DEVIATIONS BETWEEN PLANNED AND ACTUAL POSITION OF WOOD SCREWS - CONSEQUENCES FOR MINIMUM SPACING

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KEYWORDS

Screw connection, inclined screws, crossed screw couple, position tolerance, damages to wood screws

1 INTRODUCTION AND TECHNICAL BACKGROUND

1.1 Motivation and aim

The insertion of self-tapping (self-threading) or self-drilling wood screws is usually accompanied by minor or major deviations between the planned screw axis and the actual one. The actual positions can be seen as a result of an individual insertion process influenced by a complex interaction between multiple parameters. A concise representation of this issue is for example given by Trautz and Koj 2015. They stress amongst others the necessity of sufficient spacing between adjacent screws to avoid contact problems.

Occasionally, screw connections comparable to those in Fig. 1 have shown harmful contact between narrow placed screws although minimum spacing was observed in design and execution. The minimum spacing between the represented crossed screw couples is usually given as a multiple (k) of the nominal screw diameter (d).

Several European technical assessments stipulate at least 1.5 for k. Eurocode 5 contains the general rules for minimum spacing rules being completed and extended by European technical assessments (ETAs).

Müller 2017 and Blaß 2017 recently reported contact problems with crossing screws. Furthermore, skilled carpenters, practitioners and designers have experienced such contact problems. Fig. 2 shows typical damages to screws of a crossed couple caused by contact. Even in reinforcement measures with long screws for shear and stresses perpendicular to the grain, critical deviations of the actual screw channel occur (Krüger 2010). Otherwise, reinforcing techniques based on controlled contact between screws and dowels require very accurate screw placements to ensure the intended load distribution between these components (e.g. Bejtka and Blaß 2005).

These aspects show the necessity to realistically estimate deviations between the planned and actual screw axis. For that purpose, about 350 insertion tests with wood screws were conducted and evaluated in a preliminary study (Jordan 2017). The aims of this study were 1. the identification of some crucial parameters influencing deviations, 2. the experimental determination of such deviations and

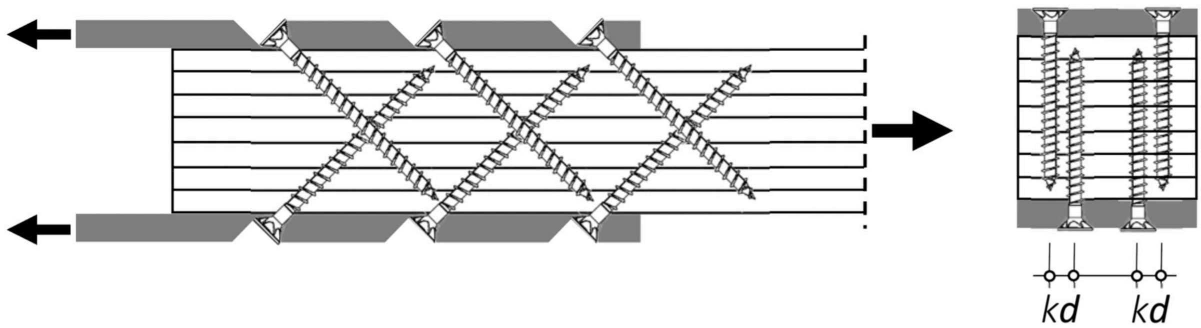


Figure 1: *Crossed screw couples with hazard of contact in case of too narrow mutual spacing.*

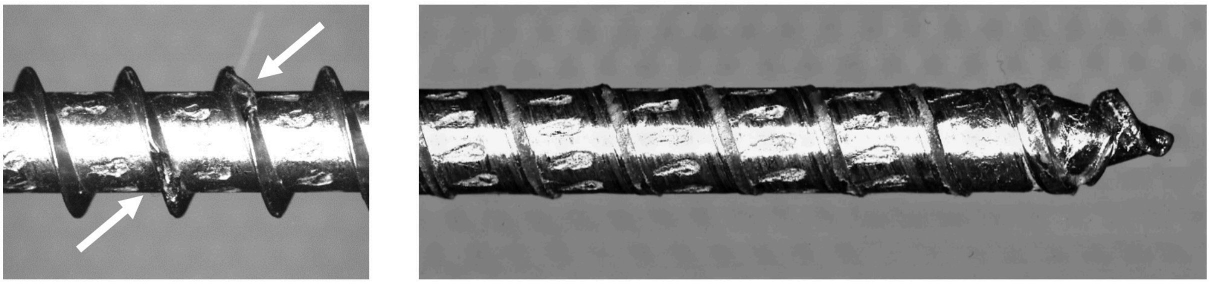


Figure 2: *Damages to wood screws caused by mutual contact. Local damage to a firstly screwed-in screw (left) hit by a secondly screwed-in one (right) resulting in almost complete loss of the thread.*

3. a proposal for a first tentative model predicting appropriate minimum spacing.

