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ENERGY DEMAND FOR THE DRIVING IN OF SELF-TAPPING TIMBER SCREWS AND ITS APPLICABILITY

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ABSTRACT: The following paper proposes a test method to evaluate the insertion energy of self-tapping timber screws in order to gain data that can be used in life cycle assessments. The proposed test configuration is based on an established setup to test the torsional resistance for driving in screws. Experimental data show the usability of the test method to distinguish different screw types with regard to their energy consumption. It was found that the insertion energy is highly influenced by timber density, screw diameter and insertion length. This correlation was used to derive an empirical model to predict the insertion energy of Tenz® screws. Of course, the presented approach may also be adapted for other screw types and serve as a tool for screw comparison and optimisation. Furthermore, the insertion energy has the potential to serve as a key value in the quality control of screwed connections.

KEYWORDS: self-tapping timber screws, screw application, insertion moment, insertion energy, RILEM TC TPT

1 INTRODUCTION AND THEORETICAL BACKGROUND

The ongoing climate crisis has been a major topic in engineering and has also put a spotlight on energy consumption in construction. Although nowadays the energy demand for the production of construction materials and engineering products is relatively well known as it is vital for the life cycle assessment (LCA) of structures, lesser is known about the energy consumption during their application or usage. In timber engineering, one of these widely used products are self-tapping timber screws. The amount of energy needed to drive in a screw has not yet received much attention and as a result, the comparability of different products in regard to the demanded insertion energy is not given.

Furthermore, although some influencing factors on the insertion energy such as timber density and screw diameter have been hinted at in previous work (cf. [1]), their effect has not been quantified while other screw related characteristics such as screw type, head type and insertion length or timber related characteristics such as axis to grain angle and timber species did not receive any attention at all. Such information however may become very valuable in the future as the insertion energy has the potential to serve as a predictor for the withdrawal strength and the axial stiffness of a screwed connection (cf. [2]) and be therefore used in quality control.

In the following the insertion energy W is defined as the amount of work performed during the insertion of the screw, which is equivalent to the Integral of the power demand P during that process. In the scope of screw insertion, P can be determined in two ways:

- Measurement of voltage U and electric current I and calculation of the electric power demand of the electric drive with $P = U \cdot I$
- Measurement of insertion moment M and angular velocity ω and determination of the rotational power demand during the insertion process with $P = M \cdot \omega$

The determination of the electric power demand can be done relatively easy. However, the hereby calculated insertion energy also includes losses within the setup itself. As a result, the approach using M and ω is favourable for standardized testing as it only contains the energy demand of the screw-timber-interaction.

The synchronized measurement of the insertion moment M and the angle of rotation φ allows the calculation of the insertion energy according to Equation (1):

$$W_\omega = \int M \cdot \omega \, \partial t \tag{1}$$

where $\omega = \partial\varphi / \partial t$ = angular velocity. To be able to calculate the insertion energy without direct measurement of the angle of rotation, the following correlation between angular velocity ω, thread pitch p and insertion length l_i is utilised:

$$l_i = \frac{\varphi}{2\pi} \cdot p \rightarrow \frac{\partial l_i}{\partial t} = \frac{\partial \varphi}{\partial t} \cdot \frac{p}{2\pi} \rightarrow \partial t = \frac{\partial l_i}{\omega} \cdot \frac{2\pi}{p} \tag{2}$$

Inserting Eq. (2) in Eq. (1) yields:

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$$W_l = \frac{2\pi}{p} \int M \, \partial l_i \quad (3)$$

2 MATERIAL AND METHODS

2.1 Test setup and evaluation

On basis of the established test configuration for testing the torsional resistance when driving in screws provided in EN 15737:2009 [3], an adapted test configuration was developed to determine the energy demand as an additional property, see Figure 1.

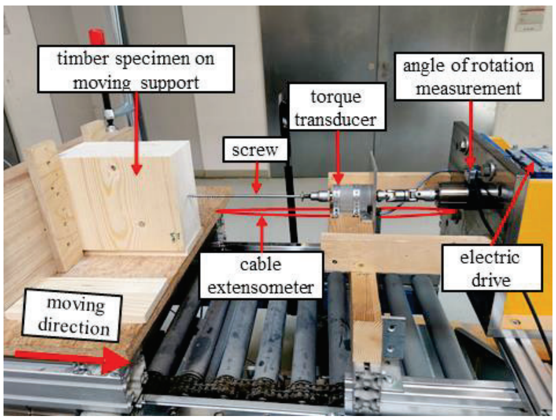

Figure 1: *Test configuration to determine the insertion energy*

The proposed configuration consists of a fixed electric drive and a moving support on which a timber block is placed. At the shaft of the electric drive a sensor to measure the angle of rotation as well as a torque transducer are installed. A pneumatic cylinder presses the moving support with the timber block against the screw, which is placed horizontally between timber and torque transducer. A cable extensometer, which is connected to both fixed and moving support, measures the insertion length.

