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FIRE RESISTANCE OF PRIMARY BEAM – SECONDARY BEAM CONNECTIONS WITH FULL THREAD SCREWS

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ABSTRACT: Within the German research project "Fire resistance of primary beam - secondary beam connections in timber structures" solutions for a fire-safe design have been developed. The project concentrated on connections with self-tapping full thread screws and joist hangers. This paper describes the investigations, calculations and experiments on the former type of connections. Herein, a series of loaded fire tests and numerical simulations were conducted with the objective to develop design rules and determine the load-bearing capacity.

KEYWORDS: fire resistance, self-tapping full thread screws, timber connections, fire tests

1 INTRODUCTION

The demand for timber as a construction material is notably increasing all over the world. This is particularly true for residential, office and administration buildings as well as for special constructions. The benefits of timber construction are visual and tactile attractiveness, high energy efficiency, quick erection time and a low carbon footprint.

Despite these advantages, there are large concerns and limitations imposed by authorities and design codes due to fire safety. To consider this aspect in a sufficient way European and international design codes have been developed over the past years to assess fire safety in buildings. The design rules for fire exposed timber structures such as the ones listed in EN 1995-1-2 are mostly focused on determining the charring and residual cross section of linear timber members, such as beams and columns. General regulations and design methods for assessing the fire safety of engineered joist-to-beam connections do not exist. Approved and reliable systems are rare.

To overcome this knowledge gap, a German research project was conducted to investigate the thermal and structural performance of screwed and joist hanger connections for timber structures in the event of fire. (see Figure 1).

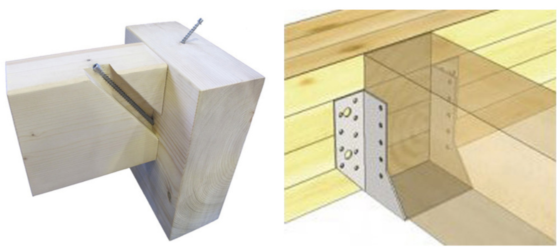

Figure 1: *typical joist connections for timber structures. Left: pair of full thread screws, Right: joist hanger*

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2 RESEARCH CONCEPT

The research program was divided into five steps:

I Tests under ambient conditions to gather knowledge about the load bearing behavior of the different connection types
II unloaded fire tests to gather information regarding the temperature behavior and to preselect connection types expected to perform satisfactorily in loaded fire tests
III loaded fire tests on preselected connection types to determine the load bearing behavior and load bearing capacity under fire exposure
IV numerical finite element analysis in order to perform further parametrical studies
V Assessment of additional protective measures and development of design rules and standards

This publication extends the results of the unloaded fire tests presented at WCTE 2014 in Quebec City by the authors.

3 TESTS AT AMBIENT CONDITIONS AND UNLOADED FIRE TESTS

As loaded fire tests are rather complex and expensive, unloaded fire tests as well as tests under ambient condition were conducted at the beginning of the research project to minimize the number of loaded tests. Parameters such as side distances, lengths, diameters of the screws as well as protective methods were varied and their influence on the potential and charring behavior investigated. Further a series of tests was performed to experimentally determine the temperature dependent withdrawal capacity of full thread screws embedded in timber members. Results of these investigations were summarized and published in [3].

4 LOADED FIRE TESTS

4.1 GENERAL DESCRIPTIONS

A series of loaded tests exposed to ISO fire were conducted. The T-shaped specimens consisted of a primary beam (PB) and a secondary beam (SB) (see Figure 2) made of glued laminated timber. The length of each primary beam was 2000 mm and of each secondary beam 1200 mm.

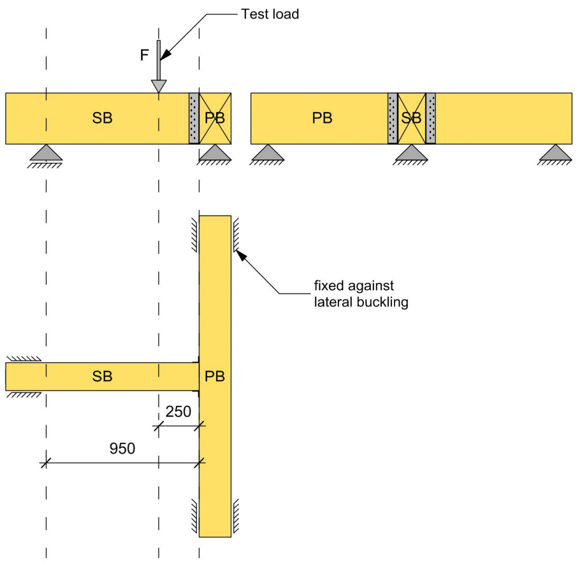

Figure 2: *general setup of the tests*

The primary beam secondary beam connection was made with pairwise crossed full thread screws. The cross section of the beams varied as a result of the assessed side covering of the screws. The screw angle of 45° results in the maximum of shear force resistance for the connection and was used for the pairwise crossed screws. Thereby one screw is screwed in from the primary beam and the other screw from the secondary beam (see Figure 3). The edge distances ($a_{4,c}$, a_3 see Table 1) and the distance between the screws (a_2=1,5*d_{nom}) were minimized to reach an expected shear force resistance under fire exposure of 50 % to 60 % of $R_{k,\,20°}$.