1.2 Interaction between insertion and wood structure

Potential parameters influencing deviations between the planned and actual screw axis are amongst others (cf. Trautz and Koj 2015): the technical equipment, the way someone screws in, with/without pre-drilling, use of short pilot holes, insertion angle between screw axis and wood surface (*β*), shape of the screw tip, straightness of the screw, angle between screw axis and grain direction (*α*), natural growth characteristics along the screw channel, glue lines, insertion length (*ℓ*), wood species, physical wood properties, screw stiffness or even unintended contact with other screws crossing the actual screw channel.

The glulam cube in Fig. 3 exemplifies that a planned screw axis can be described by a vector $\vec{a}$ in the spatial wood structure. Hence, the connection between the screw axis and the glulam structure is defined by a given orientation of the cube in the coordinate system

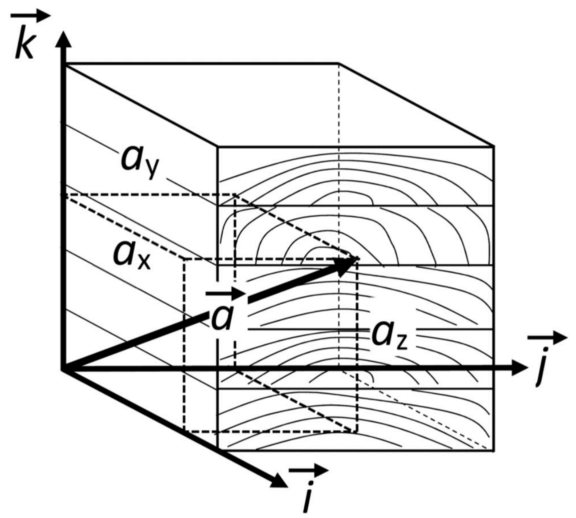


Figure 3: *Direction of a planned screw axis by means of the vector* $\vec{a}$.

and the coordinates a_x, a_y and a_z defining the screw axis. Using this system, the examined placements of screws in glulam are described below.

2 MATERIALS AND METHODS

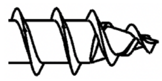
72 specimens for the insertion tests were made of spruce glulam GL24c. The specimens were realised from four glulam members, each 12 m in length, 180mm in width and 200mm in depth. The members consisted of five laminations. Where necessary, specimens were glued together to obtain sufficient dimensions for the intended insertion lengths. The density and the moisture content were measured by means of a cross-sectional slice at one third of the specimens. The results are compiled in Table 1. Table 2 contains the properties of the screws. Crucial variations refer to the screw length (to realise three different insertion lengths), the thread length and the tip shape. The nominal diameter was uniformly 8mm.

Four different screw placements (I, II, III and IV) were examined. The corresponding section planes, in which the planned screw axes lie, are visualised in Fig. 4. The vectors of the screw axes and the resulting angles (*α*) between screw axes and grain direction are quoted in Table 3. The screws were inserted by a single person using a hand-hold electric-powered screwdriver. The holes were neither pre-drilled nor pilot holes were provided. At the beginning of the insertion wedge-shaped screw guides equipped with grooves were used to ensure the intended insertion angle (β = 45° and 90°) between screw axis and surface as accurately as possible. Up to six screws were inserted in each specimen. Deviations between the planned exit points (*E*) and the actual ones were measured at the surface of the exit point. The coordinates Δ1 and Δ2 defined as orthogonal vectors originating from *E* were then computed by means of vector calculations. Fig. 4 in total represents the connection between the planned exit points, the actual ones and the positive directions of the computed coordinates Δ1 and Δ2.

Table 1: Density and moisture content of the glulam specimens.

Glulam property	N	Mean	SD	Min	Max
Density in kg/m^3	21	428	24	388	470
Moisture content in %	21	11.4	0.89	10.4	14.7

Table 2: Wood screws.

