WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

QUANTIFICATION OF POSITIONAL IMPERFECTIONS OF SELF-DRILLING SCREWS AND EXAMINATION OF THE TECHNICAL CAUSES

Eva Baldauf[1], Matthias Frese[2]

ABSTRACT: Unforeseen contact and collisions between adjacent screws are technical problems with respective safety relevance. They are due to positional imperfections, which arise both systematically and randomly during insertion of self-drilling wood screws. The causes of such positional imperfections have been systematically examined in experimental studies reported here. The results show that these factors significantly influence positional imperfections: angle between screw axis and grain direction of the wood, timber product, screw type, and insertion length. Based on the experimental data, a numerical model was developed to describe and predict positional imperfections. It can be used to determine screw spacings and limit insertion lengths under which mutual contact between screws takes place with very low probability only. The project results raise awareness for positional imperfections. They provide practical solutions to avoid and handle respective problems. Its findings contribute to improving the quality, safety, and durability of screw connections in timber engineering.

KEYWORDS: Self-drilling wood screws, positional imperfections, minimum spacings, glued timber products

1 – INTRODUCTION

Self-drilling wood screws with large insertion length are primarily used to connect and to reinforce structural members. When driven in, the screw-in angle β between the screw axis and the member surface initially determines the direction of the screw channel. Following the screw-in angle, the screw moves into the wood with each further rotation. However, with increasing insertion length it becomes more likely that the screw deviates from the planned screw channel and positional imperfections then occur. Due to their flexibility, long slender screws are particularly affected.

The minimum spacings between self-drilling screws and edge distances are specified in Eurocode 5 [1] and in European Technical Assessments (ETA) only as a multiple of the nominal diameter. There is no dependence on the insertion length. Therefore, deviations from the planned screw channel of long slender screws may not sufficiently be compensated for by the minimum spacings.

If positional imperfections of screws exceed the minimum spacings, screws may stick out of the member uncontrollably [2], [3]. Within crossed screw arrangements, screws can come into harmful contact causing damage to the threads and the corrosion protection [4], [5]. Screw collisions are even a risk for reaching the torque moment or breaking off [6]. Such effects influence the mechanical effectiveness of a screw connection and reduce the load-carrying capacity and durability [7].

It is reported in [3] that wood screws inserted into glued laminated timber (glulam) deviate approximately 10% of their insertion length from the planned screw channel. This relative deviation is based on unspecified screw-in tests with an insertion length up to 500 mm. Previous studies on positional imperfections [8] showed that self-drilling wood screws inserted into glulam can deviate between 8 and 12% of the insertion length.

A comprehensive study on positional imperfections was still missing. Knowledge was lacking how the wood structure, various timber products and the length of slender screws condition positional imperfections. Following

[1] Eva Baldauf, Timber Structures and Building Construction, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, baldauf@kit.edu

[2] Matthias Frese, Timber Structures and Building Construction, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, matthias.frese@kit.edu

https://doi.org/10.52202/080513-0556

on from the results in [8], the causes of positional imperfections and damage mechanisms due to mutual contact or collision were therefore systematically examined in a research project reported hereafter. It was carried out under participation of the industry and craft. The aims were the development of models to describe positional imperfections and technical solutions to avoid contact and collision-related problems in screw connections. The paper's focus is on the causes of positional imperfections and on their model-based description. It is partly based on results in [9-13].

2 – CAUSES OF POSITIONAL IMPERFECTIONS

2.1 MATERIAL AND METHODS

To investigate the causes of positional imperfections, approximately 1000 screws were driven into glulam, cross-laminated timber (CLT), and laminated veneer lumber (LVL). The mean density and the wood moisture content of the test specimens are compiled in Table 1. Within the test series, the angle α between the screw axis and the grain direction, the slenderness λ (insertion length ℓ_{ef} divided by nominal diameter d), and the shape of the screw were varied. Table 2 provides an overview of the test series and their parameters.

Table 1: Density and wood moisture content of the test specimens.

Material	N	Density		Wood moisture content	
		ρ_{mean} [kg/m^3]	COV [%]	u_{mean} [%]	COV [%]
Glulam *(GL24, GL30)*	135	441	5,92	13,6[1)]	10,6
CLT *(C24)*	16	450	2,45	12,4[1)]	4,95
LVL S	2	556	1,09	5,70[2)]	9,93

[1)] *Electronic resistance measurement with Gann-Hydromette*
[2)] *Darr method*

The screw-in tests were carried out in accordance with [8]. The angle β between the screw axis and the specimen surface was 90° for all tests (see Figure 1). Screws with a insertion length up to 420 mm were screwed in using a handheld electric powered screwdriver. For longer insertion lengths, the screws were initially attached using a screwdriver and then screwed in using a low-speed drilling machine. All screws were inserted into the specimens without pre-drilling and pilot holes. The use of screw guides at the beginning of the screw-in process ensured the screw-in angle according to plan. The screws were driven completely through the specimens, so that the coordinates of the deviations $\Delta 1$ and $\Delta 2$ between the planned and the actual exit point could be measured directly on the back of the specimen. Equation (1) applies to the absolute deviation r.