Table 1: *setup with full thread screws*

No.	Dimension of full thread screws d_{nom} x l [mm]	Covering the head of screws	$a_{4,c}$ [mm]	a_3 [mm]
S1	6 x 180	25 mm solid spruce board	36	33
S2	6 x 180	25 mm solid spruce board + 15 mm gypsum plasterboard	64	61
S3	6 x 180	25 mm solid spruce board	32	29
S4	12 x 350	-	73	67

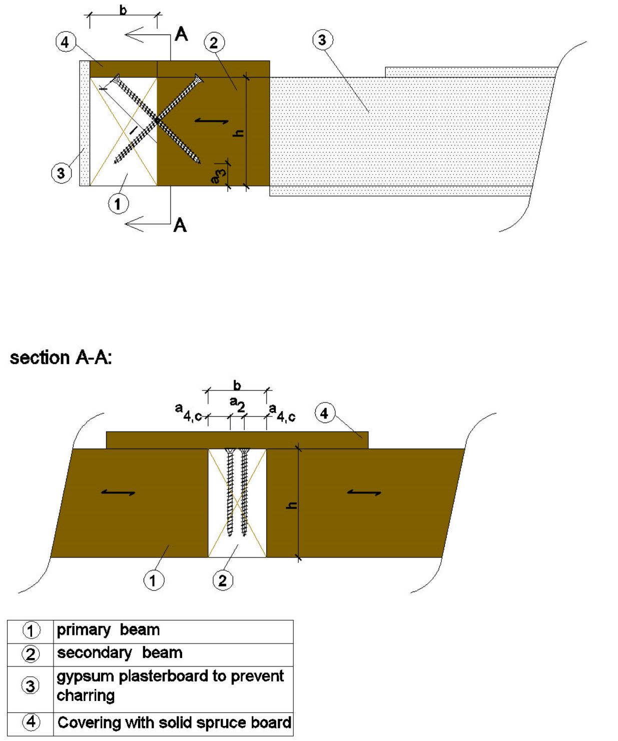

Figure 3: *primary beam secondary beam connection with pairwise crossed full thread screws*

All specimens were supported on two points of the primary beam (pinned) and one point of the secondary beam (roller) and were fixed against lateral buckling. The T-shaped specimens were placed in a diesel fired furnace and exposed to standard fire in accordance with EN 1363-1 [5]. A comparable setup, considering the requirements of EN 26891 [6] was also used to determine the load displacement behaviour and failure load at ambient conditions for each connection type as a basis for the loaded fire tests.

In the fire tests a constant load of 40 % of the estimated capacity after fire exposure was applied by a force controlled hydraulic jack during the fire exposure. At the end of the designated exposure time (30/60 minutes) the load was increased until the connection failed.

4.2 EXPERIMENTAL RESULTS

Connections using full thread screws do not deform significantly during the time of fire exposure, provided a sufficient side coverage of the screws. The deformation behavior may be described as quasi brittle, similar as under ambient conditions (see Figure 4).

Failure occurs by pulling out the screws (see Figure 5 and Figure 6) and came along with a vertical relative displacement of circa-35 to 40 mm.

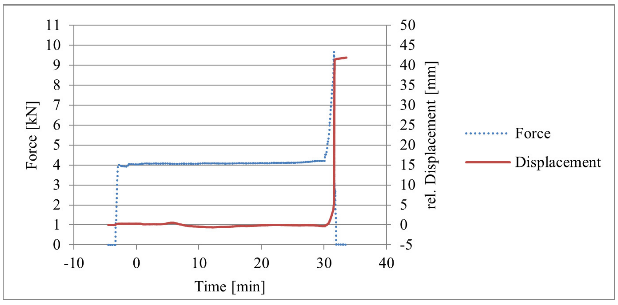

Figure 4: *typical load and displacement course in the loaded fire test of a connection with a crosswise pair of screws*

Figure 5: *relative displacement combined with a gap between the primary and secondary beam (specimen S3)*

