COST Action FP1402

“Basis of Structural Timber Design”

- from research to standards

Short Term Scientific Mission (STSM) Report

“Stiffness Properties of
Axially Loaded Self-Tapping Screws”

COST-STSM-FP1402-30283

by

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1 Introduction and purpose of the STSM

Since 25 years modern self-tapping screws are frequently applied in timber engineered structures. 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 predominately in axial direction. Consequently, they represent an efficient alternative to conventional laterally loaded fasteners such as nails, dowels and bolts. Their application can be classified as (a) fastener, i.e. transmitting loads in connections between structural components, and (b) reinforcement of timber members, i.e. persisting exceedance of internal resistances in timber’s weak directions.

In the past, several investigations concentrated on the derivation of approaches for predicting withdrawal capacities F_{ax} of axially loaded self-tapping screws covering their application for a huge bandwidth of varying parameters (timber density ρ, screw outer thread diameter d, effectively inserted thread length l_{ef}, axis-to-grain angle α, timber moisture content u, type of timber product, wood species, etc.), see e. g. Blaß et al. (2006), Pirnbacher et al. (2009), Frese and Blaß (2009), Hübner (2013) and Ringhofer et al. (2015).

With regard to $K_{ser,ax}$, herein defined as the stiffness of axially loaded single screws, works focusing on the determination of this property also significantly influenced by the aforementioned parameters, are comparatively scarce. Summarising a literature review related, three sources, namely Blaß et al. (2006), ETA-11/0063 (2013) and Ringhofer et al. (2015) have been found so far including approaches in form of empirical, multiplicative regression functions for the estimation of this property. Restricting the bandwidth of main influencing parameters to α = 90 ° and solid timber out of Norway Spruce (*picea abies*) at u = 12 %, all of these models base on the general form given in eq. (1), see

$$K_{\text{ser,ax}} = c_1 \cdot \rho^{c_2} \cdot d^{c_3} \cdot l_{\text{ef}}^{c_4}, \tag{1}$$

with c_i as model constants fitted to the experimental data related approaches are basing on. As shown in Table 1, treatment of these constants remarkably differs between the models compared. Consequently, therewith predicted stiffness values $K_{ser,ax,pred,i}$ remarkably deviate from each other, see Figure 1. In case of outer thread diameters commonly applied for high-stressed screwed connections or reinforcements (d = 8 ÷12 mm), c_4 as the power value related to l_{ef} has major impact on the course of each $K_{ser,ax,pred,i}$ corresponding differences reach ratios up to 700 %.

Table 1: Comparison of models for estimation of $K_{ser,ax}$ and therein applied model constants c_i

source	model	c_1	c_2	c_3	c_4
Blaß et al. (2006)	$K_{\text{ser,ax}} = 234 \cdot \rho^{0.20} \cdot d^{0.20} \cdot l_{\text{ef}}^{0.40}$	234	0.20	0.20	0.40
ETA-11/0063 (2013)	$K_{\text{ser,ax}} = 25.0 \cdot d \cdot l_{\text{ef}}$	25.0	0.00	1.00	1.00
Ringhofer et al. (2015)	$K_{\text{ser,ax}} = 77.6 \cdot \rho^{0.75} \cdot d^{-0.70} \cdot l_{\text{ef}}^{0.40}$	77.6	0.75	-0.70	0.40

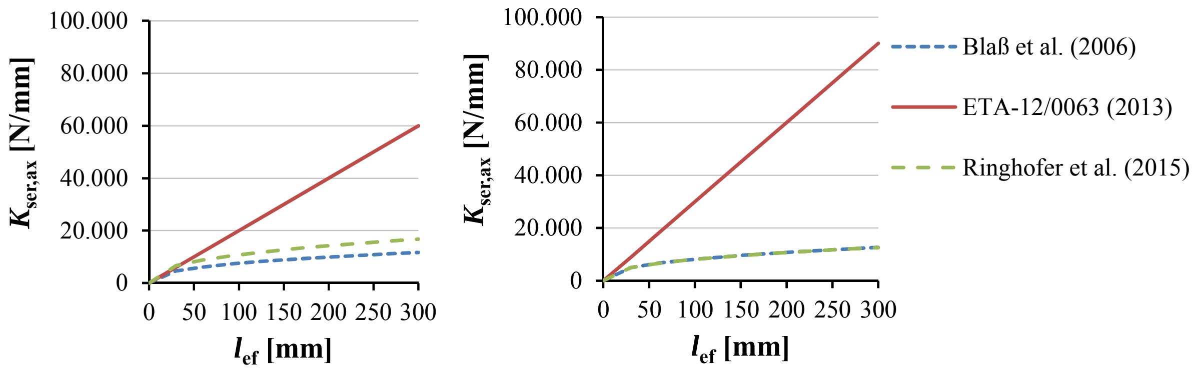

Figure 1: Comparison of axial stiffness estimated by the approaches discussed; left: d = 8 mm; right: d = 12 mm; ρ = 430 kg/m³

Main reason for these high deviations regarding input parameter treatment and model prediction is seen in the way of testing axially loaded single screws and hereby especially the method applied for recording and assessing local deformations v_i. As shown in section 3, recorded v_i are very small if e. g. compared to those of laterally loaded fasteners. Consequently, additional deformations such as those of the test rig and the timber specimen themselves (bending or compression perp. to grain), which are eventually also recorded but not part of the timber-screw connection, influence the size of $K_{\text{ser,ax}}$ in a major way and may lead to wrong results related.

