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Fire resistance of primary beam – secondary beam connections in timber structures

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Abstract

Purpose – This paper deals with the fire resistance of primary and secondary beam connections in timber structures.

Design/methodology/approach – This paper describes a series of unloaded and loaded furnace fire tests in different configurations of these types of connectors.

Findings – The main objective is the fire safety design of joist hangers and full thread screws.

Originality/value – Design recommendations are given.

Keywords Fire resistance, Timber buildings, Joist hangers, Self-tapping screws, Full thread screws

Paper type Research paper

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 and special constructions. The benefits of building in timber 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 by authorities and design codes linked 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 the fire safety in buildings. The design rules for fire-exposed timber structures, such as the ones listed in European Committee for Standardization (CEN) (2004), NZS 3,606 (1993) or in the USA AWC-DCA2 (American Wood Council: Design for Code Acceptance, 2010), 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 and joist to column connections do not exist (Deutsche Gesellschaft für Holzforschung, 2009). Approved and reliable systems are rare.

To overcome this gap of knowledge, a German research project has been started in early 2013, which seeks to investigate the thermal and structural performance of typical engineered connections for timber structures in the event of fire, such as joist hangers, screwed connections, concealed joist ties and corbels (see Figure 1).

Joist hangers and other connectors, which are not defined in the European standards (EC5), need a technical approval document (ETA) to be applied in the European market. The necessary approval tests for the ETA are defined in a guideline (ETAG) for each type of product. For example, applicable for joist hangers is ETAG 015 "Three dimensional nailing plates". This ETAG mentions that fire tests have to be conducted according to EN 13501-2, but no provisions are made regarding a specific test method. It is stated that the test configuration shall be determined based on the intended use conditions, which led the thoughts on how to build the test configuration in this research project. Tests under ambient conditions have to be conducted regarding to EN 26891.

2. Conception of investigations
2.1 Methodical approach
Because experimental investigations allow only a limited number of tests in general, it is projected to extend the results by numerical modelling for further parametrical studies and optimization processes. The investigations conducted in this research project are based on a three-pillar strategy:

(1) unloaded small-scale fire tests to assess the influence of geometry and material interaction;

(2) mechanical testing of the connections at ambient conditions under consideration of the results and residual cross-sections gained in step (1); and

(3) loaded full-scale fire tests of selected and optimized connection systems based on the results gained in the previous steps (1) and (2) and the associated Finite Element (FE) Modeling.

3. Experimental testing
3.1 Unloaded fire tests
3.1.1 General configurations and setup of small-scale tests
3.1.1.1 Testing facilities. Each of the unloaded U-shaped specimens were assembled from one cross laminated timber (CLT) floor and two CLT wall panel with a thickness of 100 mm, made of spruce in grade Gl24h without edge-bonding. The three-layered CLT panels were used as a support structure representing the primary beams. On the inside
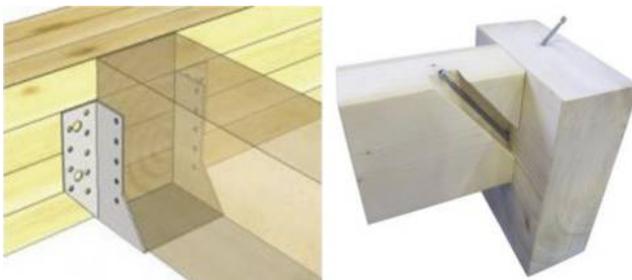

Figure 1.
Typical joist
connections for
timber structures.
Left: joist hanger;
right: pair of full
thread screws

of the CLT wall panels, 300-mm-long glulam and sawn timber beam sections were attached with joist hangers and fully threaded screws, respectively, as illustrated in Figure 2. All beams were orientated in such a way that each bottom side was facing the burner and no thermal shading effects occurred among the beam sections. Each free-beam end-grain side was covered with 18-mm-gypsum boards to ensure an even four-sided fire exposure of the beam sections and to exclude an additional thermal influence on the examined connections.

All timber members were made from spruce with a moisture content of approximately 12 per cent. The resulting U-shaped specimens were placed in a diesel fuel-fired furnace, as shown in Figure 2, and exposed to ISO 834 fire for 30 and 60 min, respectively. The tests were carried out under variation of beam dimension, type of connectors and fasteners and joint dimension to cover a wide spectrum of configurations.

3.1.2 Instrumentation. Temperature measurements during the fire tests were conducted using Type-K thermocouples inside the timber members at the connectors and fasteners. For selected nails and screws, thermocouples were welded to head and tip to ensure precise measurements alongside the fasteners. The thermocouples of fastener tips were fed through pre-drilled holes in the timber members and sealed at the fire-unexposed side with mastic.