$$r = \sqrt{\Delta 1^2 + \Delta 2^2} \qquad (1)$$

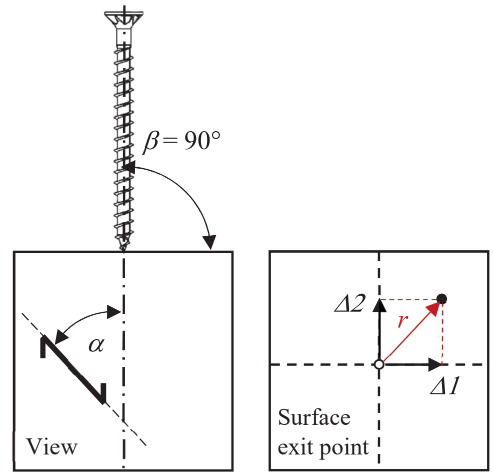


Figure 1: Experimental setup (left) and absolute deviation r on the surface of the screw exit (right).

2.2 RESULTS

This paper presents the results obtained with the following screws: nominal diameter d = 8 mm, insertion lengths ℓ_{ef} = 214, 320, 420, 520 mm, and angles α = 90° and 45°. See the research report [13] for results of all examined parameters compiled in Table 2.

Angle α:

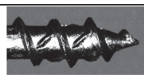
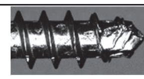
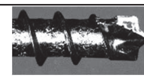
Figure 2 shows the deviations $\Delta 1$ and $\Delta 2$ of the fully threaded screws (type C) screwed into glulam for α = 90° and 45°. The exit points of the screws are differentiated according to their dimension (dxℓ_{ef}). At α = 90°, the exit points are distributed almost symmetrically around the coordinate origin (= planned exit point). At α = 45°, they shift in the positive $\Delta 1$ and $\Delta 2$ direction and scatter more in the $\Delta 1$ direction than in the $\Delta 2$ direction. In this case, the screws therefore deviate from the planned exit point more strongly and approach the grain direction during insertion. This is particularly pronounced by long screws (8x520).

Insertion length ℓ_{ef}:

Figure 3 shows the deviation r of the fully threaded screws for α = 90° and 45°. The median and maximum values of r increase with increasing insertion length. At α = 45°, the course of the maximum values is progressive. The comparatively small deviations of the screw 8x420 are an exception. Table 3 summarises the median and maximum values of the deviations r and the ratio of r to the insertion length ℓ_{ef} for the investigated screw-in configurations. For the fully threaded screws, the largest deviations occur at α = 45° and ℓ_{ef} = 520 mm. They amount up to 15% of the insertion length.

Table 2: Test parameters within the individual test series. Values in grey are not included in the paper's results.

Series	Material	Screw type	Thread	Drill tip	d [mm]	ℓ_{ef} [mm]	λ [-]	α [°]
I	Glulam	A B C D	partial partial full partial	without[1)] without[2)] with[3)] centring[4)]	6, 8, 10	60, 160, 240, 80, 214, 320, 420, 520, 400, 650	10, 27, 40, 53, 65	90, 60, 45, 30
II	CLT	A, B	partial	without	6, 8	240, 320	40	90, 45, 0
III	LVL	A, B	partial	without	6, 8	240, 320	40	90, 45, 0

1)  2)  3)  4) 