During the tests in the scope of this paper, the pressure of the pneumatic cylinder and the renditions per minute of the electric drive were varied depending on the screw length but not recorded, as they show no influence on the insertion energy according to investigations in [2]. The dimensions of the timber specimens were chosen in agreement with the specifications given in EN 15737:2009 [3] meaning that the specimens were at least 20 *d* in length, 10 *d* in width and the screw length in height. Unless stated otherwise in one of the detailed descriptions of the test series in the following Sections 2.2 to 2.5, the timber specimens were made of spruce softwood (*picea abies*) with an almost equal mean density $\rho_{12,mean}$ of approx. 420 kg/m³ for all test series, which was done by matched sampling.

After the insertion test, the moisture content and density were determined according to EN 13183-1 [4] respectively ISO 13061-2 [5] on small scale specimens with a quadratic cross section and a length equal to the screw's insertion length. The small-scale specimens included the whole screw channel which was positioned in the centre of the specimen. For the evaluation, the density was corrected to a reference moisture content of 12 % according to ON EN 384 [5].

Figure 2 exemplarily shows the results of an insertion test carried out with a screw with a nominal diameter d_{nom} = 8.0 mm and a length l =240 mm in a piece of spruce softwood. The top graph shows the relationship M vs. t, which is used for the determination of the torsional resistance of driving in screws. The peak at the end of the driving in marks the insertion of the screw head in the timber. The middle graph shows power P vs. time t. The similar shape compared to the graph M vs. t is a result of the constant angular velocity for the majority of the test run. The bottom diagram shows the increase in insertion energy over time, which is equal to the area under the P vs. t relationship (marked in grey in the middle diagram). The insertion energy was then evaluated at two points: W_{shaft} including the insertion of screw tip, thread and shank but without the portion of the head insertion and W_{head}, including a flush head insertion to the timber surface.

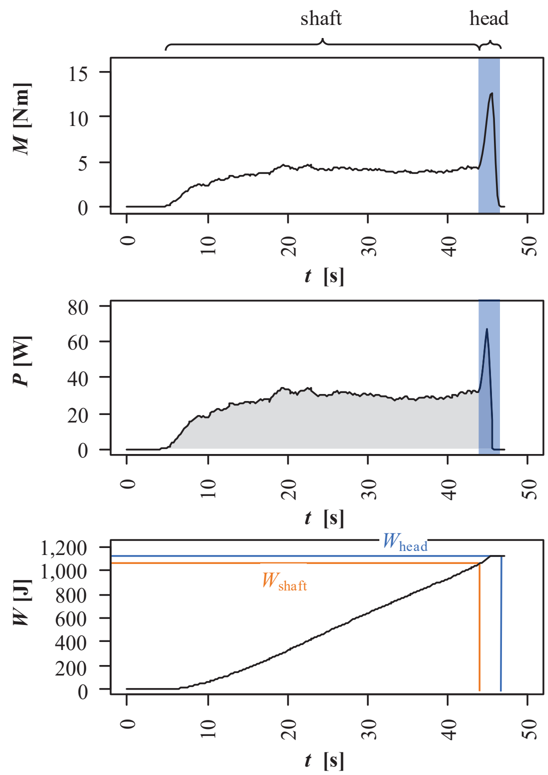

Figure 2: *M, P and W vs. t exemplarily for a TENZ® screw with d_{nom} = 8.0 mm and l = 240 mm*

2.2 Set 1: Comparison of different screw types from different manufacturers

The main aim of this set was to compare different screw types from different manufacturers with regard to the insertion energy. The tested screws are given in anonymized form in Table 1 and visualized in Figure 3. Groups one and two consist of partially threaded screws

with a nominal diameter of 6.0 mm respectively 8.0 mm;, the screw length was 160 mm respectively 240 mm. The test series were then compared to Tenz WBS screws of test series 29 respectively 30, see Section 2.3, Table 2. The Tenz screw of test series 23 with diameter 6.0 mm had a length of 240 mm; the insertion energy was therefore also evaluated at an insertion length of 160 mm. Group three included dry wall screws with diameters varying between 3.0 mm and 4.2 mm and lengths in the range of 35 mm to 70 mm. For a better comparison in-between this group, the insertion energy of the dry wall screws was evaluated at an insertion length of 30 mm.
All screws except for screw types one, nine and 18 had a countersunk head (CS) with or without additional features. Screw types one and nine had a staggered head with saw tooth, screw type 18 had a washer head (WH).