Further concentrating on the application of single screw mechanical properties F_{ax} and $K_{\text{ser,ax}}$ for estimating those of connections such as timber-to-timber and steel-to-timber joints wherein screws are inclined positioned and thus predominately axially loaded. Investigations carried out in the past, namely by Blaß et al. (2006), Krenn (2009) and Tomasi et al. (2010) indicate high conformity between calculated (estimated capacity of the single fastener combined with an approach for the specific joint detail) and experimentally determined joints' bearing capacities. In case of their stiffness however, model prediction is widely insufficient, significantly underestimating experimental observations in major cases, c. f. Blaß et al. (2006) or Tomasi et al. (2010). In both latter mentioned sources approaches recommended in Blaß et al. (2006) and ETA-11/0063 (2013) are applied for theoretically determining the single fastener's axial stiffness thus covering the whole bandwidth of $K_{\text{ser,ax}}$ as discussed before.

Similarities are also found in Jockwer et al. (2014) who achieve adequate correspondence with test results not till increasing model parameter c_1 in the approach according to ETA-11/0063 (2013) from 25 to 40 (160 %). Additional investigations focusing on the (shear) reinforcement of one- and two-dimensional timber members with self-tapping screws also indicate that stiffness predicted by current approaches (e. g. Blaß et al., 2006) significantly deviates from own findings regarding the spring constant of the timber-screw composite interaction applied for corresponding design, c. f. Mestek (2011) and Dietsch (2012).

As intermediate conclusion it can thus be summarised that currently a certain lack of knowledge exists regarding the property axial screw stiffness and its application for the design of screwed connections and reinforcements. Main objective of this STSM was consequently to gain a deeper understanding concerning the determination of this property. Two topics were thereby focused in detail: First, the way of measuring local deformation and comparison of experimentally determined single screw stiffness $K_{ser,ax,exp}$ with values predicted by the aforementioned models and second, the evaluation of $K_{ser,ax,exp}$ with stiffness values $K_{ser,i}$ gained from tests on timber-to-timber connections with inclined positioned self-tapping screws.

The following sections of this report thus comprise the description of the experimental programme related, summary and conclusion of main outcomes as well as an outlook regarding further measures planned in this field, partially to be conducted as cooperation between both institutions participating at this STSM.

2 Materials and methods

2.1 Single screw withdrawal tests

As introduced in section 1, related experimental program contained tests of axially loaded self-tapping single screws for determination of withdrawal properties according to standard ÖNORM EN 1382 (1999). The screw type used therefore was fully threaded with an outer thread diameter $d = 8.00$ mm and a total length of $l = 430$ mm, supplied by the manufacturer Adolf Würth Gmbh & Co. KG, c. f. ETA-11/0190 (2013). Timber specimen were made out of Solid Timber (ST) beams in Norway Spruce (*picea abies*) with final dimensions of $b \times l \times h$ = 110 x 160 x {113, 130} mm³, see Figure 2. Before testing, specimen were stored at standard climate conditions 20 °C and 65 % rel. humidity so that moisture content varies in a range of $u = 12 \pm 2$ %, representing service class 1 according to ÖNORM EN 1995-1-1 (2014).

All in all, two test series have been carried out within the experimental program. As shown in Table 2, parameter variation thereby included the insertion angle α (angle between screw and force axis to grain direction) as well as the effective insertion length l_{ef}, which is equal to the specimen's height as consequence of inserting the screw totally through the specimen. This measure deviates from the regulations given in ÖNORM EN 1382 (1999) but was decided to avoid possible influence of the screw tip on withdrawal performance. Main reason for angle as well as length variation was to test the single screws with the same values for both α and l_{ef} as applied for the tests on screwed connections, c. f. section 2.2.

Figure 2 furthermore illustrates the number and position of devices recording local deformations (denoted as LVDT). As shown there, all in all four LVDTs (two per each specimen side) were situated close to the specimen's gravity centre, measuring displacements v_i to fixed points of the screw's threaded part above and below the timber specimen. This configuration is comparable to that published in Blaß and Krüger (2012); LVDTs were consequently denoted as "KIT, 1 ÷ 4". Two additional LVDTs were placed at the screw's threaded part above the timber specimen, recording relative movements of their location to the surface of the steel plate serving as support of this so-called "push-pull" test configuration. Since this application is presented in Ringhofer et al. (2015), related LVDTs were denoted as "TUG, 1 ÷ 2".