Drill tip	*d*	Screw length	Thread length	Insertion length	Tip shape
	mm	mm	mm	mm	
		220	200	160	
with	8	280	260	220	
		370	350	340	
		220	100	160	
without	8	260	100	220	
		380	100	340	

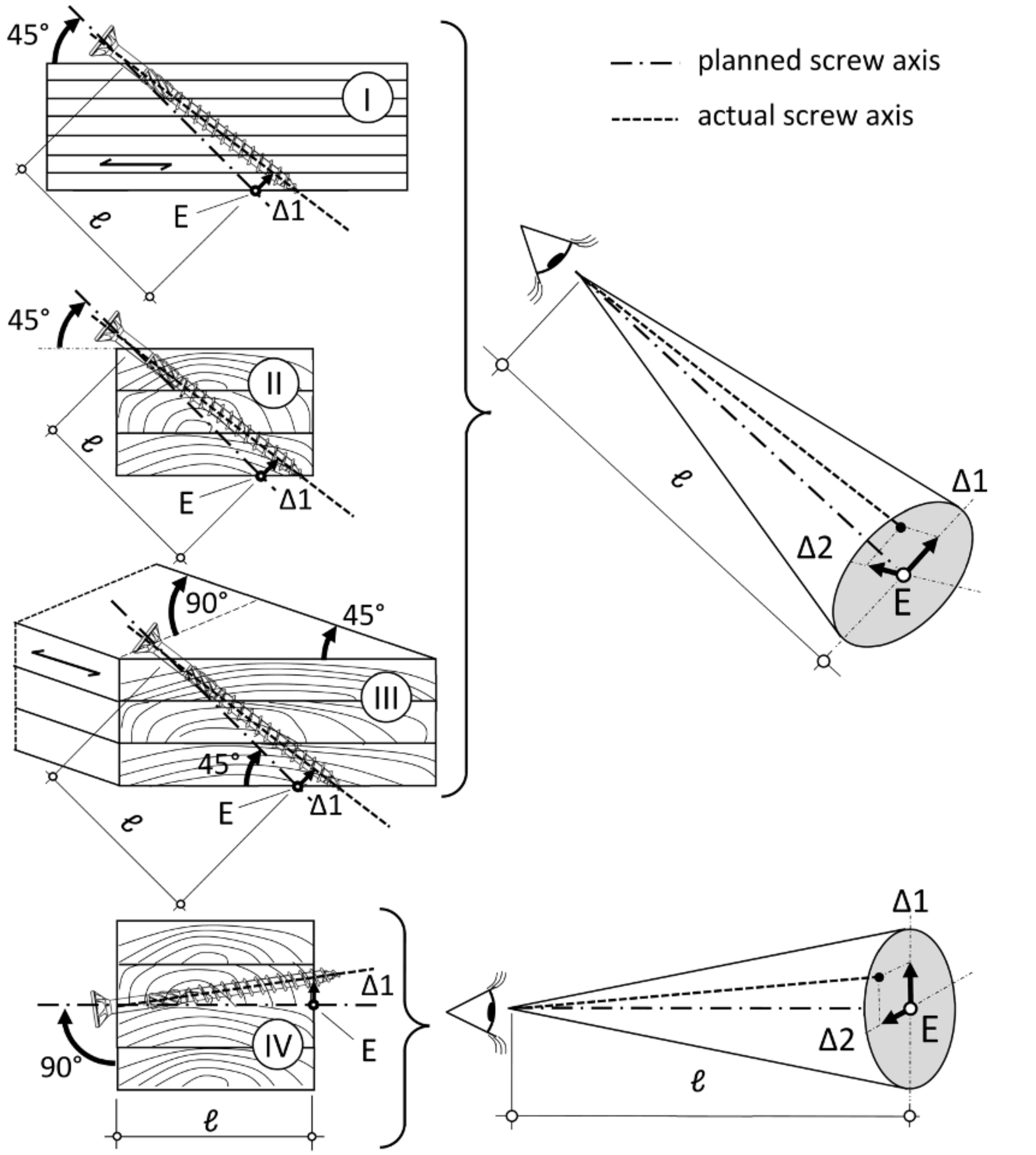


Figure 4: *Examined placements.*

Table 3: Coordinates of the examined vectors $\vec{a}$.