Table 1: *Summary of the tested screws for set 1*

	Screw Type [-]	*n* [-]	*l* [mm]	l_{thread} [mm]	p^* [mm]
d_{nom} = 6.00 mm	1	7	160	70	4.9
	2	7	160	75	4.6
	3	7	160	70	2.7
	4	7	160	65	5.0
	5	7	160	70	3.7
	6	7	160	70	3.7
	7	7	160	70	4.7
d_{nom} = 8.00 mm	8	7	240	80	5.3
	9	7	240	95	5.6
	10	6	240	95	5.6
	11	7	240	100	5.8
	12	7	240	100	6.7
	13	7	240	100	5.6
	14	7	240	100	6.5
	15	7	240	90	4.8
	16	7	240	100	5.6
	17	7	240	100	5.6
	Screw Type [-]	*n* [-]	d_{nom} [mm]	*l* [mm]	p^* [mm]
dry wall screws+	TENZ DWS	7	4.20	50	2.8
	18	7	4.20	38	3.6
	19	7	4.20	70	3.6
	20	6	4.20	70	3.5
	21	7	4.20	70	3.3
	22	7	4.20	70	2.8
	23	7	3.90	45	2.8
	24	7	3.90	55	3.2
	25	7	3.90	35	2.9

*the mean thread pitch was measured on one screw per series along 10 turns
+dry wall screws were evaluated at an insertion length of 30 mm

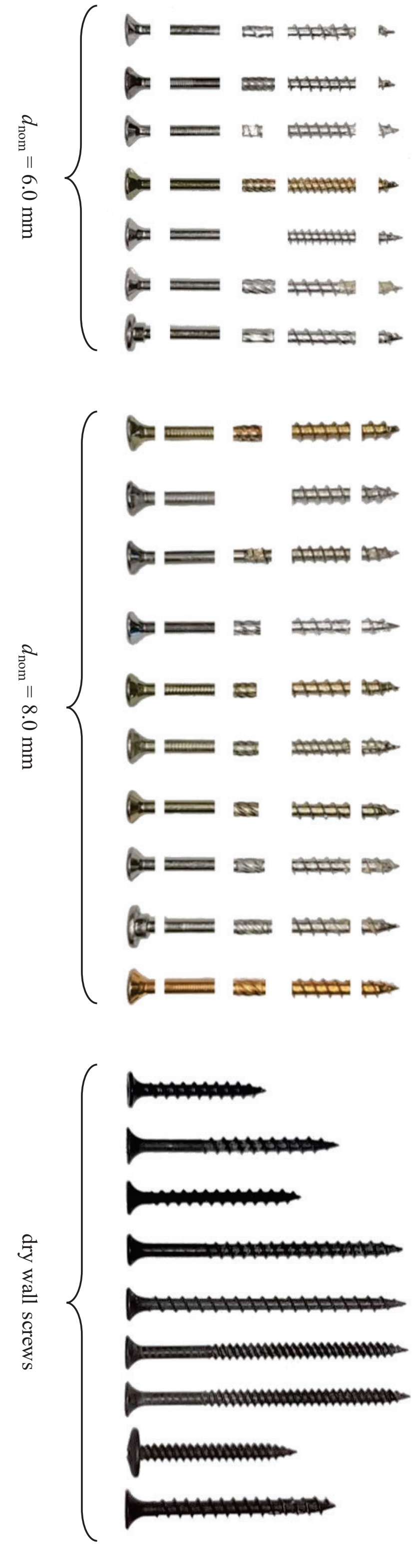

Figure 3: *Screws compared in set 1; also included are Tenz screws used in series 29 and 30 see section 2.3*

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2.3 Set 2: Influence of density, length and diameter

The test series within this set were used to quantify the influence of timber density, screw length and screw diameter which have been identified to have a major impact on the insertion energy in [1]. For this purpose, three density classes were formed, which contained three test series each, one for each tested diameter. The test data of this set were also used to derive an empirical model to estimate the insertion energy for the whole Tenz screw portfolio. Consequently, additional test series were included on selected screws of type Tenz WS and Tenz DS. The test series of set 2 are given in Table 2 and depicted in Figure 4. The head types of all screws, except for Tenz WBS 8.0x600 mm which had a WH, were CS.

Table 2: *Test series of set 2*

	series [-]	*n* [-]	targeted ρ_{12} [kg/m³]	d_{nom} [mm]	*l* [mm]	p^* [mm]
TENZ WBS	26	10	370	6.0	240	4.5
	27	10	370	8.0	240	5.2
	28	10	370	10.0	240	5.6
	29	10	420	6.0	240	4.5
	30	10	420	8.0	240	5.2
	31	10	420	10.0	240	5.6
	32	10	520	6.0	240	4.5
	33	10	520	8.0	240	5.2
	34	10	520	10.0	240	5.6
	35	10	420	6.0	30	4.5
	36	10	420	8.0	600	5.2
	37	10	420	10.0	100	5.6
	38	10	420	10.0	600	5.6
TENZ WS	39	10	420	4.0	25	2.8
	40	10	420	6.0	240	4.7
	41	10	420	8.0	240	5.2
	42	8	420	8.0	400	5.4
TENZ DS	43	10	420	6.0	150	3.6

*the mean thread pitch was measured on one screw per series along 10 turns

Figure 4: *Screws used in test set 2*

2.4 Set 3: Influence of axis-to-grain angle and head type

This test set served to investigate the influence of the axis-to-grain-angle α and the head type on the insertion energy. The tested screw type was Tenz WBS 8.0x240 mm with a pitch *p* =5.2 mm. A summary of the test series can be found in Table 3.