Table 2: Main facts regarding single screw withdrawal test series conducted in the frame of this STSM

test series	**denotation**	**no. of tests**	***d***	**l_{ef}**	**α**
1	Rf-1-45-20/65-n	11	8 mm	113 mm	45 °
2	Rf-1-30-20/65-n	10	8 mm	130 mm	30 °

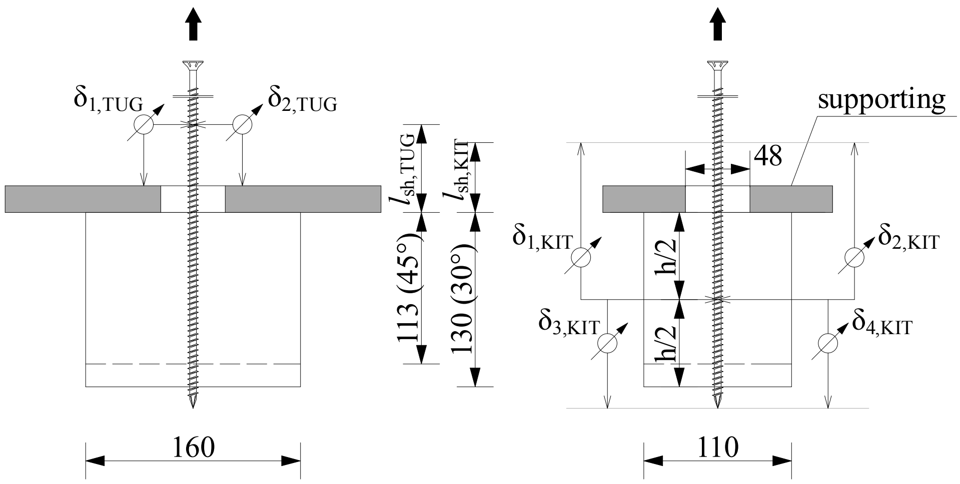

Figure 2: Illustration of specimen dimensions, test set-up and local way measurement; left: front view; right: side view (dimensions in mm)

As shown in Figure 3, a loading protocol deviating from that proposed in ÖNORM EN 1382 (1999) but in accordance to ÖNORM EN 26891 (1991) was chosen. Again, this due to enable equal conditions as applied for the tests on screwed connections summarised in section 2.2.

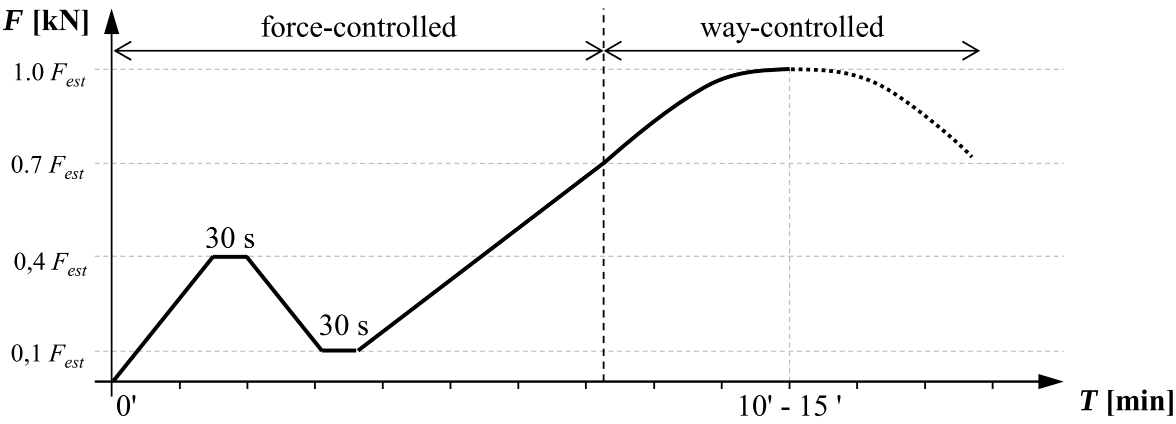

Figure 3: Illustration of the chosen loading protocol; in accordance to ÖNORM EN 26891 (1991)

From each specimen and after testing (about) $4d$ x 4 x l_{ef} clear wood samples were cut centrically around the screw hole determining density and moisture content as well as to evaluate possible influences on the withdrawal properties caused by knots or other growth characteristics.

Due to three different types of deformations recorded by all in all six LVDTs shown in Figure 2, three values for single screw stiffness $K_{ser,ax,i}$ per test, each with the mean value of two related LVDT measurements, have been subsequently determined. This again in accordance to ÖNORM EN 26891 (1991) except the fact, that the maximum force reached per test, F_{max}, was applied instead of the estimated, F_{est}; see eq. (2):

$$K_{\text{ser,ax,i}} = \frac{F_{04} - F_{01}}{v_{i,04} - v_{i,01}}, \tag{2}$$

with F_{04} and F_{01} as recorded load data closest situated to 40 % and 10 % of F_{max} and $v_{i,04}$ and $v_{i,01}$ as corresponding deformations. Since all LVDTS with index 1 and 2 in Figure 2 recorded deformations including those of the screw's unembedded and tensile loaded threaded part with length $l_{sh,i}$, corresponding values v_i had to be corrected as follows:

$$v_i = \frac{\delta_{i,1} + \delta_{i,2}}{2} - v\left(l_{\text{sh,i}}\right) = \frac{\delta_{i,1} + \delta_{i,2}}{2} - \frac{\sigma_{\text{ax}}}{E} \cdot l_{\text{sh,i}}, \tag{3}$$

with σ_{ax} as the axial stress in the screw's threaded part and E as its elastic modulus.