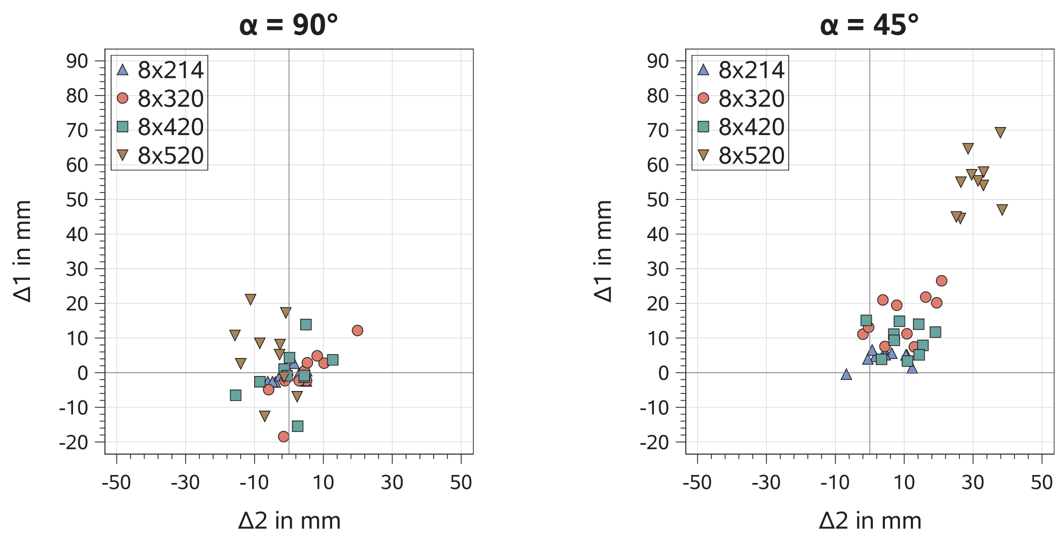


Figure 2: Deviation Δ1 over Δ2 of the fully threaded screws of series I for α = 90° and 45° differentiated according to the screw dimension (nominal diameter x insertion length).

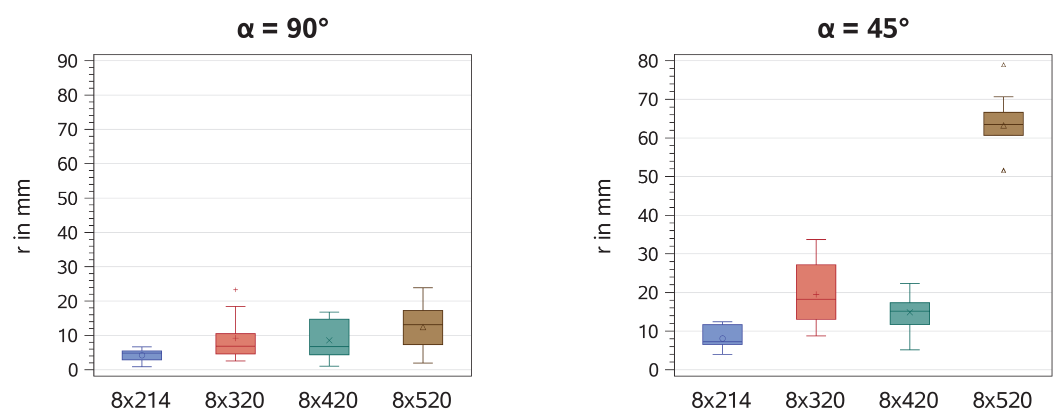


Figure 3: Deviation r of the fully threaded screws of series I for α = 90° and 45°.

https://doi.org/10.52202/080513-0556

Table 3: Deviations r and ratios r / ℓ_{ef} of fully threaded screws with d = 8 mm of series I for α = 90° and 45°.

d [mm]	α [°]	λ [-]	ℓ_{ef} [mm]	N [-]	r_{median} [mm]	s* [mm]	r_{max} [mm]	r_{median} / ℓ_{ef} [%]	r_{max} / ℓ_{ef} [%]
8	90	27	214	10	4.84	1.75	6.66	2.26	3.11
		40	320	10	6.87	6.71	23.3	2.15	7.28
		53	420	10	6.74	6.06	16.8	1.61	4.00
		65	520	10	13.1	6.66	23.8	2.52	4.59
	45	27	214	10	7.24	2.96	12.4	3.38	5.80
		40	320	10	18.3	8.16	33.7	5.71	10.5
		53	420	10	15.2	4.86	22.4	3.61	5.33
		65	520	10	63.5	8.14	79.0	12.2	**15.2**

** Standard deviation*

Screw type and tip design:

Figure 4 shows the deviation *r* of the screws 8x214 and 8x320 differentiated according to the screw type for α = 90° and 45°. ANOVA tests show a significant difference in the deviations of the four screw types for the screw-in configurations considered (exception: α = 90° and 8x320). The median, the maximum value, and the scatter of *r* are lowest for the partially threaded screw with centring drill tip (type D).

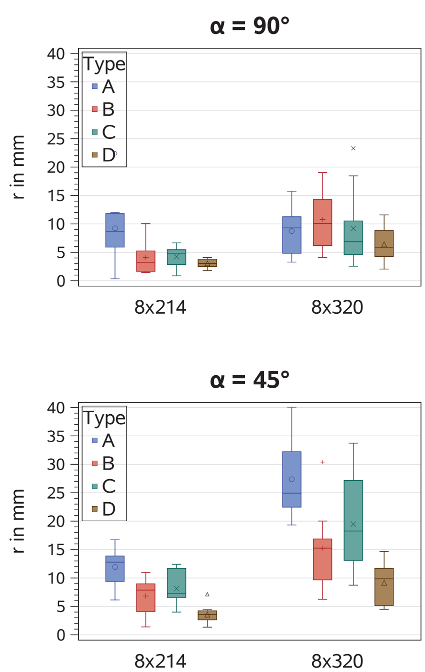


Figure 4: Deviation r for α = 90° and 45° differentiated according to the screw type.