Table 3: *Test series of set 3*

	series [-]	*n* [-]	α [°]	*head type* [-]	*additional characteristic* [-]
TENZ WBS	44	10	45	CS	-
	45	10	0	CS	-
	46	10	90	WH	WH flush on timber surface
	47	5	90	CS	CS sunk approx. 1 cm in timber

2.5 Set 4: Influence of timber material

The investigation of different timber species and timber products was carried out in set 4. Within this set, Tenz WS 5.0x60 mm screws with *p* = 3.3 mm were used. The test series of this set are summarised in Table 4.

Table 4: *Test series of set 4*

	series [-]	*n* [-]	*timber species / timber product* [-]
TENZ WS	48	6	spruce (*picea abies*)
	49	6	MDF board
	50	6	beech (*fagus sylvatica*)
	51	6	beech LVL

3 RESULTS AND DISCUSSION

3.1 Comparison of different evaluation methods

Figure 5 shows the residuals of the insertion energy of the whole data set calculated by Eq. (1) versus Eq. (3) for the insertion energy including screw head insertion (Figure 5 left) and without screw head insertion (Figure 5 right).

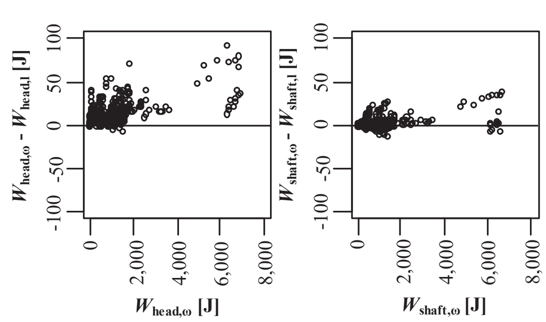

Figure 5: *Residuals for the insertion energy in dependence of the evaluation method. left: W_{head} including the head; right: W_{shaft} for the shaft only*

It can be seen that although the scatter does not show a trend along the tested spectrum, suggesting both calculation methods to be comparable, there is a shift to the positive side for the insertion energy including the head. This should be kept in mind when evaluating W_{head}. However, the knowledge of the thread pitch p is crucial for the applicability of Eq. (3) in both cases.

For the more detailed discussion in the remaining paper, the results of W_{ω} acc. to Eq. (1) will be discussed as it is seen as the more reliable method.

3.2 Set 1: Comparison of different screw types and manufacturers

The overall mean density $\rho_{12,mean}$ for test series of screws with d_{nom} = 6.0 mm of set 1 was 420 kg/m³. The minimum $\rho_{12,mean}$ of a single test series was 414 kg/m³and the maximum $\rho_{12,mean}$ was 424 kg/m³ indicating a successful matched sampling process. The average moisture content was u = 14.0 %. For more details regarding each test series, please refer to Table A-1 in the Annex.

Figure 6 compares the insertion energy of each test series of set 1 with diameter 6.0 mm with the corresponding Tenz screw (test series 29) which was for this purpose evaluated at an l_i of 160 mm. Except for series 1 and 5, statistically significant differences between Tenz and the other test series were found using unpaired two-sample t-tests assuming a significance threshold of $\alpha = 0.05$. Especially test series 3 differs from the other test series. Although not analysed in detail, this was the only series without any screw features (no compactor, cutter etc.) which could be the reason for the higher insertion energy.

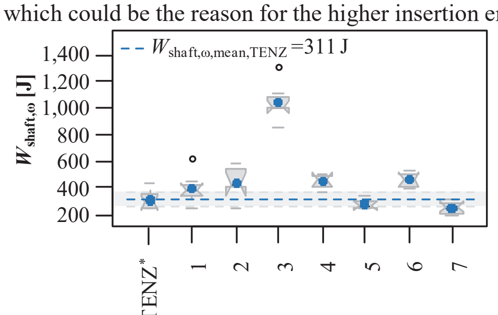

Figure 6: *Boxplots and mean values for $W_{shaft,\omega}$ of screws with d_{nom} = 6.00 mm and l =160 mm; 95%-CI for TENZ. *TENZ screw with l =240 mm was used and evaluated at an insertion length of =160 mm*

For the screws with diameter 8.0 mm, $\rho_{12,mean}$ of all series was 429 kg/m³. The minimum $\rho_{12,mean}$ of a single test series was 401 kg/m³ and the maximum $\rho_{12,mean}$ was 433 kg/m³. The average u was 14.2 %. A detailed summary can be found in Table A-2 in the annex.

The insertion energy results of each test series of this group can be seen in Figure 7. Again using unpaired two-sample t-tests statistically significant deviations can be found between Tenz (test series 30) and test series 8, 11, 12, 13 and 16.