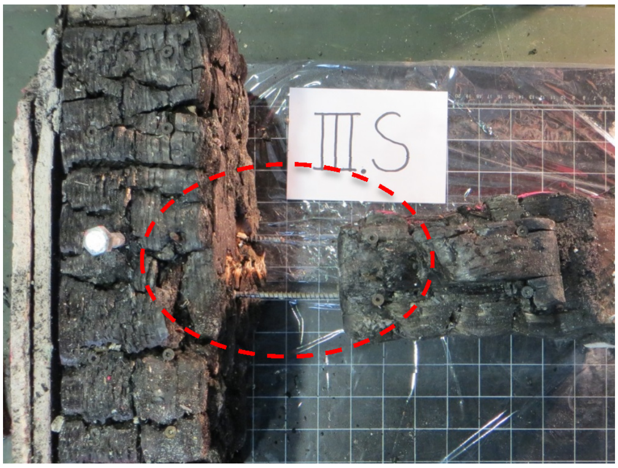

Figure 6: *pulled out screws after the fire test (specimen S3)*

The load ratios $R_{fi}/R_{k,20°}$, calculation of Test No. S1 and S3 are nearly identical, although a lower load bearing capacity of S3 has been anticipated due to the smaller side coverage. Generally, the load ratios have been higher than calculated according to EN 1995-1-2 [8]. A side coverage of 29 mm (as in S3) leads to a calculated $R_{fi}/R_{k,20°} = 0.50$, the test measurement is 0.59. Test S4 resulted in the highest load ratio of $R_{fi}/R_{k,20°}= 0.84$. The heat absorbed by the uncovered screw head could be thoroughly distributed in the surrounding timber along the length of the screw.

Table 2: *load bearing capacities of connections with pairs of full thread screws, characteristic values at ambient conditions compared to experimental results after 30 resp. 60 minutes fire exposure.*

No.	Exposure [min]	R_{fi} [kN]	$R_{k,20°C}$[kN]	$R_{fi}/R_{k,20°C}$
S1	30	7.21	12.4	0.58
S2	60	5.89	11.6	0.51
S3	30	7.46	12.7	0.59
S4	30	35.20	42.1	0.84

5 PROTECTIVE MEASURES

In the unloaded fire tests some protective measures were investigated (see WCTE 2014 [3]). Hereby the effect of various side distances $a_{4,c}$ of full thread screws with unprotected heads were assessed.
The consequences of using unprotected or protected screw heads are shown in the loaded fire tests and clearly lead to different temperatures along the screw.
Moreover, the effect of different insertion depth of screws as well as the additional effect of a wooden plug over the sunken screw were analyzed.
Therefore four screws with a diameter of 8 mm and a length of 200 mm and four screws with a diameter of 12 mm and a length of 200 mm with different insertion depths were compared.

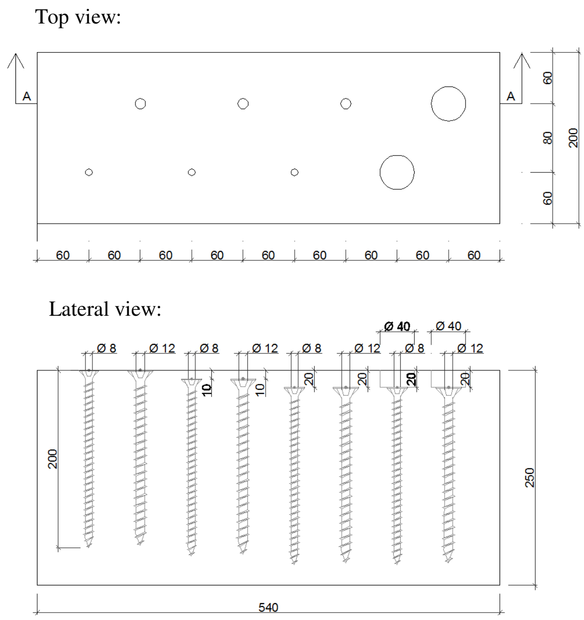

Figure 7: *drawing of specimen to assess the effect of different insertion depth of the screws*

The specimen was made of GLT. All sides were insulated by mineral wool except the top surface.
The specimen was exposed to fire in accordance with EN 1363-1 for 30 minutes.
Temperature measurements during the fire tests were conducted using Type K thermocouples. (see Figure 8).

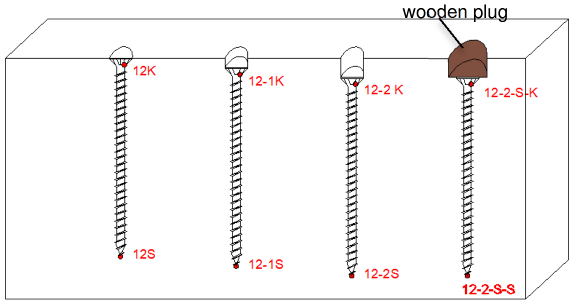

Figure 8: *section A-A of Figure 7–temperature measuring points on the head and tip of the screws (d_{nom}=12 mm)*

The effects of differing insertion depths were compared based on the temperature as measured at the screw head and tips as well as the charring depths along the screws.

In Figure 9, it can be seen that a 10 mm deep sunken screw shows no marked differences in temperature course compared to a screw which is inserted plan with the sample surface.
The maximum temperature of the surface plan screw head (8K) represents approximately the temperature of the standard temperature time curve in accordance with EN 1363- after 30 minutes. Sinking the 8 mm screw head (length 200 mm) 10 mm into the sample results in a drop of only 10 °C as measured on the screw head. A sinking depth of 20 mm however leads to a drop of circa 100 °C at the screw head compared to the surface plan screw after exposure to fire for 30 minutes. Only the additional protection of a 20 mm thick wooden plug results in a maximal temperature of 350 °C (8-2-S-K).
The temperature at the screw tip were generally around 20 °C with only the surface plan screw showing temperatures of 100 °C. Similar results are to be found amongst the 12 mm screws.