Placement	a_x	a_y	a_z	$\vec{a}$	α	β	placement in the ...
I	1	0	1	(1,0,1)	45°	45°	longitudinal section
I	1	1	0	(1,1,0)	45°	45°	longitudinal section
II	0	1	1	(0,1,1)	90°	45°	cross-section
III	0.71*	0.71*	1	(0.71,0.71,1)	60°	45°	diagonal section
IV	0	1	0	(0,1,1)	90°	90°	cross-section / glue line

* = $\sqrt{1/2}$

3 RESULTS

3.1 Deviations Δ1 and Δ2

Fig. 6 shows the results for the placement imperfections I-IV. The four pairs of diagrams contain the deviations Δ1 and Δ2 differentiated by insertion length (top/left) and tip shape (bottom/right). Amongst others, these observations were made:

- **Placement I:** Δ1 is almost exclusively positive (Fig. 6-I); Δ2 is obviously higher for screws with drill tips compared to Δ2 for those without drill tips (Fig. 6-I bottom). Independent of the insertion length and tip shape, Δ2 is more or less symmetrically distributed around the vertical axis with Δ2 = 0.
- **Placement II:** Δ1 is almost exclusively positive except for the insertion length of 340mm (Fig. 6-II left). The screws inserted with 340mm having negative Δ1 values are equipped with a drill tip. Independent of the insertion length and tip shape, Δ2 is more or less symmetrically distributed around the vertical axis with Δ2 = 0.
- **Placement III:** Δ1 is exclusively positive; however, screws inserted with 220mm exhibit also almost exclusively positive Δ2 values (Fig. 6-III top). The distribution of Δ2 is symmetrical.
- **Placement IV:** The scatter of Δ1 is larger than the one of Δ2 (Fig. 6-IV top). Independent of the insertion length and tip shape, both deviations are symmetrically distributed around their corresponding axes with Δ = 0. Only three screws kept their screw channel exactly in the glue line.

3.2 Absolute deviation and cone model

Using equation (1) the absolute deviation denoted as radius r was computed. The radius r and the corresponding insertion length yield a deviation angle ε, see equation (2). Fig. 7 shows all relations between the radius r and the insertion lengths. The maximum of tanε (max tanε) is quoted in Table 4 for the four placements and the corresponding insertion lengths.

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

$$\tan\varepsilon = r/\ell \qquad (2)$$

Table 4: Statistics of the absolute deviation.

Placement	Insertion length	$r = \sqrt{\Delta 1^2 + \Delta 2^2}$				max tanε
		N	Mean	CV	Max	
	mm		mm	%	mm	
I	160	41	8.02	33	13.5	0.084
	220	48	10.4	36	22.2	0.101
	340	37	23.8	32	37.1	0.109
II	160	37	5.24	31	8.82	0.055
	220	31	9.17	31	14.6	0.066
	340	30	10.3	50	20.7	0.061
III	160	19	10.7	41	19.3	**0.121**
	220	20	9.89	33	19.6	0.089
	340	21	13.5	40	26.1	0.077
IV	160	23	5.38	37	8.06	0.050
	220	20	6.09	38	11.4	0.052
	340	21	11.6	45	26.1	**0.077**

Total: 348 insertion tests

The placements I/III and II/IV are grouped because of comparable placement conditions and similar magnitude of deviations. In doing so, the maximum angles given by tanε are 0.121 and 0.077 for the placement groups I/III and II/IV, respectively.

Fig. 5 shows a general cone model. This model would basically be suitable to estimate the cone shaped clear space around a planned screw axis a screw[1] needs to be inserted without having contact with other screws. Based on the presently available data the space should be calculated with tanε of about 0.12 (≈0.121) and 0.08 (>0.077) for the groups I/III and II/IV, respectively. These proposed values for the tangent do not contradict deviations published by Trautz and Koj 2015.