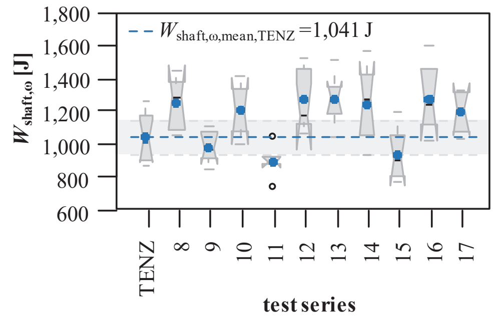

Figure 7: *Boxplots and mean values for $W_{shaft,\omega}$ of screws with d_{nom} = 8.00 mm and l =240 mm*

The timber specimens of the test series with the dry wall screws had an overall $\rho_{12,mean}$ of 414 kg/m³, the minimum density of a single series was 407 kg/m³, the maximum was 428 kg/m³ while the average u was 10.9 %. The main statistics of this set is summarized in Table A-3 in the Annex. Figure 8 shows the insertion energy of dry wall screws evaluated at a constant insertion length of 30 mm.

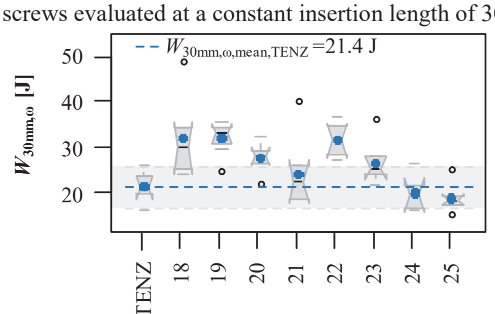

Figure 8: *Boxplots and mean values for $W_{30mm,\omega}$ evaluated at an insertion length of 30 mm for dry wall screws; 95%-CI for TENZ.*

Unpaired two-sample t-tests between Tenz and test series 18, 19, 20 and 22 showed a statistically significant difference while the difference to the remaining test series of this group were statistically insignificant.

3.3 Set 2: Influence of density, length and diameter

The main statistics of this set can be found in Table A-4 in the Annex.

During the execution of test series 36 with screws 8.0 x 600 mm, a bending of the screws was observed during insertion. As this was the only test series showing such behaviour, it is likely that the high slenderness of this specific screw is the reason for the bending. It is assumed that the bending causes the screw shank to press against the screw channel during insertion resulting in a higher insertion energy due to the increased friction.

As ρ, d and l were identified as the predominant factors regarding the insertion energy in a past investigation (see [1]), a nonlinear least squares regression analysis to describe $W_{shank,\omega}$ was made using the basic approach according to Eq. (4).

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$$W_{\mathrm{TENZ}} = W_0 \left(\frac{\rho}{420}\right)^{k_\rho} \left(\frac{d_{\mathrm{nom}}}{8.0}\right)^{k_d} \left(\frac{l}{100}\right)^{k_l} \quad (4)$$

Furthermore, it was assumed that the factors k_ρ, k_d and k_l are constant irrespective of the screw type (WBS, WS or DS). The initial regression was executed on the data of Tenz WBS screws though test data from test series 36 were excluded from this regression analysis due to the aforementioned bending effects. The resulting factors are $k_\rho = 1.713$, $k_d = 1.976$ and $k_l = 1.480$, which in the following were set to $k_\rho = 1.7$, $k_d = 2$ and $k_l = 1.5$. Based on these factors, screw specific nominal insertion energies W_0, definded as the insertion energy needed to drive in an 8.0x100 mm screw in spruce with density 420 kg/m³, were derived see Table 5.

Table 5: *nominal insertion energies W_0 for Tenz screw types*

screw type	W_0 [J]
Tenz WBS	267
Tenz WS	371
Tenz DS	496

The prediction of the empirical model is plotted against experimental data in Figure 9. An - especially in timber engineering - unusually high agreement between model prediction and experimental data is given ($R_{adj}^2 = 0.99$) when test series 36 is excluded. The correlation remains high even if series 36 is considered ($R_{adj}^2 = 0.95$).

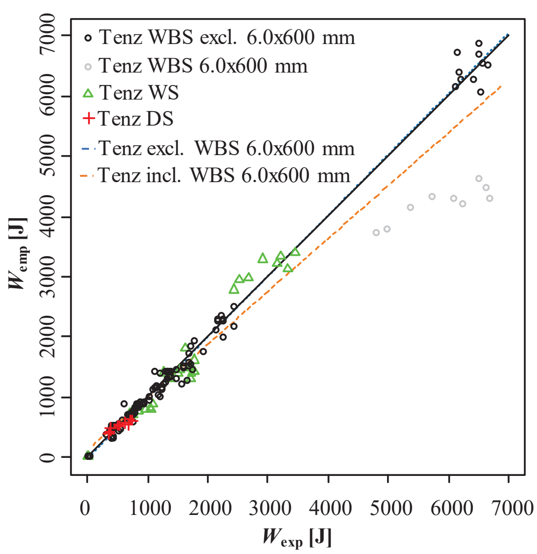

Figure 9: *Model prediction vs. experimental data for Tenz screws*

Figure 10 shows the accompanying residuals of the model. Overall, a uniform distribution of the residuals can be observed for the whole dataset (again excluding test series 36), confirming the general suitability of the model. Because the residuals for Tenz WS are also distributed without a recognizable trend along the tested spectrum even though the model's underlying factors (except for the nominal insertion energies W_0) were derived based on Tenz WBS screws it can be concluded that the assumption of the factors' independency of the screw type is valid. However, it remains uncertain whether this also applies for other screw manufacturers and especially for fully threaded screws.