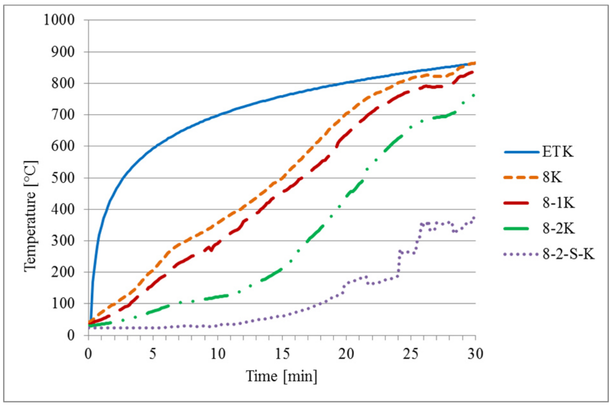

Figure 9: *comparison of the protective effect of different insertion depth of screws (d_{nom} 8 mm, length 200 mm)*

The comparison shows that the good building practice of sinking screws 10 mm provides little to no advantage over an unsunk screw. Sinking depths of 20 mm lead to 100 °C lower temperature loads after 30 minutes.
The coverage of the screw head leads to the lowest temperature on the screw. As a result, the lateral coverage can be significantly reduced and the required timber cross section can be minimized.

In a sectional view, the different charring depths of differing insertion depths are clearly visible (Figure 10 and Figure 11). The 8 mm screws develop a charring depth along the screw of ca. 30 mm in addition to the usual charring depth of the timber cross section. When the screw is sunken 10 mm, this charring is reduced to 20 mm. A sinking depth of 20 mm shortens the charring depth by a further 10 mm. The additional preventative measure of a wooden plug over the screw head has the result that charring is no longer to be found.
Similar charring depths are also observable in tests with 12 mm screws.

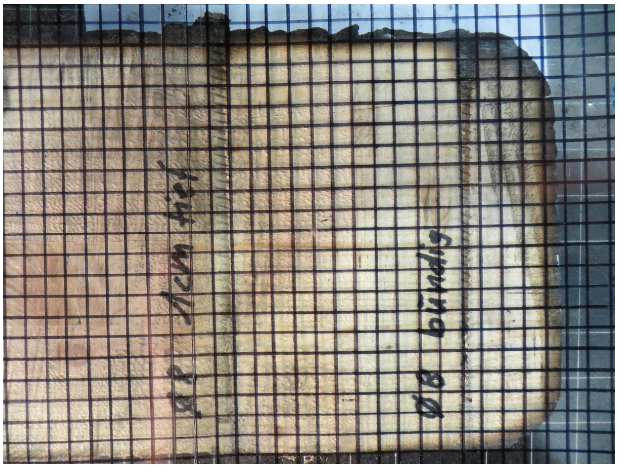

Figure 10: *cross section of the specimen (screws: d_{nom} 8 mm) – illustrating the charring depth using different insertion depth (right: 0 mm, left:10 mm) of the screws*

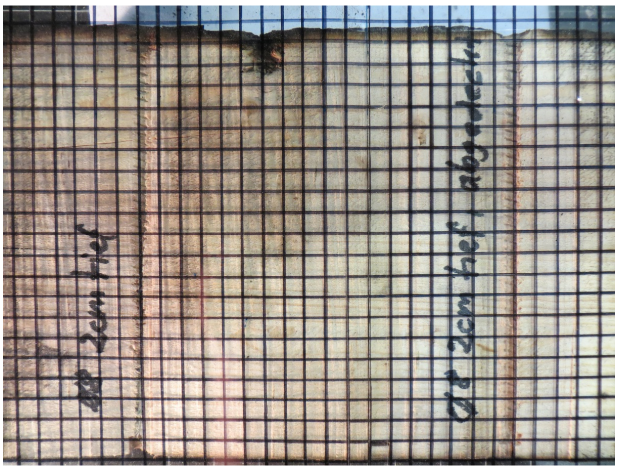

Figure 11: *cross section of the specimen (screws: dnom 8 mm) – illustrating the charring depth using different insertion depth (left: 20mm, right: 20 mm+ wooden plug) of the screws*

6 NUMERICAL SIMULATIONS

6.1 INTRODUCTION

In addition to the experimental part of the research program, numerical simulations were carried out with the objective to understand the influence of specific parameters in detail and extend the results to further types, sizes and configurations of screws. The simulations were calibrated using the experimental results.

6.2 INITIAL PARAMETERS UTILIZED

In order for a thermal simulation to be run, the temperature dependent characteristics of gross density, thermal conductivity, emissivity and the specific heat capacity of all construction materials (solid timber and carbon steel) must be assigned. The thermal load is a further simulation requirement.