Finally, (logarithmic) stiffness properties of both test series were evaluated by Tukey's criteria regarding statistical outliers (values outside the inter-quartil-range (IQR) ± 1.5-times the IQR). However, no value was found below and above these boarders, the whole dataset could thus be considered for assessment and discussion given in section 3.

2.2 Tests on connections with inclined screws – brief overview

The experimental program concentrating on stiffness properties of screwed connections is part of an ongoing research project being executed by Ms. Yvonne Steige at Karlsruhe Institute of Technology. Thus, this subsection solely contains a brief overview of those tests (two series with 5 tests each), which are further used for verification of experimentally determined single screw stiffness properties. Figure 4 illustrates the related test configuration in form of a compression shear test of a timber-to-timber connection with $n = 2$ inclined positioned self-tapping screws. As discussed in section 2.1, both $\alpha = \{30\,°, 45\,°\}$ and $l_{ef} = \{113, 130\}$ mm as main geometrical influencing parameters are equal to those applied for the single screw tests. Furthermore, the same screw type as well as the same timber raw material was used, the latter especially to obtain a comparable density distribution. Local way measurement was realised by two LVDTs (one per side) recording relative displacement of the two timber specimen in the connection. With regard to test execution, the loading protocol according to ÖNORM EN 26891 (1991) and shown in Figure 3 has been applied.

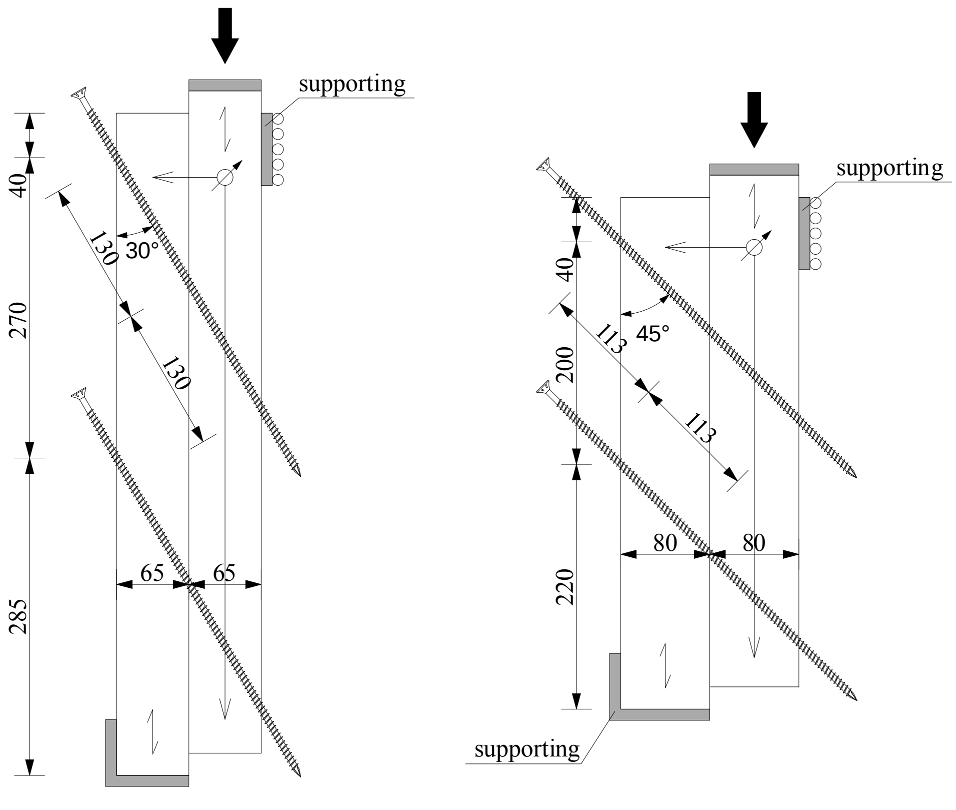

Figure 4: Compression shear test configuration of the screwed connections; left: α = 30 °; right: α = 45 ° (dimensions in mm)

The connection's elastic stiffness, herein denoted as K_{ser}, has again been determined according to eq. (2). Since the initial slip of some connections exceeded v_{01}, it was decided to determine an additional value for K_{ser} per each test according to eq. (4), see

$$K_{\text{ser,ax,exp,i}} = \frac{F_{04} - F_{02}}{v_{04} - v_{02}}, \tag{2}$$

with F_{02} as recorded load data closest situated to 20 % of F_{max} and v_{02} as corresponding deformation.

3 Test results and discussion

3.1 Single screw tests

In Table 3, mean values and coefficients of variation (CV) of single screw test series' densities (referred to u = 12 %) as well as mean, minimal and maximal moisture contents u are given, the latter confirming the aimed bandwidth of u = 12 ± 2 %. Since average densities of both test groups show no remarkable deviation, it was decided to subsequently desist from any density related correction of test results.