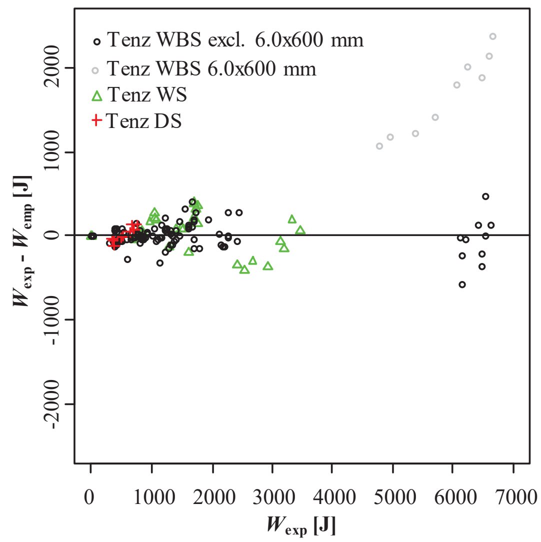

Figure 10: *Residual plot for data according to Eq. (4)*

3.4 Set 3: Influence of screw axis to grain angle and head type

A summary of the results of set 3 can be found in Table A-5 in the Annex. The mean densities of the respective test series range from $\rho_{12,mean} = 412 \div 423$ kg/m³ with a mean density of 418 kg/m³ of the total set 3. The average moisture content was 13.8 %.

Figure 11 shows the influence of the axis to grain angle α on the insertion energy. Between 90° (perpendicular to grain insertion) and 45°, a decrease of around 20 % of the insertion energy is observed. However, between 45° and 0° (parallel to grain insertion) no further reduction is given.

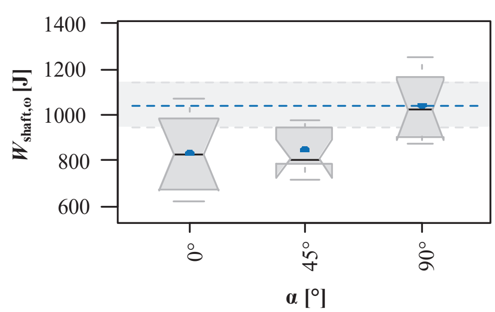

Figure 11: *Screw axis to grain angle α vs. insertion energy $W_{shaft,\omega}$*

The effect of different head types can be seen in Figure 12 with the head portion of the insertion energy calculated as $\Delta W_{head} = W_{head} - W_{shaft}$. In the presented case of an 8.0 x 240 mm screw, the CS placed level on the timber surface results in an increase of the total insertion energy of approximately 10 % W_{shaft} ($W_{shaft,mean}$ = 1,041 J). However, if the CS is sunk 10 mm into the timber, the ratio ΔW_{head} / W_{shaft} is 25 %, which will increase even further for shorter screws. It is assumed that the higher ΔW_{head} of the WH compared to the CS mainly results from the larger diameter of the head though the shape of the head may also be of importance.

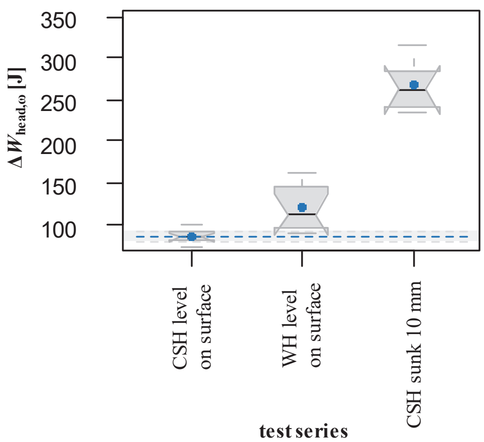

Figure 12: *Head portion of the insertion energy*

3.5 Set 4: Influence of timber material

In Figure 13 and Figure 14 the densities and insertion energies for set 4 are compared; a detailed summary of the test data can be found in Table A-6 in the annex. The low scatter of the densities of MDF board, beech and beech LVL results from the single specimens being manufactured from the same respective base material.