The EN 1995-1-2 [8] provides the ratio of gross density to dry density for solid wood subject to its temperature. The gross density of the examined wood corresponds to 480 kg/m³. In the given ratio of gross density to dry density of the EN 1995-1-2, the timber moisture content is taken into account for temperatures under 100 °C.
The specific heat capacity of coniferous wood and carbon steel are also taken from the EN 1995-1-2 and EN 1993-1-2 [7].
Unlike carbon steel, coniferous timber displays an anisotropies behavior. The thermal conductivity differs radial, tangential and axial to the grain. A three dimensional system was used to model the in timber inserted screw. As such, the thermal conductivity must be given separately for each fiber direction.

The EN 1995-1-2 provides only the temperature dependent thermal conductivity for the radial direction.

Published values [1], [2] for thermal conductivity tangential and axial to the grain vary significant. To determine a value for the model, different conduction values were tested during the validation of the simulation models. The application of the following factors led to a very good reproduction of the fire tests.

- $\lambda_{tangential} = 1.1 * \lambda_{radial}$
- $\lambda_{axial} = 2.4 * \lambda_{radial}$

The conductivity of carbon steel was taken from the EN 1993-1-2.
The heat transfer from the furnace to the examined screw connections is described based on the given convection and the emissivity of both materials. A heat transfer coefficient of 25 W/m²K was used. For coniferous woods, an emissivity coefficient of 0.8 was assumed. For carbon steel, an emissivity coefficient of 0.6 was applied.
The uniform temperature curve described in the EN 1991-1-2 was chosen as the temperature load. The three dimensional model represents only a quarter of the screw. Only the surface of the timber through which the screw is inserted (Pos. 2), and a section of the screw head are affected by convection and thermal radiation in the model (see Figure 12). Adiabatic change behavior is ascribed to the wooden surfaces (Pos. 1) as symmetry caused heat transfer neither exists nor is caused.

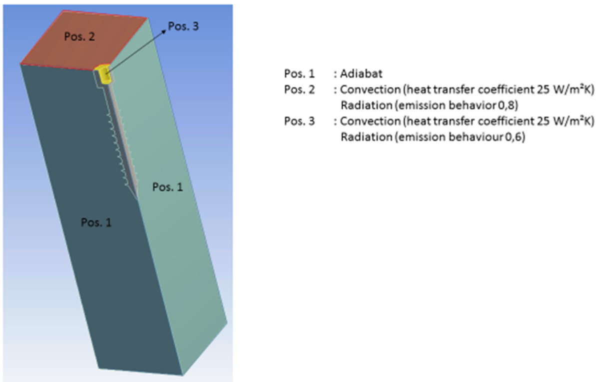

Figure 12: *different thermal boundary conditions in the three-dimensional model*

6.3 VALIDATION OF THE SIMULATION MODEL

To validate the simulation model, unloaded fire tests were carried out on full thread screws (cf. WCTE 2014). The tangential and axial heat transfer capacity was iteratively adjusted to ensure the tests were realistically representative. Additionally, the simulation was based on the actual furnace temperature, not the standard temperature time curve in accordance with EN 1363-1.
To compare the simulation results with the experimental results, the temperatures along the screw were tabulated and the positions of the 300 °C isotherm were compared with the charring depth test results.
The position of the 300 °C isotherm is consistent with the charring depth of the test samples. With the help of the chosen input parameters, the model achieved an adequately qualitative representation of the fire tests.

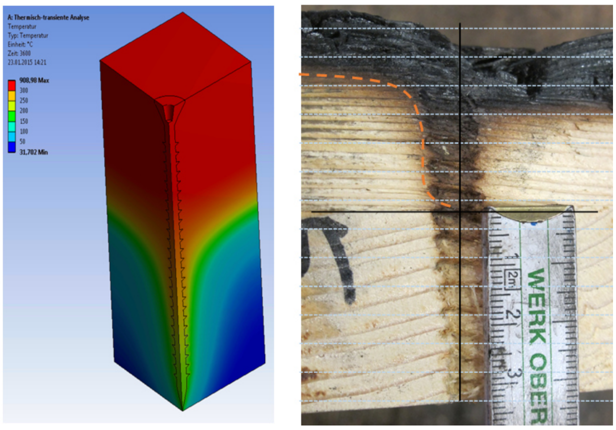

***Figure** 13: left: temperature distribution along a full thread screw in the model, right: comparison with the charring depth of a test specimen (orange dotted line represents the 300°C isotherm of the simulation)*

6.4 PARAMETER STUDY

Subsequently, the following parameter for full thread screws in timber were examined within the numerical simulations.

- Length: 60 mm to 220 mm (40 mm increments)
- Diameter: 4, 8 and 12 mm

- Screw head type: Countersunk, Cylinder and Roundhead
- Duration of Fire Exposure: 30 and 60 minutes

The results of the study are as follows:
The parameter study shows independently that the choice of a small diameter causes lower temperatures along the screw. Furthermore, the length of the screw used plays a defining role for the temperature distribution. The longer the chosen screw is, the lower the temperature along the screw is. This can be attributed to a longer screw delving deeper into the cooler areas of the wood and dissipating more heat.
However, from a certain length onwards the temperature distribution is no longer influenced by the diameter.