Timber Products:

Figure 5 shows the deviations *Δ1* and *Δ2* of the screws 8x320 type A and B for α = 90° and 45°. The exit points are differentiated by material only, not by type. At α = 90°, the screws in glulam, CLT, and LVL exit almost symmetrically around the origin. In glulam, the maximum deviations are 6% and in CLT 7% of the insertion length. In LVL, the maximum deviations are slightly lower at 3%. At α = 45°, there is an obvious shift of the exit points in the positive *Δ1* direction in glulam and LVL. As a result of the strong approach of the screws to the grain direction during screwing in (see Figure 6), maximum deviations are 13% of the insertion length in glulam and 24% in LVL. The deviations in CLT are comparatively small at 4% of the insertion length.

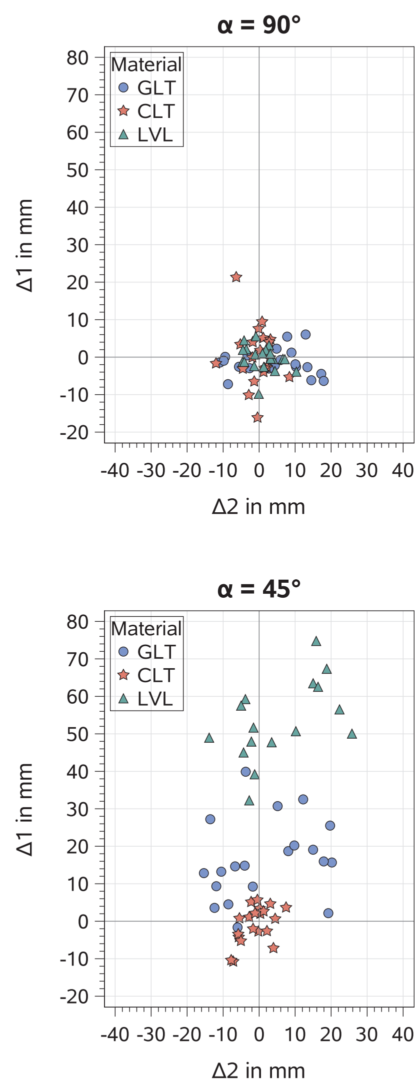


Figure 5: Deviation Δ1 over Δ2 of the screw 8x320 for α = 90° and 45° with differentiation by material.

Figure 6: Deviation of a screw 8x320 in LVL at α = 45°.

3 – MODELLING POSITIONAL IMPERFECTIONS

Based on the test results in section 2.2, a numerical model was developed to quantitatively describe positional imperfections. The model and the screw spacings calculated with it are presented below.

3.1 METHODS

Test data from screws with d = 8 mm of the types A, B, and C were used in the modelling. To increase the sample size, the data of the types were merged and analysed together. The experimentally determined deviations $\Delta 1$ and $\Delta 2$ were considered for the numerical simulation separately and were assumed to be independent variables from each other. The statistical analysis system SAS was used for the numerical and stochastic analyses.

First, the mean values and the standard deviations of $\Delta 1$ and $\Delta 2$ were determined for the respective screw-in configurations each. Based on this, normally distributed random variables $\Delta 1_{num}$ and $\Delta 2_{num}$ were generated in the second step using a Monte-Carlo-Simulation. The amount of values per variable was 5000. $\Delta 1_{num}$ and $\Delta 2_{num}$ were then randomly combined so that the same number of screw exit points were available for a screw-in configuration. In the third step, 95% prediction ellipses were determined for the generated exit points (see Figure 7). A 95% prediction ellipse surrounds an area in which the exit point of a screw occurs with a probability of 95%. Finally, the vertices V_1, V_2, V_3 and V_4 of individual prediction ellipses were determined (see Figure 7) and plotted over the insertion lengths. A linear or quadratic regression was used to derive functional equations for the operative values $\Delta 1_{max/min}$ and $\Delta 2_{max/min}$ (see section 3.2).