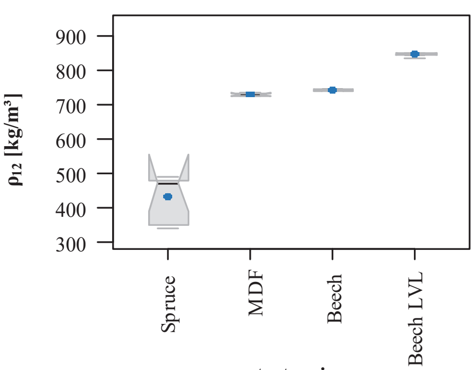

Figure 13: *densities of different timber materials of set 4*

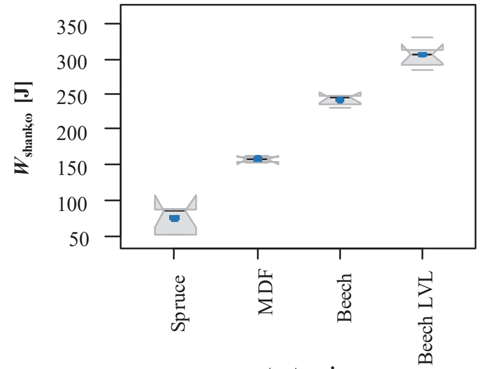

Figure 14: *insertion energy of different timber materials of set 4*

Based on the findings in 3.3, it comes to no surprise that the observation of an increased insertion energy with increasing density qualitatively is also true for different timber species and timber materials. However, when comparing the insertion energies in MDF and beech, they differ greatly even though the densities are very similar. This leads to the conclusion that the correlation between density and insertion energy is a material specific property.

4 SUMMARY AND CONCLUSION

This contribution deals with the insertion energy for screws, its influencing factors and possible applications. In the following, the main outcome of the paper at hand is summarized:

- The insertion energy of screws may become an important input factor for life cycle assessment of structures due to their widespread and still increasing use.
- A test configuration for the insertion energy is presented, which is based on the existing setup according to EN 15737:2009 for the torsional resistance of driving in screws by simply adding a measurement for the rotation angle.
- A simplified calculation method is derived that uses the correlation between insertion length, thread pitch and rotation angle that allows the evaluation of the insertion energy without direct rotation angle measurement. Both methods are equivalent if the head portion of the insertion energy is excluded and the exact thread pitch is known.
- Tests carried out with the mentioned configuration show a strong correlation between insertion energy and insertion length, screw diameter and timber density. The latter however can only be applied within a timber species/ timber product and the magnitude of the effect is currently only quantified for spruce.
- The insertion energy is highest when a screw is inserted perpendicular to the grain and is reduced

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up to 20 % for axis to grain angles of 45° or lower.

- The correct placement of the screw has a great effect on the insertion energy, as the insertion of the head through inaccuracies during screw insertion significantly increases the energy needed.
- Regarding quality assessment of screw connections, the insertion energy may serve as an important benchmark due to its correlation with the density and subsequently with the withdrawal properties.

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5 ANNEX

Table A-1: *Main statistics for screws from set 1 with d_{nom} = 6.00 mm and l = 160 mm; mean values and CoV*

Screw Type	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{shaft,\omega}$	CoV [$W_{shaft,\omega}$]	$W_{shaft,s}$	CoV [$W_{shaft,s}$]
[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
1	7	424	8.25	14.1	439	24.9	429	25.1	395	24.8	393	24.7
2	6	424	7.10	13.6	475	24.2	465	24.2	439	24.4	435	22.3
3	7	422	8.05	13.8	1,112	11.0	1,089	11.1	1,041	11.5	1,026	11.5
4	6	420	6.80	13.7	485	10.4	481	10.4	450	10.9	453	10.7
5	7	414	4.42	14.2	309	10.8	300	10.7	279	10.8	275	10.7
6	7	414	6.09	14.4	505	11.2	487	11.0	459	11.6	449	11.4
7	7	420	6.43	14.3	279	15.9	270	15.7	248	15.5	245	15.3

Table A-2: *Main statistics for screws from set 1 with d_{nom} = 8.00 mm and l = 240 mm; mean values and CoV*

Screw Type	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{shaft,\omega}$	CoV [$W_{shaft,\omega}$]	$W_{shaft,s}$	CoV [$W_{shaft,s}$]
[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
8	6	426	4.64	14.0	1,334	11.4	1,300	11.3	1,253	11.5	1,230	11.4
9	7	420	5.10	14.3	1,076	8.44	1,068	8.43	986	9.28	988	9.26
10	4	433	7.38	14.4	1,262	12.6	1,266	12.7	1,208	12.5	1,219	12.5
11	5	421	6.49	14.3	930	11.0	916	10.9	891	11.0	883	10.8
12	7	419	4.70	14.1	1,347	14.4	1,339	14.3	1,276	14.7	1,277	14.6
13	7	422	5.54	14.2	1,331	10.7	1,326	10.8	1,269	11.6	1,272	11.6
14	7	401	6.33	14.4	1,307	16.8	1,292	16.8	1,244	18.0	1,237	17.9
15	7	424	7.82	14.2	1,008	17.2	995	17.1	938	17.9	932	17.8
16	6	422	5.75	14.2	1,354	14.1	1,347	14.0	1,277	15.7	1,278	15.6
17	6	432	5.97	14.0	1,267	11.4	1,264	11.4	1,194	10.8	1,199	10.8

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Table A-3: *Main statistics for dry wall screws; mean values and CoV*