Table 3: Density and moisture content of single screw test series

denotation	**no. of tests**	$\rho_{12,mean}$ [kg/m³]	$CV[\rho_{12}]$ [%]	u_{mean} [%]	u_{min} [%]	u_{max} [%]
Rf-1-45-20/65-n	11	406.3	8.66	12.3	11.5	13.3
Rf-1-30-20/65-n	10	410.5	9.26	12.4	12.0	12.8

Concentrating on mechanical screw properties, Table 4 comprises mean values of experimentally determined withdrawal capacities F_{ax} and strength values f_{ax} as well as corresponding coefficients of variation $CV[f_{ax}]$ of both test series conducted. In contrast to ÖNORM EN 1382 (1999), calculation of f_{ax} was as follows:

$$f_{ax} = \frac{F_{max}}{d \cdot \pi \cdot l_{ef}}. \tag{3}$$

Worth mentioning, that in one test of series 2 (Rf-1-30-20/65-n) steel failure of the screw had to be observed, related dataset was thus excluded from assessment. All other specimen failed in withdrawal.

Similar to observations made in the past (see e. g. Blaß et al., 2006), it can be observed that withdrawal strength slightly decreases with decreasing angle between screw axis to grain direction α. In contrast, withdrawal capacity $F_{ax,i}$ has the opposite behaviour, which is caused by the higher value of l_{ef} in case of α = 30 °.

Table 4: Withdrawal capacity and strength of single screw test series, mean values and coefficients of variation

denotation	**no. of tests**	$F_{ax,mean}$ [kN]	$f_{ax,mean}$ [N/mm²]	$CV[f_{ax}]$ [%]
Rf-1-45-20/65-n	11	16.2	5.69	13.3
Rf-1-30-20/65-n	9*	18.2	5.56	11.3

* one test steel failure in tension, excluded from assessment

In Table 5, mean values and coefficients of variation of axial screw stiffness $K_{ser,ax,i}$, determined by the three way measurement set-ups as discussed in section 2.1 are shown.

Table 5: Experimental axial stiffness properties $K_{ser,ax,i}$ of single screw test series, mean values and coefficients of variation

denotation	**no.**	**TUG | mean(δ₁, δ₂)**		**KIT | mean(δ₁, δ₂)**		**KIT | mean(δ₃, δ₄)**	
		$K_{ser,ax,mean}$ [kN/mm]	$CV[K_{ser,ax}]$ [%]	$K_{ser,ax,mean}$ [kN/mm]	$CV[K_{ser,ax}]$ [%]	$K_{ser,ax,mean}$ [kN/mm]	$CV[K_{ser,ax}]$ [%]
Rf-1-45-20/65-n	11	20.1 (100 %)	15.3	26.6 (132 %)	15.1	50.5 (251 %)	17.8
Rf-1-30-20/65-n	10	22.4 (100 %)	13.2	29.4 (131 %)	19.3	69.1 (308 %)	25.9

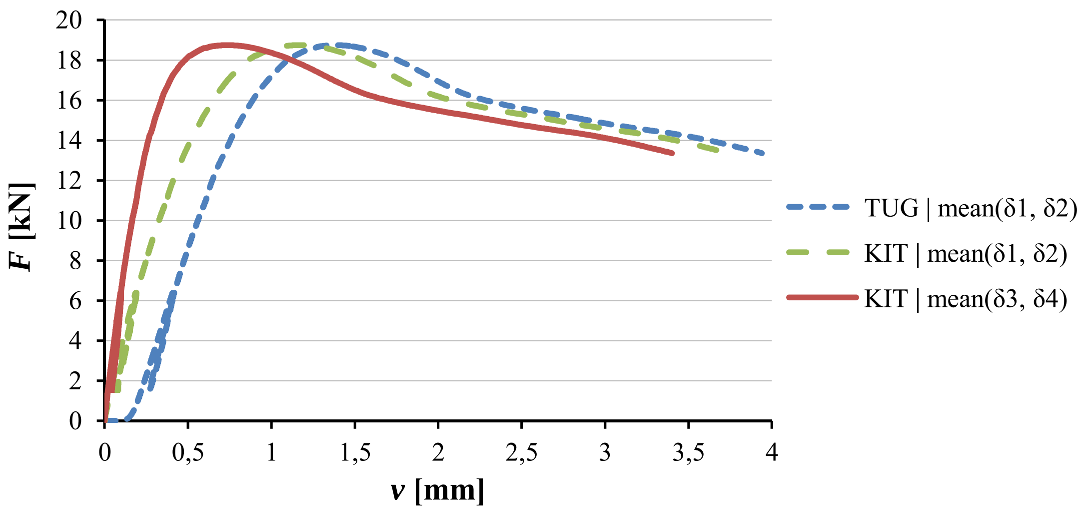

Figure 5: Illustration and comparison of load-displacement curves; test series 1, α = 45 °

The main outcomes in brief: First, all different $K_{ser,ax,i}$ increase with decreasing angle α, which confirms similar observations made in the past, c. f. Ringhofer et al. (2015). Furthermore, the slightly higher value for l_{ef} in case of α = 30 ° additionally contributes to the differences given.