From the following lengths the isotherm position is consistent during a 30-minute thermal load with adequate timber cover (ca. 40 mm) relative to the diameter.

- d_{nom}= 4 mm, l > 100 mm
- d_{nom}= 8 mm, l > 140 mm
- d_{nom}= 12 mm, l > 200 mm

During a 60-minute temperature load, the following lengths are representative.

- d_{nom}= 4 mm, l > 120 mm
- d_{nom}= 8 mm, l > 180 mm
- d_{nom}= 12 mm, l > 260 mm

The type of screw head is for the temperature distribution along the screw negligible.
The influence of the screw spacing was examined further. When multiple screws are arranged together, the possibility of mutual thermal influence arises and higher temperatures can be expected. For this examination the minimum spacing according to the EN 1995-1-1 and the national technical approval for SPAX-S full threaded screws (Z-9.1-519) [9] were applied.

From these minimum distances many cases present themselves in which higher temperatures can be reached compared to singular connections. One main focus is on the required spacing from the national technical approval for SPAX screws. From this, four different arrangements were selected for which a range of full threaded screws of various diameters and lengths were examined.
The arrangements are shown in Figure 14.

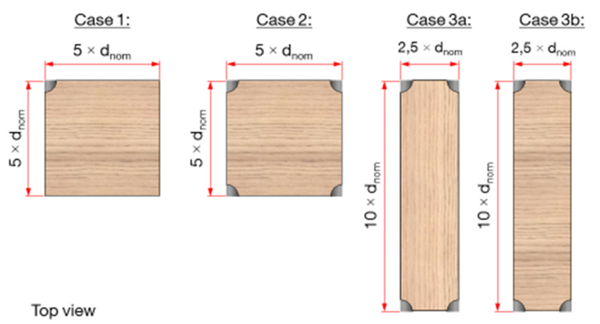

Figure 14: *drawing of the investigated cases of the minimum distances between the screws*

Case 1 represents the reference. Here is a full thread screw numerical assed. The lateral surfaces, with the exception of the fire exposed surface, were assumed to be adiabatic to enable the usage of the symmetrical condition. In case 2, four screws were arranged with a distance of 5 x d_{nom}. This represents the minimum spacing in the direction of, and perpendicular to the grain for SPAX screws. The distance a_2 (perpendicular to the grain) may be reduced to 2.5 x d_{nom} if a_1 x a_2 is at least equal to 25 x d_{nom}^2. This was taken into consideration in Case 3a.
No clear minimum distances for glued laminated timber could be found. If the connection arrangement of Case 3a is used for cross laminated timber, the required distance is 2.5 x d_{nom} in some positions in the direction of the grain. To compensate for this, Case 3b was also examined thermally. Here, the distance a_1 (with the grain) was 2.5 x d_{nom} (Figure 14).
Finally, the screw temperatures of each case were compared to each other. To ensure that the same temperature in each screw was reached within each case study, an assessment path was defined and evaluated for the individual screws. Figure 15 shows by way of example that the temperatures of all four screws in Case 3a are virtually identical.

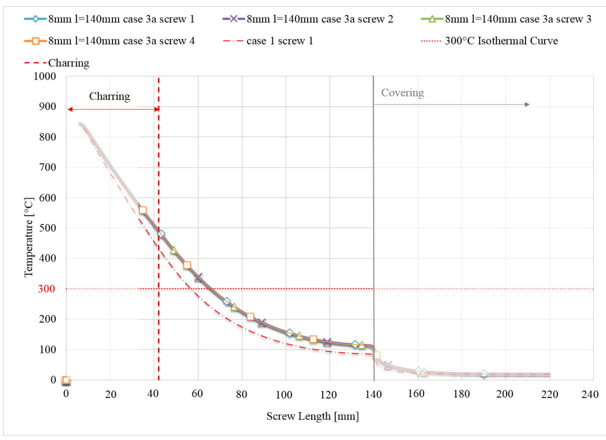

Figure 15: *comparison of temperature along the screws 1-4 of Case 3a (d_{nom}= 8mm, length= 140 mm)*

This could be also ascertained for all other screw configurations and cases. Figure 16 shows a comparison of the screw temperatures of the various cases for an 8 mm 140 mm long full thread screw.