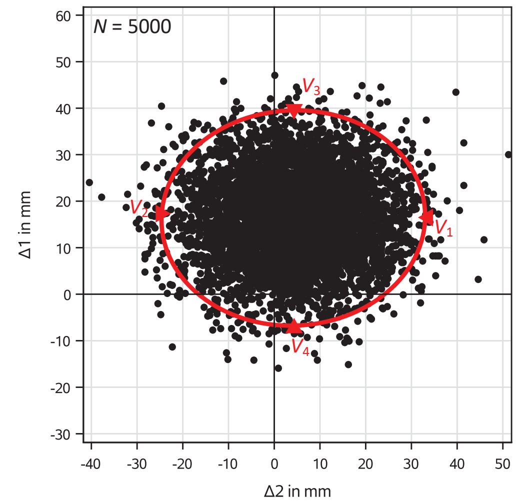


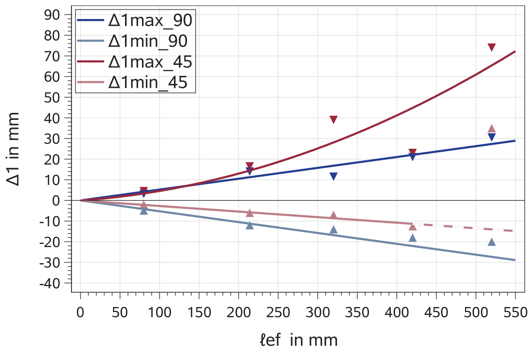
Figure 7: Generated exit points for α = 45° and ℓ_{ef} = 320 mm (black dots), 95% prediction ellipse (red) and vertices (red triangles).

3.2 DEVIATIONS AS A FUNCTION OF THE INSERTION LENGTH

Figure 8 shows the results of the regression for $\Delta 1_{max/min}$ (top) and $\Delta 2_{max/min}$ (bottom) for the angles $\alpha = 90°$ and 45°. The diagrams clarify the vertices of the prediction ellipses (triangles) and show the function graphs determined by the regression analysis. The graphs for $\alpha = 90°$ are represented in blue and the ones for $\alpha = 45°$ in red. The functional equations for $\Delta 1_{max/min}$ and $\Delta 2_{max/min}$ as well as the coefficient of determination R^2 are indicated below the diagrams.

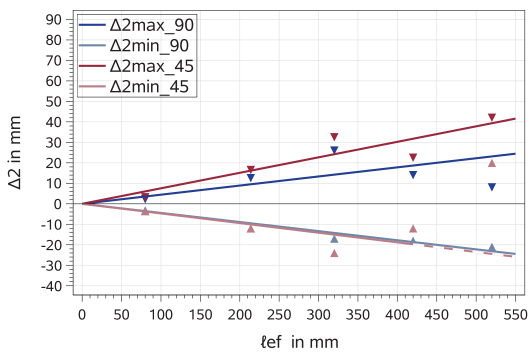
At $\alpha = 90°$, the deviations $\Delta 1_{max/min}$ and $\Delta 2_{max/min}$ increase linearly and symmetrically over the insertion length. At $\alpha = 45°$, the progressive approach of the screws to the grain direction with increasing insertion length is represented by a quadratic increase in $\Delta 1_{max}$. The regression line for $\Delta 1_{min}$ applies up to 420 mm, as the minimum vertice of the prediction ellipse in the $\Delta 1$ direction is positive at ℓ_{ef} = 520 mm. For ℓ_{ef} > 420 mm, a linear increase of the deviation $\Delta 1_{min}$ is assumed. The same applies to $\Delta 2_{min}$ at $\alpha = 45°$ and ℓ_{ef} > 420 mm. The increased deviation of the long screws in the positive $\Delta 2$ direction at $\alpha = 45°$ is taken into account by a larger opening angle of $\Delta 2_{max}$ compared to $\Delta 2_{min}$.

https://doi.org/10.52202/080513-0556



α = 90°: $\Delta 1_{max/min}(\ell_{ef}) = \pm 0.05256 \cdot \ell_{ef}$, $R^2 = 0.972$

α = 45°: $\Delta 1_{max}(\ell_{ef}) = 0.02692 \cdot \ell_{ef} + 0.00019 \cdot \ell_{ef}^2$, $R^2 = 0.914$
$\Delta 1_{min}(\ell_{ef}) = -0.02699 \cdot \ell_{ef}$ for $\ell_{ef} \leq 420$ mm, $R^2 = 0.983$



α = 90°: $\Delta 2_{max/min}(\ell_{ef}) = \pm 0.04447 \cdot \ell_{ef}$, $R^2 = 0.984$

α = 45°: $\Delta 2_{max}(\ell_{ef}) = 0.07562 \cdot \ell_{ef}$, $R^2 = 0.953$
$\Delta 2_{min}(\ell_{ef}) = -0.04706 \cdot \ell_{ef}$ for $\ell_{ef} \leq 420$ mm, $R^2 = 0.836$

Figure 8: Vertices of prediction ellipses (triangels) and regression results for $\Delta 1_{max/min}$ (top) and $\Delta 2_{max/min}$ (bottom) over the insertion length for α = 90° and 45°.