Second, $K_{ser,ax}$ determined with data of measurement set-up "KIT | mean(δ_3, δ_4)" is remarkably higher than both others with indices 1 and 2; see also Figure 5. Concentrating on the latter mentioned representing the axial stiffness of the single screw including all of its deformation components, $K_{ser,ax}$ related to "TUG | mean(δ_1, δ_2)" result to be about 30 % lower than those determined by the "KIT | mean(δ_1, δ_2)" configuration. This difference could be caused by the "push-pull" test configuration applied.

Thereby, the steel plate located at the stressed timber's surface serves as supporting responsible to transmit (compressive) loads from the specimen into the test rig, c. f. Figure 2. Although they are not part of the composite interaction timber-screw, occurring compressive deformations v_c of the timber specimen are also recorded by the "TUG | mean(δ_1, δ_2)" measurement device, leading to higher absolute vertical displacements of the location of corresponding LVDTs. In contrast, both LVDTs related to "KIT | mean(δ_1, δ_2)" are situated at the specimen's gravity centre, relatively moving upwards by increasing v_c and consequently don't consider (at least the majority of) this additional but unwanted deformation component. Based on this assumption, the aforementioned difference between both methods of determining $K_{ser,ax}$ significantly depends on the specimen's dimensions as well as on α, governing corresponding mechanical timber properties.

Within the next step, experimentally determined axial screw stiffness is compared with values predicted by the approaches discussed in section 1. Table 6 overviews corresponding estimations for both test series, indicating again a significant difference between $K_{ser,pred}$ as result of the model given in ETA-11/0063 (2013) and both others according to Blaß et al. (2006) and Ringhofer et al. (2015). Verification with test results is subsequently illustrated in Figure 6; error bars thereby represent the bandwidth of mean value plus/minus standard deviation. As shown there, both models published in Blaß et al. (2006) and Ringhofer et al. (2015) apparently underestimate experimental $K_{ser,ax,i}$ by far, which widely confirm the approach according to ETA-11/0063 (2013) leading to results especially quite close to $K_{ser,ax}$ determined with the "KIT | mean(δ_1, δ_2)" set-up.

Table 6: Predicted axial stiffness properties $K_{ser,ax,pred,i}$ of single screw test series

denotation	**Blaß et al. (2006)** $\boldsymbol{K_{ser,ax,pred}}$ [kN/mm]	**ETA-11/0063 (2013)** $\boldsymbol{K_{ser,ax,pred}}$ [kN/mm]	**Ringhofer et al. (2015)** $\boldsymbol{K_{ser,ax,pred}}$ [kN/mm]
Rf-1-45-20/65-n	7.81	22.6	10.9
Rf-1-30-20/65-n	8.28	26.0	12.9

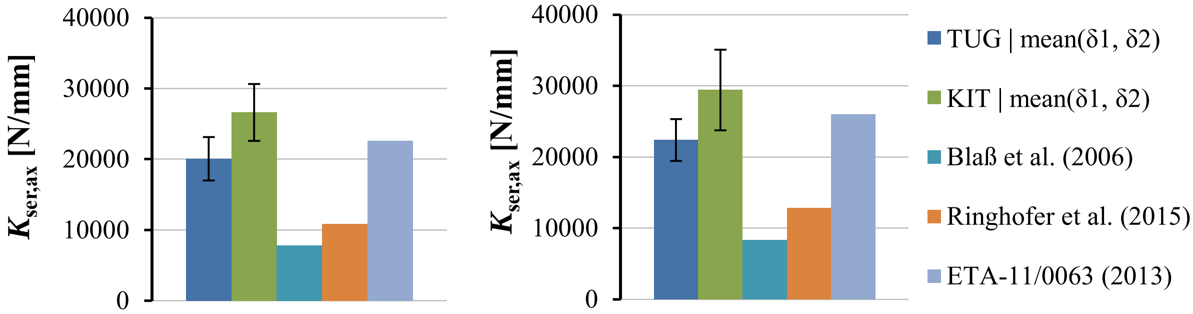

Figure 6: Comparison of experimentally determined and predicted mean values of axial stiffness $K_{ser,ax}$; left: test series 1, α = 45 °; right: test series 2, α = 30 °

3.2 Tests of screwed connections

In Table 7, mean values and coefficients of variation (*CV*) of densities (referred to u = 12 %) as well as mean, minimal and maximal moisture contents u of the timber specimen applied for the screwed connections are given. Data considered for this statistic are mean values of both timber specimen in the connection. Again, measured moisture contents confirm the aimed bandwidth of $u = 12 \pm 2$ %. Comparing determined densities with each other and with single screw test values in Table 3, corresponding differences are negligible, thus no density related correction of test results was necessary.