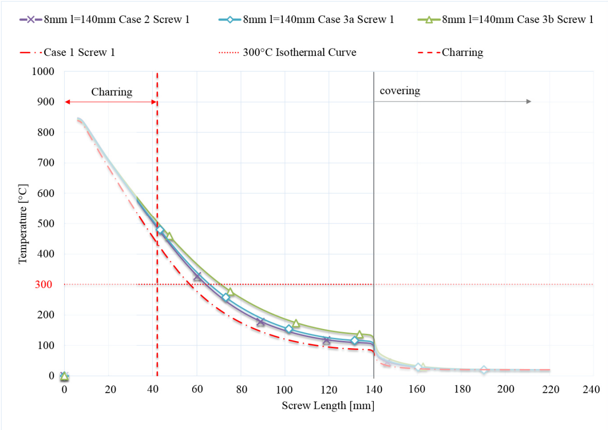

Figure 16: comparison of temperature along the screws of Case 1 to Case 3b (d_{nom}= 8mm, length= 140 mm)

As can be seen, large differences appear between the reference curve (Case 1) and the further cases with regard to the temperatures. The deviations amount to an average difference of 30 °C between Case 1 and Case 2. Case 3a behaves similarly. The deviation to Case 3b is noticeably higher. On average this is 60 °C. In Figure 17, the isothermal plot is shown for the screw arrangement found in Case 3a. In the area of the minimum distance (a_2 = 2.5 x d_{nom}) the isothermal curves are almost parallel to each other. The timber reached nearly the same temperatures as the heated screw. This means that the timber no longer contributes to the cooling of the screw. In areas where the distances are larger, this is still the case (Figure 17).

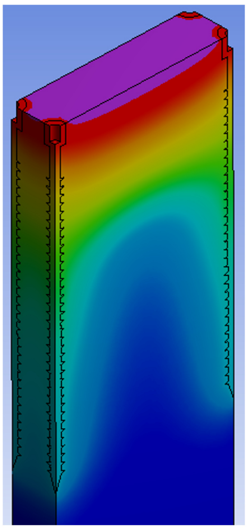

Figure 17: Isothermal curves of case 3a (screws with d_{nom}= 8mm and length= 140 mm)

A further comparison of the various screw arrangements provides the following results. The influence of the screw distances is, regarding absolute temperature difference, larger the shorter the screws are. The absolute temperature differences increase as the full threaded screw diameter is reduced. Within the comparison of Case 3b with Case 1, the temperature deviation of a long and thick screw (d_{nom} = 12 mm; l= 220 mm) lies on average around 30 °C while the variation of a relatively short and thin screw (d_{nom}= 4 mm; l= 60 mm) is already ca. 180 °C.

6.5 ESTIMATION OF THE PULL OUT RESISTANCE

Low temperatures along the screw lead to higher pull-out strength (cf. WCTE 2014 [3]). To be able to estimate the pull out resistance relative to the diameter and screw length, average resistances must be assigned to particular temperature bands (see Figure 18).

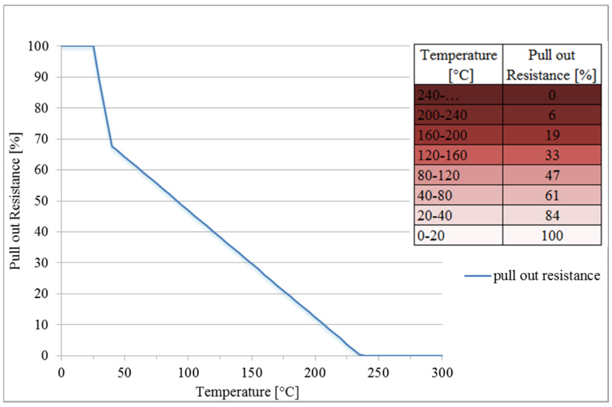

Figure 18: percentage pull out resistance of a full thread screw depending on the temperature in reference to the pull out resistance under ambient conditions

Upon knowing the temperature distribution along the screw, the pull out resistance may be estimated. This is shown exemplary in Figure 15.

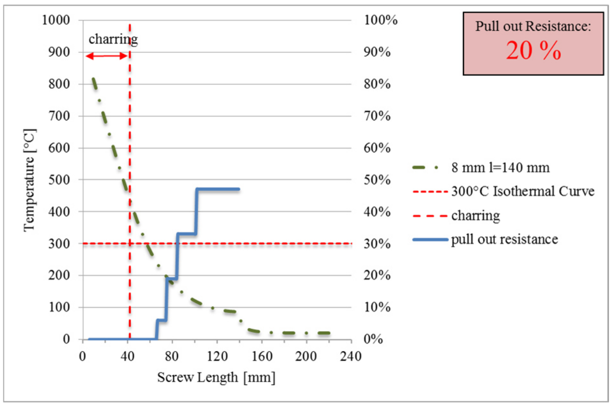

Figure 19: pull out resistance of a full thread screw (d_{nom}= 8 mm, length= 140 mm,) exposed to standard fire in accordance to EN 1363-1 for 60 minutes

When all pull out resistances along the screw are added together and divided by the total length, an 8 mm screw with a length of 140 mm can be estimated with an averaged pull out resistance of ca. 20 % compared to the ambient situation.
In Figure 20, the pull out resistances for full thread screws of 4, 8 and 12 mm screws with lengths of up to 220 mm after a 60-minute fire exposure are shown.