3.3 SCREW SPACINGS

The equations given in Figure 8 were developed to determine the operative values $\Delta 1_{max/min}$ and $\Delta 2_{max/min}$ as functions of the insertion length. These values describe an ellipse that surrounds an area in which a screw deviates from the planned channel with a probability of 95% (see Figure 9). The counter-probability for an exit outside the deviation ellipse is therefore 5%. Figure 10 illustrates the deviation ellipses of two pairs of screws positioned behind and next to each other, respectively. The minimum spacings $a_{\Delta 1}$ and $a_{\Delta 2}$ are calculated using equations (2) and (3).

$$a_{\Delta 1} = \Delta 1_{max} + |\Delta 1_{min}| + d \qquad (2)$$

$$a_{\Delta 2} = \Delta 2_{max} + |\Delta 2_{min}| + d \qquad (3)$$

Two screws inserted with spacing $a_{\Delta 1}$ or $a_{\Delta 2}$ would touch each other if both of them exit outside their respective deviation ellipses (necessary criterion) and if their deviations are also directed towards each other so that they actually touch each other (sufficient criterion). The conditional probability for the necessary criterion is 0.25% (corresponds to 0.05·0.05). However, the one for actual contact is significantly lower than 0.25% [8]. Therefore, 0.25% takes into account the probability of two screws exiting outside their respective deviation ellipses, but not the probability that they exit at the same point.

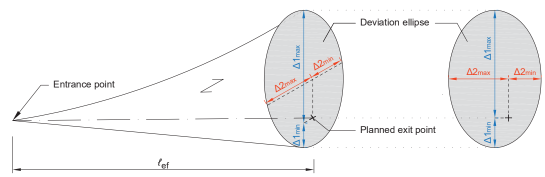


Figure 9: Visualized model (left) and deviation ellipse with $\Delta 1_{max/min}$ and $\Delta 2_{max/min}$ (right).

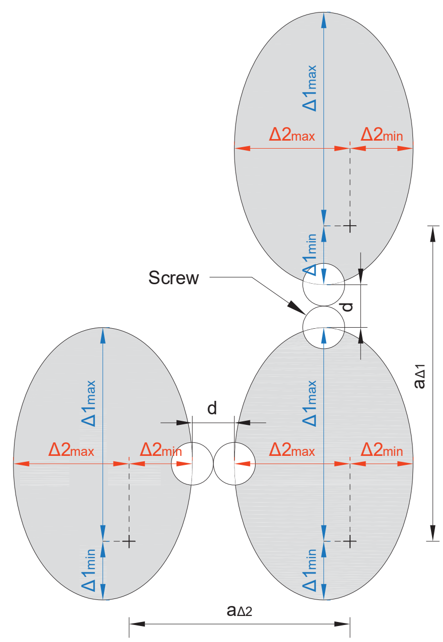


Figure 10: Spacings $a_{\Delta 1}$ and $a_{\Delta 2}$ of adjacent screws.

Figure 11 and 12 clarify the spacings $a_{\Delta 1}$ and $a_{\Delta 2}$, calculated with the equations (2) and (3) as a function of the insertion length ℓ_{ef} (blue line). Figure 11 applies for $\alpha = 90°$ and Figure 12 for $\alpha = 45°$. In the diagrams, minimum spacings according to ETA, e.g. [14], are added in red: for spacings of adjacent screws in grain direction $a_1 = 5 \cdot d$ and perpendicular to the grain $a_2 = 2.5 \cdot d$. The minimum spacings between crossed screws a_X is $1.5 \cdot d$ (red dashed).

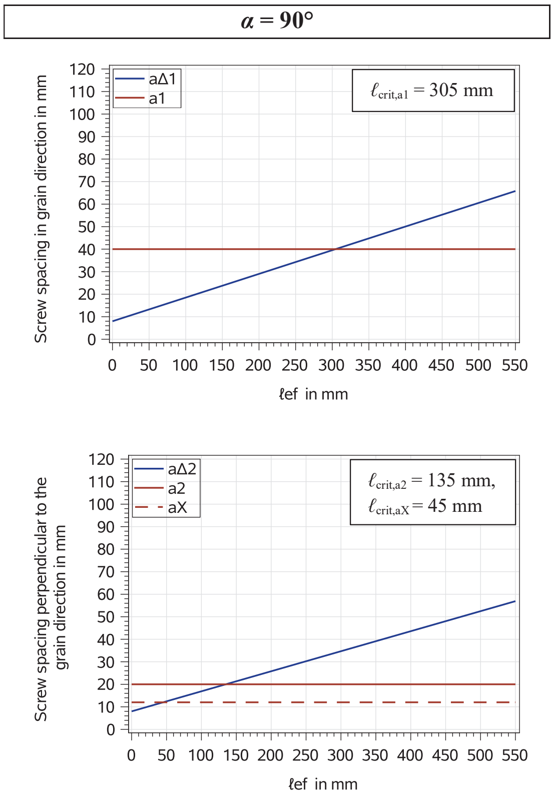


Figure 11: Screw spacings in grain direction (top), perpendicular to the grain (bottom) and limit insertion lengths for α = 90°.