Table 7: Density and moisture content of screwed connection tests

denotation	no. of tests	$\rho_{12,mean}$ [kg/m³]	$CV[\rho_{12}]$ [%]	u_{mean} [%]	u_{min} [%]	u_{max} [%]
Dr-2-45-20/65-n	5	408.1	9.46	12.3	11.5	12.9
Dr-2-30-20/65-n	5	410.4	8.21	12.5	11.9	13.2

Mean values and coefficients of variation of experimentally determined loadbearing capacities F_i of both test series are subsequently given in Table 8. Again, tests with α = 30 ° result in higher values for F_{mean}. One reason therefore is the higher value of l_{ef} in case of α = 30 °. Presupposing the truss-model (eq. 4) published e. g. in Blaß et al. (2006) sufficiently describes the loadbearing behaviour of connections with inclined positioned self-tapping screws, a further reason for differences of F_i given can be addressed to the impact of the axis-to-force angle (equal to α) in this model.

$$F = F_{ax} \cdot \cos\alpha + \mu \cdot \sin\alpha\,, \tag{4}$$

with μ = 0.30 as assumed friction coefficient according to Bejtka and Blaß (2002). In case of equal $F_{ax,i}$, η as the ratio between α = 30 ° and 45 ° results as follows:

$$\eta_{30°/45°} = \frac{\cos(30) + 0.30 \cdot \sin(30)}{\cos(45) + 0.30 \cdot \sin(45)} = 1.11, \quad (5)$$

which is more or less equal to the experimentally determined ratio. Table 8 additionally comprises loadbearing capacities estimated by the approach given in eq. (4) considering $F_{ax,i}$ as single screw test results (Table 4) and $\mu = 0.30$. Comparing them with experimentally determined values, differences ΔF_i (referred to F_{pred}) of up to 20.5 % can be observed, indicating a conservative estimation of the real behaviour.

Table 8: Comparison of experimentally determined and predicted loadbearing capacities of screwed connections

denotation	**no. of tests**	***n***	F_{mean} [kN]	$CV[F]$ [%]	F_{pred} [kN]	ΔF [%]
Dr-2-45-20/65-n	5	2	35.9 (100 %)	18.7	29.8	20.5
Dr-2-30-20/65-n	5	2	39.7 (111 %)	10.8	37.0	7.30

Further concentrating on the screwed connections' stiffness, Table 9 shows corresponding test results $K_{ser,mean,(10/40)}$ and $K_{ser,mean,(20/40)}$ determined as explained in section 2.2. In case of $\alpha = 30$ °, remarkably higher values for $K_{ser,mean,(20/40)}$ if compared to $K_{ser,mean,(10/40)}$ are given, which is caused by initial slips exceeding v_{01} in many cases. Since this circumstance is also part of the investigations planned in the ongoing research project at KIT, possible effects influencing this specific behaviour are herein not discussed in detail. However, it was decided to consider $K_{ser,(20/40)}$ for further discussion. Corresponding mean values are observed to significantly increase with decreasing α. This trend is similar to the behaviour of single screw stiffness discussed in section 3.1 but in fact much more pronounced.

Table 9: Experimental stiffness properties K_{ser} of screwed connections, mean values and coefficients of variation

denotation	**no. of tests**	$K_{ser,mean,(10/40)}$ [kN/mm]	$K_{ser,mean,(20/40)}$ [kN/mm]	$CV[K_{ser,mean,(20/40)}]$ [%]
Dr-2-45-20/65-n	5	24.2	24.6	15.9
Dr-2-30-20/65-n	5	32.4	37.4	5.24

In Figure 7, experimentally determined connection stiffness $K_{ser,mean,(20/40)}$ (error bars represent the bandwidth of mean value plus/minus standard deviation) are compared with values predicted by the approach according to Blaß et al. (2006), see eq. (6):

$$K_{\text{ser},n=1} = \frac{1+\mu \cdot \tan\alpha}{\dfrac{1}{K_{\text{ser,ax,1}}} + \dfrac{1}{K_{\text{ser,ax,2}}}}, \text{ with} \tag{6}$$

$K_{\text{ser},n=1}$ as connection stiffness for $n = 1$ screw and $K_{\text{ser,ax,i}}$ as axial screw stiffness in each timber member the screw is situated. Considering further assumptions $\mu = 0.30$ and $K_{\text{ser,ax,1}} = K_{\text{ser,ax,2}}$ as well as $n = 2$, K_{ser} was calculated as follows:

$$K_{\text{ser}} = K_{\text{ser},n=2} = K_{\text{ser,ax}} \cdot (1 + 0.30 \cdot \tan\alpha). \tag{7}$$

Results determined by both measurement set-ups "TUG | mean(δ_1, δ_2)" and "KIT | mean(δ_1, δ_2)" as well as by the approach given in ETA-11/0063 (2013) served as input values for $K_{\text{ser,ax}}$. With regard to the location of test results and model estimations, following conclusions can be made: First, the aforementioned remarkable difference between $K_{\text{ser,mean,(20/40)}}$ at $\alpha = 30$ ° and 45 ° cannot be covered by the approach given in eq. (7) leading to an opposite but minor pronounced trend. Second, in dependence of the input value chosen for $K_{\text{ser,ax}}$, model estimations coincide well with test results. Especially for K_{ser}, calculated with the approach according to ETA-11/0063 (2013), a high overall confirmation can be observed. Third, if compared to the high deviations of calculated and experimentally determined connection stiffness – as found in prior investigations (c. f. discussion in section 1) – model estimations illustrated in Figure 7 are far closer located to test results.