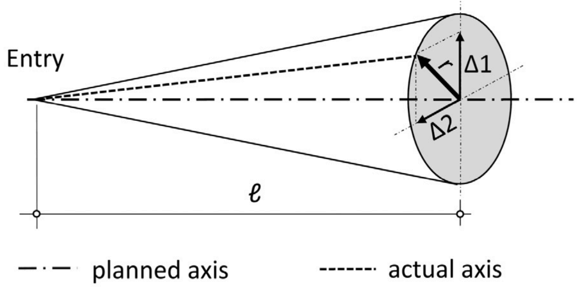


Figure 5: *Visualised cone model.*

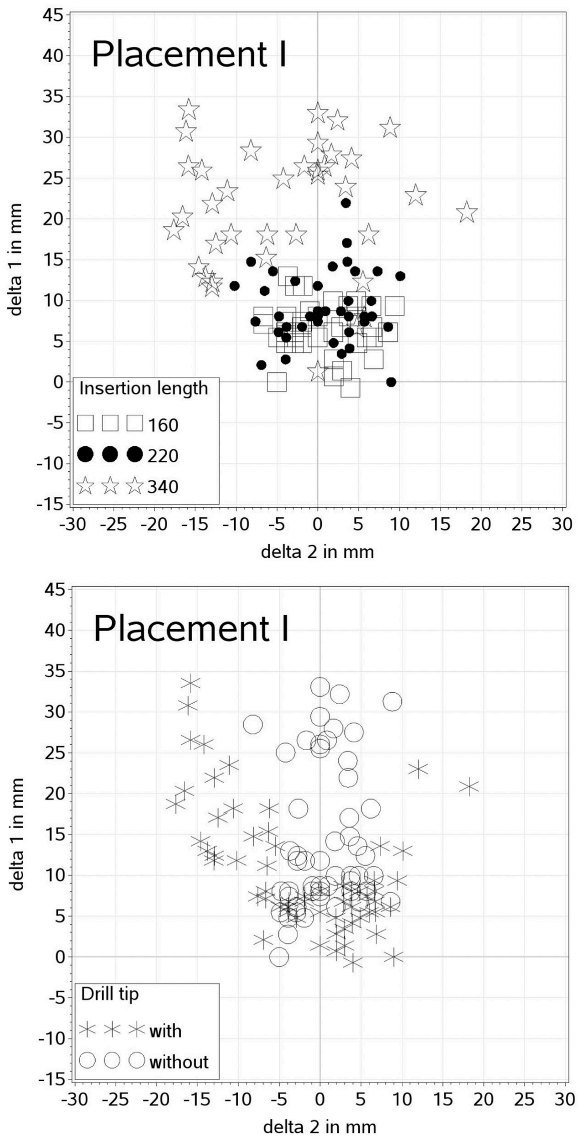


Figure 6-I: *Placement I.*

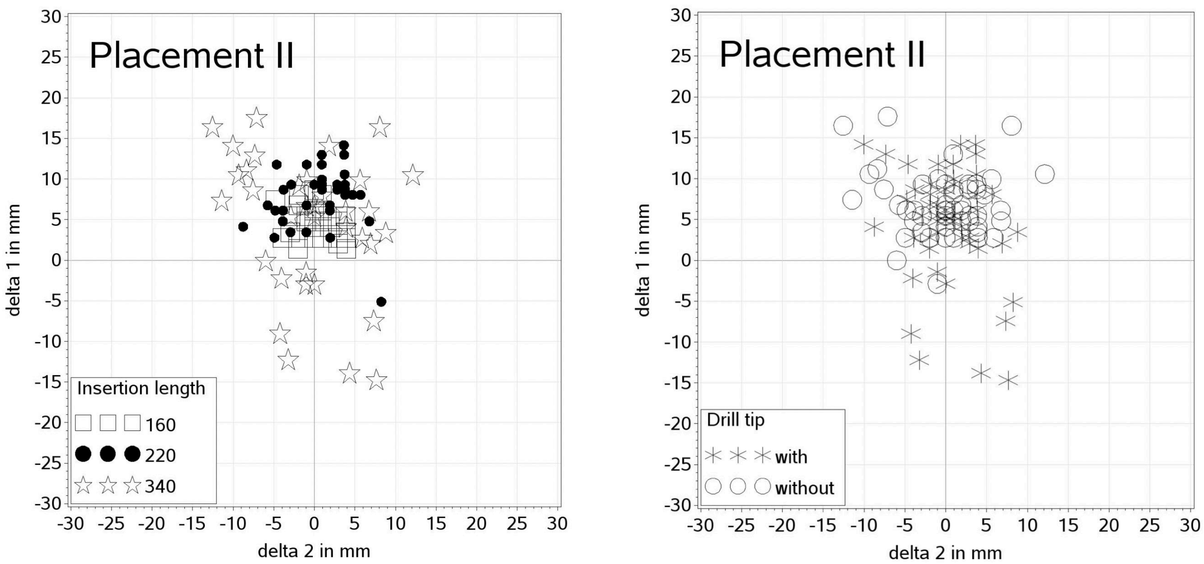


Figure 6-II: *Placement II.*

[1] Nominal diameter here assumed as 0

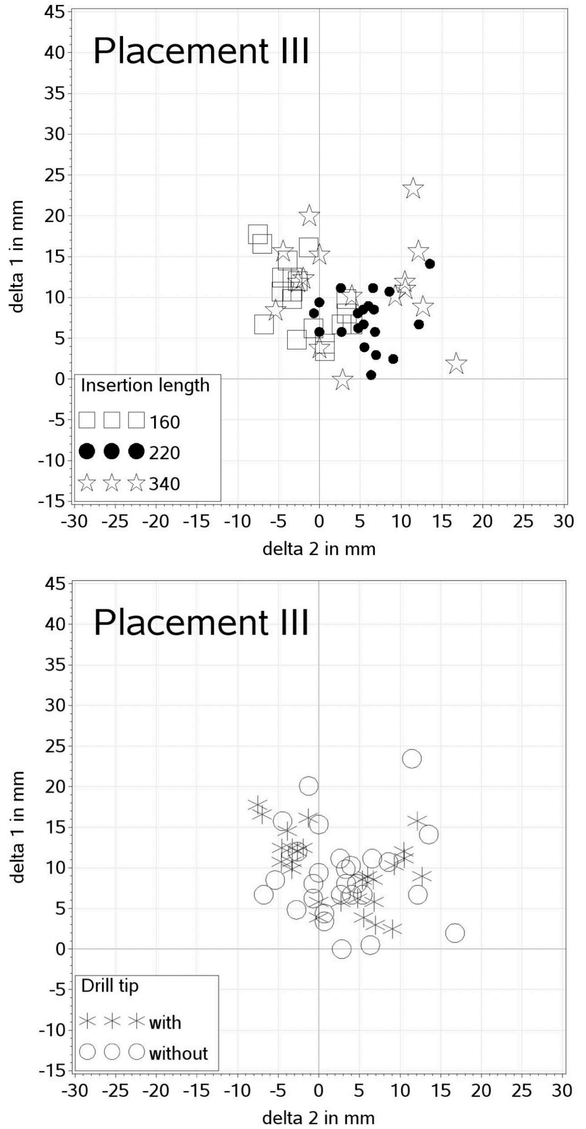