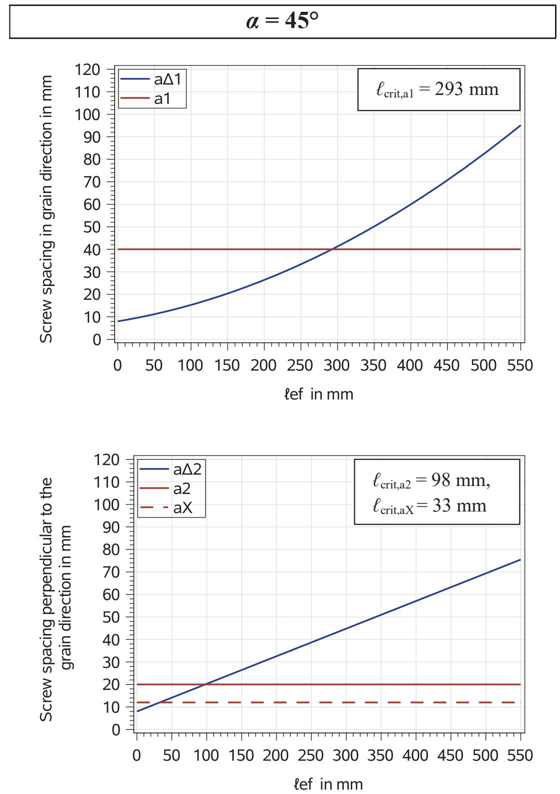


Figure 12: Screw spacings in grain direction (top), perpendicular to the grain (bottom) and limit insertion lengths for α = 45°.

The limit insertion length ℓ_{crit} indicates the point at which the model-based spacings $a_{\Delta 1}$ and $a_{\Delta 2}$ exceed the minimum spacings according to ETA [14]. The limit insertion lengths for the axial spacing in the grain direction $\ell_{crit,a1}$, perpendicular to the grain $\ell_{crit,a2}$, and between crossed screws $\ell_{crit,aX}$ are shown in Figure 11 and 12. Insertion lengths greater than the limit insertion length bare the risk of screws touching each other. However, the respective probability is significantly lower than 0.25%.

4 – DISCUSSION

4.1 CAUSES

The screws in glulam approached the grain direction during screwing in due to angles $\alpha < 90°$. In addition, screws deviated perpendicular to the grain with increasing insertion length (see Figure 2, right). This is presumably due to the right-hand thread of the screw. The screws 8x420 of type C deviated less at $\alpha = 45°$ compared to the other screw dimensions examined (see Figure 3). The reason for this has not yet been fully clarified.

In LVL, screws at $\alpha = 45°$ deviated up to 24% of the insertion length. It is still unclear whether the reason for this lies in the structure of LVL, in the higher density compared to glulam, or in both. Presumably the screw tip slips a bit when it hits the adhesive layers in LVL at 45°, which are much harder than the wood. The high proportion of adhesive layers in LVL means that the deviations due to slippage would add up over the insertion length. This could explain the pronounced progressive deviation of the screw at $\alpha = 45°$ (see Figure 6). Confirmation of this hypothesis is still required.

In CLT, the screws deviated less than in glulam and LVL. The reason for this is that CLT is glued crosswise, which means that the grain direction is not uniform. As a result, the screw does not move closer to the grain (see Figure 5).

https://doi.org/10.52202/080513-0556

4.2 MODEL

The calculation of the model-based screw spacings is based on the assumption that two screws exit outside their respective deviation ellipses with a probability of 5% each. The assumption does not imply that the deviations are directed towards each other so that the screws actually touch. The probability of this geometrical conflict is significantly lower than 0.25%. Exceeding the specified limit insertion lengths is therefore not necessarily associated with the mutual contact or collision of screws, but indicates the length from which contact or collision is basically possible.

5 – RECOMMENDATION

Figure 11 and 12 show that the model-based screw spacings exceed the minimum spacing for crossed screws of $1.5 \cdot d$ already for short insertion lengths. The following measures are recommended in practice to prevent contact between crossed screws as far as possible:

- Increase the axial spacing between screws depending on the insertion length (see Figure 8) or
- use of the spacing with $1.5 \cdot d$ in combination with pilot holes drilled to a depth of 10% of the insertion length [13].

Deviations of screws perpendicular to the grain direction in narrow members can cause the screw to stick out of the faces of the member. Beside the optical defect, this also leads to a reduction in the insertion length of the thread in wood. It is therefore advisable to determine the edge distance as a function of the insertion length.

6 – CONCLUSION AND OUTLOOK

To examine the causes of positional imperfections, approximately 1000 screws were screwed into glulam, CLT, and LVL and the deviation between the planned and actual screw exit point was measured each. The following test parameters were specifically varied during the screw-in tests: angle α between screw axis and grain direction, screw type, and insertion length.

The results show that the angle α between the screw axis and the grain direction significantly influences the magnitude of positional imperfections. Particularly in glulam and LVL, an angle α of less than 90° during screwing in causes the screw to move closer to the grain. The greatest deviations occurred in LVL at $\alpha = 45°$ and amounted to up to 24% of the respective insertion length. It was also shown that at $\alpha < 90°$ deviations increase with increasing insertion length progressively. Screws with centring drill tips exhibit the smallest deviations.