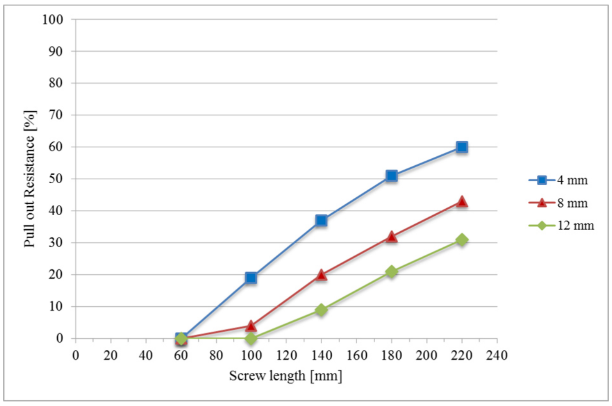

Figure 20: *average pull out resistance of thread screws(d_{nom}= 4 mm, 8 mm und 12 mm and length= 60 mm -220 mm after a 60 minutes long standard fire in accordance with EN 1363-1 combined with a sufficient side distance (approx. 80 mm))*

With the help of this diagram, the pull out resistance of screws can be estimated as long as the heat exposure takes place exclusively through the screw head and not over the shaft.
This data should however be verified by further testing.

7 CONCLUSIONS

Specific outcomes of the project are the design and calculation rules for connections with full thread screws to fulfill 30 and 60 minutes fire exposure. These rules may improve the methods given in the current standards (e. g. EN 1995-1-2) and facilitate a better design process.

For the design of 45° crosswise installed pairs of full thread screws which should provide a defined and adequate load bearing capacity over a 30 minute or 60 minute fire exposure, the following recommendations can be derived:

- The minimum cross section of the secondary beam is dependent on the choice of coverage and protective measures applied to the screw head. These measures should be chosen dependent on the required relationship between shear force bearing capacity in the event of fire and the characteristic load bearing capacity under ambient conditions.

- Protected screw heads should be assigned a side distance $a_{4,c} = max\left\{29\ mm + \frac{d_{nom}}{2};\ \beta_n \cdot t + 1.6 \cdot d_{nom}\right\}$ for a 30 minute fire exposure and a screw tip distance from an exposed surface a_3 of 29 mm to guarantee a ratio between the characteristic shear load bearing capability in the case of fire and the characteristic shear load bearing capability under ambient conditions of $R_{fi}/R_{k,20°} \geq 0.5$ as long as glued laminated timber is in use. (By using solid wood see [4]). With a 60 minute fire exposure on glued laminated timber, side distances of $a_{4,c} = 61\ mm + \frac{d_{nom}}{2}$ and coverage of the screw tip of at least 61 mm is recommended to ensure a ratio of $R_{fi}/R_{k,20°}\ \eta \geq 0.5$.

  Studies of Grabner and Ringhofer [10] show a sufficient pull out strength under ambient temperature by using a side distance $a_{4,c}$ of 1.6* d_{nom}. These tests were made with cross laminated timber. However the results are transferable to solid wood and glued laminated timber.

  Also in the case of fire a sufficient remaining side distance of $a_{4,c}$=1.6*d_{nom} should be guaranteed.

  To achieve a constant ratio between the characteristic shear load bearing capability in the case of fire and the characteristic shear load bearing capability under ambient conditions the required side distance $a_{4,c}$ is the result of the maximum of $\beta_n \cdot t + 1.6 \cdot d_{nom}$ or $29\ mm + \frac{d}{2}$ for 30 minutes fire exposure ensuring a maximum temperature of 75-100°C along the screw under one-dimensional heat influx (see equation (1) see [11]).

  $$T(dt) = 20 + 180*(\beta_n*t/dt)^{0.025*t+1.75} \qquad (1)$$

  with

  T(dt) Temperature in the depth d due to one-dimensional heat flux induced by standard temperature time curve in accordance to EN 1363-1
  β_n Design value of the charring depth
  t Time of fire exposure in accordance with EN 1363-1
  dt Depth of measuring point/timber coverage

- Larger timber coverage of the full thread screw, which are due to larger cross sections yield exclusively to positive effects on the load bearing capability in the case of fire, not only in absolute values but also relative to the cold load bearing capacity.

- Full thread screws should, when the screw head remains unprotected, be of small diameter and as long as possible to offer a beneficial ratio between the screw's cross sectioned area and the circumference upon which the heat can be released (see Figure 20).

A comparison of the minimum required cross sections in case of fire shows clearly that the required timber cross sections which were determined by this study differ greatly from the timber cross sections which result from an assessment according to EN 1995-1-2. The results of this research project offer, with about the same coverage and similar load bearing capacity, a reduction in width of up to 40 mm. The height of the cross section can also be reduced under the same conditions by up to 40 mm.
Within the scope of EN 1995-1-2, smaller side distances can be used which lead to a significant reduction in load bearing capacity.

This research project shows that the implementation of crossed full thread screws with unprotected screw heads is possible. It should then be combined with a large screw length and noticeably increased side coverage.

In general, the project contributes to a better understanding of the temperature behavior of such connections, which may help in the planning and execution of further research projects.

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