Figure 6-III: *Placement III.*

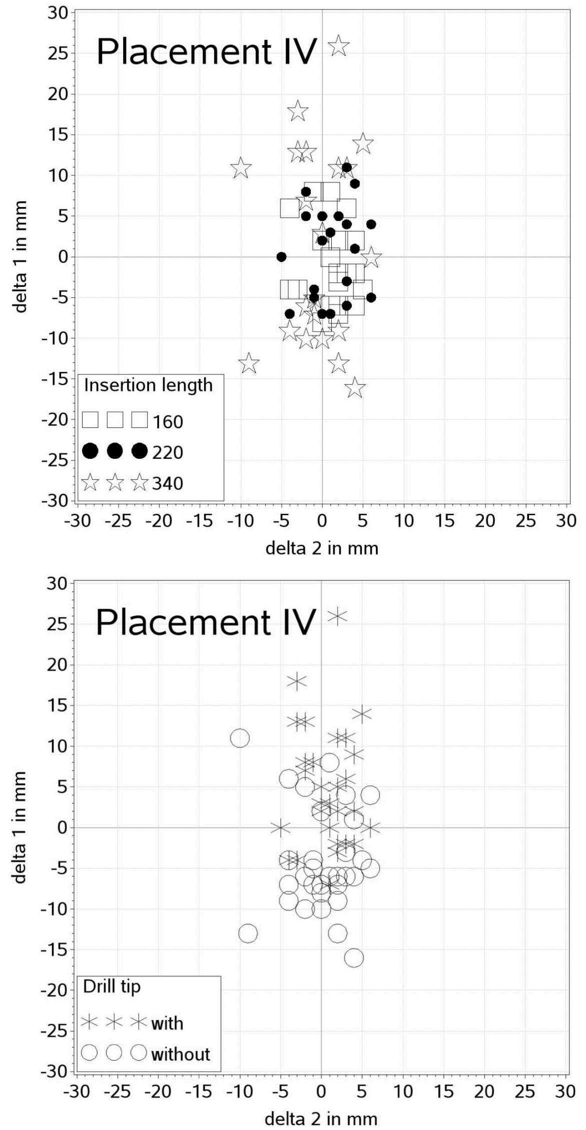


Figure 6-IV: *Placement IV.*

3.3 Proposal for minimum screw spacing considering stochastic effects

The statistics in Table 5 show that significant differences exist between the upper percentiles of tanε belonging to the corresponding placement groups.