Based on the test results, a model was developed to describe positional imperfections. Exit points were numerically generated and their deviation range was determined using prediction ellipses. Regression analyses were used to specify calculation equations for deviations as a function of the insertion length. Using the model, screw spacings were calculated and limit insertion lengths were determined, at which the calculated spacings exceed standardised minimum spacings and contact or collision is therefore possible to a certain extent.

Further investigations should address model optimisations so that deviations are described as a function of both the insertion length and the angle α. To extend the prediction range, further nominal diameters and timber products as well as the influence of methods for minimising positional imperfections should be taken into account.

According to the model presented, the probability of screws exiting outside the deviation ellipses is 5%. However, a mutual contact or collision between two screws would only occur if both screws exit outside their respective deviation ellipses and their deviations are directed towards each other. The probability of this is significantly lower than 0.25%. Further stochastic investigations are seen to be necessary for a more exact quantification of this potential geometrical conflict.

7 – REFERENCES

[1] EN 1995-1-1:2010-12 Eurocode 5: Design of timber structures – Part 1-1: General - Common rules and rules for buildings, DIN, Berlin, 2010.

[2] O. Krüger, Schubverstärkung von Holz mit Holzschrauben und Gewindestangen, 16. Internationales Holzbau-Forum IHF, 2010.

[3] M. Trautz, C. Koj, and H. Uchtmann, Laserstrahlbohrungen für richtungsgenau positionierte Vollgewindeschrauben – Einbau und Tragverhalten, Bautechnik, vol. 92, no. 6, pp. 403–411, 2015, doi: 10.1002/bate.201400075.

[4] H. J. Blaß, Selbstbohrende Schrauben und Systemverbinder – Stand der Technik und Herausforderungen, 23. Internationales Holzbau-Forum IHF, 2017.

[5] Y. Steige and M. Frese, Study on a newly developed diagonal connection for hybrid timber trusses made of spruce glulam and beech laminated veneer lumber, Wood Material Science & Engineering, vol. 14, no. 5, pp. 280–290, 2019, doi: 10.1080/17480272.2019.1626908.

[6] M. Trautz, C. Koj, A. Künstler, and F. Weber, Mit Schrauben bewehren – Selbstbohrende Vollgewindeschrauben als Verstärkung in Brettschichtholzträgern und zur Ausbildung von hochleistungsfähigen Verbindungen, Forschungsbericht 01/2007, Lehrstuhl für Tragkonstruktionen, RWTH Aachen, 2007.

[7] H. J. Blaß and Y. Steige, Steifigkeit axial beanspruchter Vollgewindeschrauben, vol. 34 Karlsruher Berichte zum Ingenieurholzbau. Karlsruhe: KIT Scientific Publishing, 2018, doi: 10.5445/KSP/1000085040.

[8] M. Frese and M. Jordan, Deviations between planned and actual position of wood screws - consequences for minimum spacing, INTER/51-7-1 – Proceedings of the International Network on Timber Engineering Research, Tallinn, Estonia, 2018.

[9] E. Baldauf and M. Frese, Lageimperfektionen von selbstbohrenden Schrauben in Holz und Holzwerkstoffen, in iVTH-Kurzberichte, Internationaler Verein für Technische Holzfragen e. V., Ed., Kurzbericht 12/22, 2022.

[10] E. Baldauf and M. Frese, Lageimperfektionen von selbstbohrenden Schrauben in Holz und Holzwerkstoffen, in iVTH-Kurzberichte, Internationaler Verein für Technische Holzfragen e. V., Ed., Kurzbericht 06/23, 2023.

[11] E. Baldauf, Lageimperfektionen von selbstbohrenden Schrauben in Holz und Holzwerkstoffen, in Doktorandenkolloquium – Holzbau Forschung + Praxis, U. Kuhlmann, Ed., Universität Stuttgart, 2024.

[12] E. Baldauf, Untersuchung der Ursachen von Lageimperfektionen selbstbohrender Schrauben und Identifikation von Methoden zu deren Minimierung, in Karlsruher Tage 2024 – Holzbau: Forschung für die Praxis, C. Sandhaas, Ed., Karlsruhe: KIT Scientific Publishing, 2024.

[13] E. Baldauf and M. Frese, Lageimperfektionen von selbstbohrenden Schrauben in Holz und Holzwerkstoffen, Forschungsbericht (in press), KIT Holzbau und Baukonstruktion, Karlsruhe, 2025.

[14] Adolf Würth GmbH & Co. KG, ETA-11/0190: Self-tapping screws for use in timber constructions, DIBt, Jul. 23, 2018.

https://doi.org/10.52202/080513-0556