Screw Type	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{30mm,\omega}$	CoV [$W_{30mm,\omega}$]	W_{30mm3s}	CoV [$W_{30mm,s}$]
[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
TENZ DWS	5	415	9.05	11.0	55.6	11.4	49.2	10.8	21.4	14.9	22.0	14.6
18	6	416	5.74	10.7	67.6	18.1	59.4	22.8	32.0	25.4	30.9	25.4
19	7	412	8.32	11.4	139	11.4	123	10.6	32.1	11.5	31.5	11.3
20	6	423	7.83	11.1	124	15.1	115	15.1	27.6	12.5	28.0	12.2
21	6	407	8.30	11.5	117	23.2	105	23.7	24.0	31.9	24.6	31.5
22	7	413	7.80	10.6	154	12.7	142	13.7	31.7	11.2	32.5	11.0
23	6	410	12.8	10.5	64.8	22.7	55.7	23.1	26.7	16.4	27.0	15.0
24	5	428	8.78	10.6	73.3	15.7	60.5	16.8	20.2	18.5	20.2	18.3
25	5	408	8.26	10.7	30.1	11.2	27.0	14.5	18.9	17.0	19.0	17.1

Table A-4: *Main statistics for test series of set 2; mean values and CoV*

	series	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{shaft,\omega}$	CoV[$W_{shaft,\omega}$]	$W_{shaft,s}$	CoV[$W_{shaft,s}$]
	[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
WBS	26	9	376	5.62	13.8	425	11.1	425	11.1	402	11.6	405	11.4
	27	9	382	8.63	14.0	879	21.1	872	21.2	813	21.1	814	21.1
	28	10	370	5.09	13.5	1,349	8.35	1,340	8.34	1,251	9.24	1,254	9.19
	29*	10	425	6.63	14.3	533	20.9	531	20.9	510 (311)	21.7 (20.2)	513 (314)	21.6 (20.1)
	30	10	422	6.24	14.5	1,126	12.7	1,116	12.6	1,041	13.0	1,041	12.9
	31	10	420	5.79	13.8	1,621	15.4	1,607	15.3	1,493	15.7	1,494	15.6
	32	9	520	5.26	14.3	823	7.12	819	7.06	784	6.56	786	6.55
	33	10	515	4.99	14.5	1,716	8.09	1,680	7.80	1,587	8.33	1,582	8.37
	34	10	517	4.26	14.7	2,374	7.19	2,349	7.05	2,209	7.92	2,204	7.78
	35	9	414	8.94	13.3	56.3	27.4	36.1	17.9	24.4	22.2	24.4	21.6
	36	9	437	3.88	15.0	6,082	11.0	6,011	11.0	5,886	11.4	5,856	11.4
	37	10	410	13.1	14.9	617	21.1	579	20.9	476	22.6	462	22.4
	38	10	432	2.30	15.4	6,618	3.23	6,592	3.13	6,380	2.94	6,379	2.92
WS	39	10	449	12.8	12.6	22.4	55.0	21.9	47.0	11.0	26.3	11.8	25.2
	40	10	424	4.22	13.8	931	15.1	931	15.2	878	15.9	883	15.9
	41	10	434	5.72	14.8	1,689	10.3	1,670	10.3	1,598	10.1	1,590	10.1
	42	10	434	3.88	15.3	3,086	12.2	3,070	12.2	2,960	12.1	2,956	12.1
DS	43	10	432	8.48	13.8	573	27.3	570	27.1	527	27.3	529	27.0

*the values in brackets were evaluated at an insertion length of 160 mm

Table A-5: *Main statistics for test series of set 3; mean values and CoV*

	series	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{shaft,\omega}$	CoV[$W_{shaft,\omega}$]	$W_{shaft,s}$	CoV[$W_{shaft,s}$]
	[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
WBS	44	9	412	6.83	13.9	923	10.5	917	10.5	851	11.0	854	10.9
	45	10	418	7.88	13.2	888	18.2	878	18.3	830	18.9	829	18.9
	46	10	423	7.25	14.1	1,260	17.5	1,233	17.5	1,140	17.4	1,139	17.4
	47	5	422	7.64	14.1	1,325	12.1	1,309	12.0	1,057	13.2	1,057	13.1

Table A-6: *Main statistics for test series of set 4; mean values and CoV*

	series	n	ρ_{12}	CoV [ρ_{12}]	u	$W_{head,\omega}$	CoV [$W_{head,\omega}$]	$W_{head,s}$	CoV [$W_{head,s}$]	$W_{shaft,\omega}$	CoV[$W_{shaft,\omega}$]	$W_{shaft,s}$	CoV[$W_{shaft,s}$]
	[-]	[-]	[kg/m³]	[%]	[%]	[J]	[%]	[J]	[%]	[J]	[%]	[J]	[%]
WBS	48	6	436	14.3	13.9	103	15.8	93.4	22.7	74.7	22.3	76.0	22.4
	49	6	731	0.64	5.77	233	5.65	222	4.65	158	2.48	155	2.65
	50	6	746	0.31	9.70	311	4.44	298	4.19	242	2.47	240	2.50
	51	6	847	0.62	7.42	394	6.71	370	5.60	305	5.08	301	4.90

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