Stochastic effects for group I/III and II/IV (values in brackets) are considered using the 95th percentile. Consequently, the exceedance probability of tanε = 0.0950 (0.0543) is less than 5 %. Hence, the probability that the unintended tangent of two independent adjacent screws exhibits 0.1 (0.06) is less than 0.25%. Fig. 8 exemplifies that the actual probability of contact between two screws in the critical area is far lower than 0.25 % due to the circular distribution[2] of possible locations after a corresponding large insertion length ℓ_{crit}.

Equation (3) reflects these considerations. Inserting tanε = 0.1 and 0.06 for group I/III and II/IV, respectively, yield the mutual spacing a between two adjacent screws in a critical area.

$$a = 2\ell_{crit} \cdot tan\varepsilon + d \quad (3)$$

Table 5: Statistics and upper percentiles of tanε.

Placement group	N	Mean	SD	95 %	99 %	Max
I/III	176	0.0542	0.0218	0.0950	0.112	0.121
II/IV	172	0.0339	0.0131	0.0543	0.0665	0.0767

[2] Uniform circular distribution of locations assumed for simplicity reasons

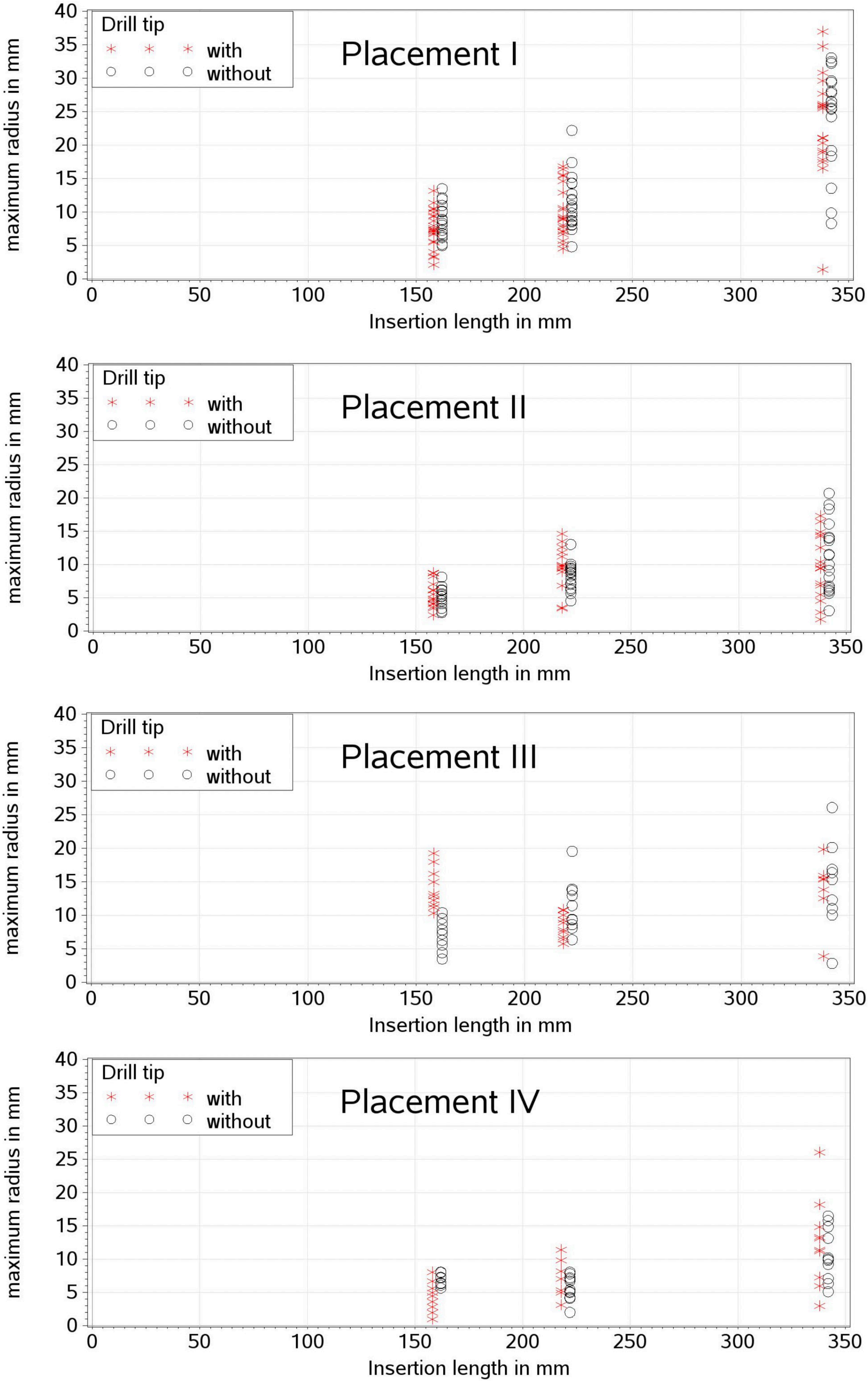


Figure 7: *Maximum radius over insertion length.*

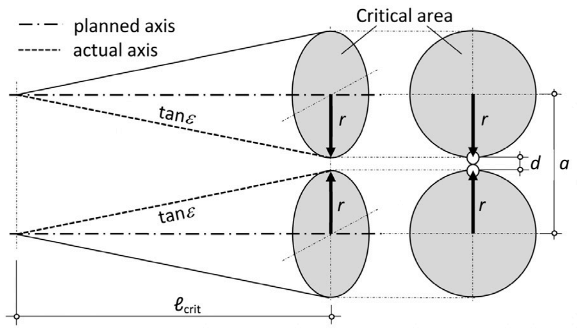


Figure 8: *Spacing a between two planned screw axes based on tanε, ℓ_{crit} and d.*

Favourable effects of almost only positive Δ1 values in group I/III are not yet considered in equation (3), compare Fig. 6-I and 6-III. Furthermore, independence of adjacent screws is a strongly simplifying assumption owing to similar wood properties in the critical area and similar insertion geometry in case of parallel oriented adjacent screws.

4 CONCLUSIONS AND CONSEQUENCES

Based on insertion tests with 8mm self-tapping and self-drilling wood screws in spruce glulam these conclusions are drawn:

- Deviations between the actual and planned screw axis depend on the insertion geometry. In unfavourable cases the magnitude amounts to 12% related to the insertion length. This maximum is covered by tests without pre-drilling and with a maximum insertion length of 340mm.