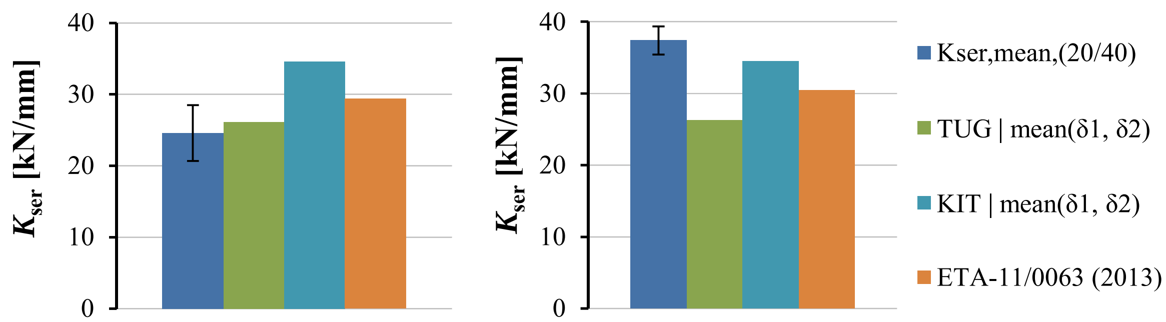

Figure 7: Comparison of experimentally determined and predicted connection stiffness; left: test series 1, α = 45 °; right: test series 2, α = 30 °

4 Summary, outlook and future collaboration with the host institution

As outlined in section 1, main intention of this short term scientific mission at Karlsruhe Institute of Technology (KIT) was to gain deeper knowledge regarding the stiffness $K_{ser,ax}$ of axially loaded self-tapping (single) screws as mechanical property relevant for design of related connections and reinforcements.

As consequence of open questions given regarding the application of $K_{ser,ax}$ for its foreseen purpose – see discussion in section 1 – an experimental campaign comprising single screw tests as well as those of screwed connections was carried out within this STSM. Main objective of single screw tests was to evaluate the influence of different measurement set-ups on the size of $K_{ser,ax}$ as well as to verify existing approaches applied for predicting this property. Subsequently, stiffness K_{ser} of screwed connections was estimated with both calculated and experimentally determined $K_{ser,ax}$ and compared with corresponding test results. The main outcomes related can be summarised as follows:

- As demonstrated in section 3.1, the bearing capacity of an axially loaded single screw is reached at small deformations. This not only consequences high values for $K_{ser,ax}$ (if e. g. compared to the stiffness of laterally loaded screws) but also a significant impact of additionally measured deformations (test rig, timber specimen, etc.) on the robustness of this parameter. Although both measurement set-ups "TUG | mean(δ_1, δ_2)" and "KIT | mean(δ_1, δ_2)" considered base on a similar principle, corresponding test results significantly deviate from each other. Timber specimen deformations caused by compressive stresses at the supporting of this "push-pull"-configuration are differently recorded by both set-ups and thus seen as main reason for these deviations. Consequently, further investigations (numerical modelling and experimental campaign) are aimed to determine the influence of specific parameters such as the dimensions of timber specimen or the axis-to-grain angle α on the size of these additionally measured deformations.
- Based on the verification of experimentally determined $K_{ser,ax}$ with model predictions, the approach given in ETA-11/0063 (2013) widely confirms with test results while both other models applied underestimate related $K_{ser,ax}$ by far. Further work should concentrate on implementing parameters (e. g. timber density ρ, moisture content u, etc.) not covered in the model according to ETA-11/0063 (2013) but may also influencing axial screw stiffness to a significant extent.
- With regard to the investigations focusing on screwed connections as part of an ongoing research project at Karlsruhe Institute of Technology, gained test results are generally in a similar range than values estimated by the approach according to Blaß et al. (2006). In

dependence of the size of the main model input parameter $K_{ser,ax}$, a high confirmation between calculated and experimentally determined properties can be achieved, which is in clear contrast to related experience made in the past. Again, K_{ser} estimated with $K_{ser,ax}$ according to ETA-11/0063 (2013) enables an adequate description of the overall average of test results. Of course, further investigations increasing the bandwidth of screwed connections tested are necessary to enable verification of single screw stiffness (and corresponding model approaches) for the majority of practical application. Especially in this topic future collaboration with the host institution is envisaged.

5 Foreseen publications/articles resulting from the STSM

Work and findings made in the frame of this STSM serve as basis of further investigations planned in this field, c. f. section 4. After finalising planned working packages (especially point three in section 4) it is aimed to publish a peer-reviewed conference (e. g. INTER'17) or journal paper together.

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7 Appendix

Confirmation by the host institution of the successful execution of the STSM.

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TO WHOM IT MAY CONCERN

Unser Zeichen: Bl/pe
Datum: 10.02.2016

FP 1402 - Confirmation of successful execution of STSM

Within the Cost Action FP 1402, Mr. Andreas Ringhofer carried out a STSM at Karlsruhe Institute of Technology (KIT) from 11. Jan. - 12. Feb. 2016.
His host institution, the Institute of Timber Structures of KIT, herewith confirms the successful execution of the STSM.

Best regards,

Univ.-Prof. Dr.-Ing. Hans Joachim Blaß