varnothing 8 mm screws on the withdrawal capacity. Wood is a known disturbance factor that should be controlled. By using screw prototypes with straight thread flanks, this test setup allows adjustment of the disturbance variable fiber direction. The screw prototypes are flat ribbed bars with uncoiled screw thread. A total of ten screw prototypes with pitches in the range between 3.04 and 5.9 mm and flank angles of 35° , 40° , and 45° were manufactured. A total of 313 tests were carried out, which were analyzed with a multifactorial ANOVA. A significant influence of the pitch could be shown. A smaller pitch results in a higher withdrawal capacity. No influence could be shown for the flank angle in the investigated range. To explain the results of the investigation, the model of bond mechanisms and cone-shaped stress distribution were used. Different explanations were formulated for this purpose. To optimize the withdrawal capacity of a \varnothing 8 mm screw, a smaller pitch is preferable. In further studies, the thread parameters lead angle and flank distance should be examined separately in order to test the explanations. Subsequently, the determined influence of the pitch can be used to improve the accuracy of the calculation models for the withdrawal capacity.

7 Availability of data and material

Some or all data, that support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with ethical standards

Conflict of interest The specially developed screw prototypes for carrying out the study were manufactured at no cost. The authors declare that they have no conflict of interest.

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