- If the intended angle between screw axis and grain direction is considerably less than 90°, the actual screw axis tends to follow the grain direction.
- The mainly positive Δ1 deviations in placement I and particularly in placement II and III are likely also caused by insertion angles systematically less than the intended 45°. The reason for this systematic inaccuracy is supposed to lie in the insertion procedure using the wedge-shaped screw guides (cf. Trautz et al. 2007, p. 67).
- If the entry point of the screw tip coincides with the glue line, it seems to be unlikely that the axis of screws remains in the glue line. This may be explained by the tendency of a screw to proceed in the lamination with lower density.
- Considering placement imperfections the necessary space for a single screw is cone-shaped. A cone model is therefore proposed in order to determine minimum screw spacing. Due to limited experimental data, the formulation of the model is in a tentative stage.

So far, consequences for screw spacing requirements are:

- Using the proposed cone model minimum screw spacing can be estimated such that harmful contact between adjacent screws is avoided. The model applies to four common insertion geometries. So far, its application is restricted to 8mm wood screws, to spruce glulam and to an insertion length of approximately 400mm.
- Screw spacing requirements should be discussed against the background of unintended deviations and harmful contact.
- Requirements in Eurocode 5 and technical assessments should at least be checked, amended where necessary or a general note should be made in provisions that deviations have to be taken into account.
- The results of the study are being used for a research proposal covering open questions. Several issues to be examined concern the use of screw guides and their influence on the actual screw axis, wood species, connection principles, insertion lengths exceeding 340mm, the influence of the screw diameter and other than the examined insertion geometries.

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