3.1.3 Individual setup

3.1.3.1 Joist hangers. In the conducted fire tests, two sizes of joist hangers for the beam dimension W × H = 100 × 240 and 200 × 300 mm were investigated, each for internal and external wings. The joist hangers were made from galvanized zinc-coated steel sheets of 2 mm thickness. To fix the joist hangers to the beam sections and CLT wall elements, rink shank nails with a diameter of 4 mm and screws with a nominal diameter of 5 mm were used as fasteners. Both types were 50 and 70 mm in length, respectively. For all setups, the 50 mm long fasteners were applied to the right side and the 70-mm-long fasteners to the left side of the symmetrical joist hangers. An exception was made for the 100-mm-wide beams, and only 50-mm-long fasteners were applied to fasten the beam to the joist hangers. Either screws or nail was used per joist hanger. Therefore, eight different combinations were assessed in total. To measure the increase in temperature, thermocouples were installed at fastener heads and tips in the joint between connector wings and timber members and in the gap between beam sections and wall elements for each configuration, as illustrated in Figure 3. To ensure practical conditions, the beam sections were fastened with a gap of 7 mm to the CLT elements

Figure 2.
Left: assembled specimen with measurement equipment; right: drawing of furnace and specimen
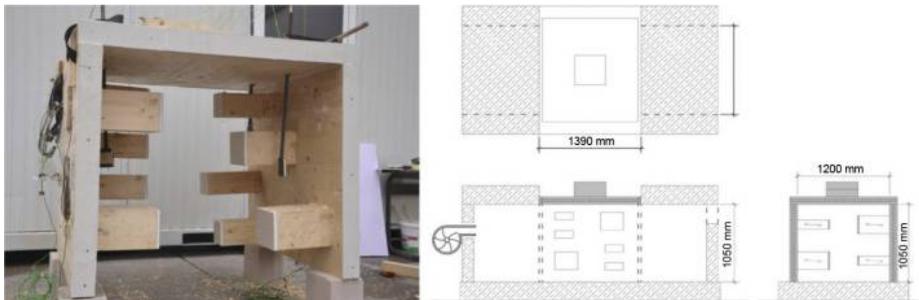
(steel sheet thickness + fastener head) in all setups. No further protection measure was applied to these gaps. The fire tests with joist hangers were conducted for 30 min.

3.1.3.2 Full thread screws. To investigate the effect of screw length, diameter, shape of screw head and steel type to the temperature development and charring rate of timber, nine screws were installed into each CLT ceiling element, as presented in position of thermocouples Figure 4 and examined in 30- and 60-min fire tests. To enable the assessment of up to 300-mm-long screws, the CLT ceiling elements were backed by two additional CLT panels with 100 mm thickness each (position of thermocouples Figure 4).

Thermocouples were attached to all heads and tips of the screws. In addition, the temperatures for the 200-mm-long screws were measured at half-length and for the 300-mm-long screws at one/three and two/three of the total length, as illustrated in position of thermocouples Figure 4.

The interaction of side distance $a_{4,c}$ and the thermal influence of the unprotected screw heads were of special interest. The beam sections were attached to the CLT panels by crosswise-installed pairs of screws. Precisely, six beam sections were tested for 30 min tests and ten for 60 min. The screws used in the fire tests had the dimensions ($d_{nominal} \times$ length) 6 × 160 mm and 12 × 300 mm, respectively, and screwed in at a 45° angle. The following side distances were examined as protecting wood covering:

(a) $a_{4,c} = 3 \times d_{nom}$ (in accordance with EN 1995-1-1);

(b) $a_{4,c} = 3 \times d_{nom} + \beta_n \times t + d_0$ (according to EN 1995-1-2); and

(c) $a_{4,c} = 3 \times d_{nom} + (\beta_n \times t + d_0)/2$ (half between a) and b)).

The position of thermocouples attached to each setup can be taken from Figure 5.

3.2 Loaded fire tests

3.2.1 General configurations and setup of loaded fire tests. The loaded T-shaped specimens were assembled each of a primary beam (PB) and a secondary beam (SB) (see Figure 6). The length of each primary beam was 2000 mm and that of each secondary beam was 1,200 mm. The primary beam–secondary beam connection was made with joist hangers or pairwise crossed full thread screws. The cross-section of the beams varied in regard to the type of the connection, as presented in Tables I and II.

The T-shaped specimens were placed in a diesel fuel-fired furnace, as shown in Figure 7, and exposed to ISO 834 fire for 30 or 60 min used measurement equipment in accordance with EN 1363-1. They were supported on two points of the primary beam and one point of the secondary beam and were fixed against lateral buckling. This was realized by adjustable vertical steel supports at the secondary beam and a fixation with
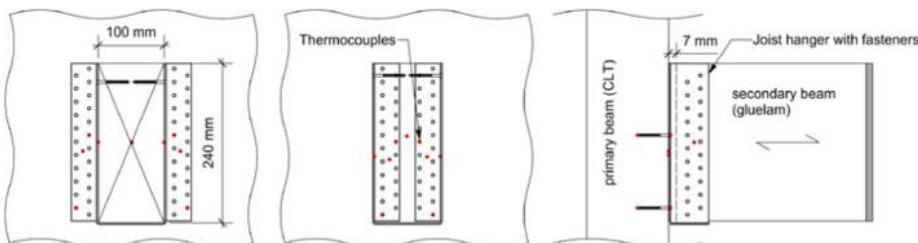

Figure 3.
Exemplary fire test setup for joist hangers

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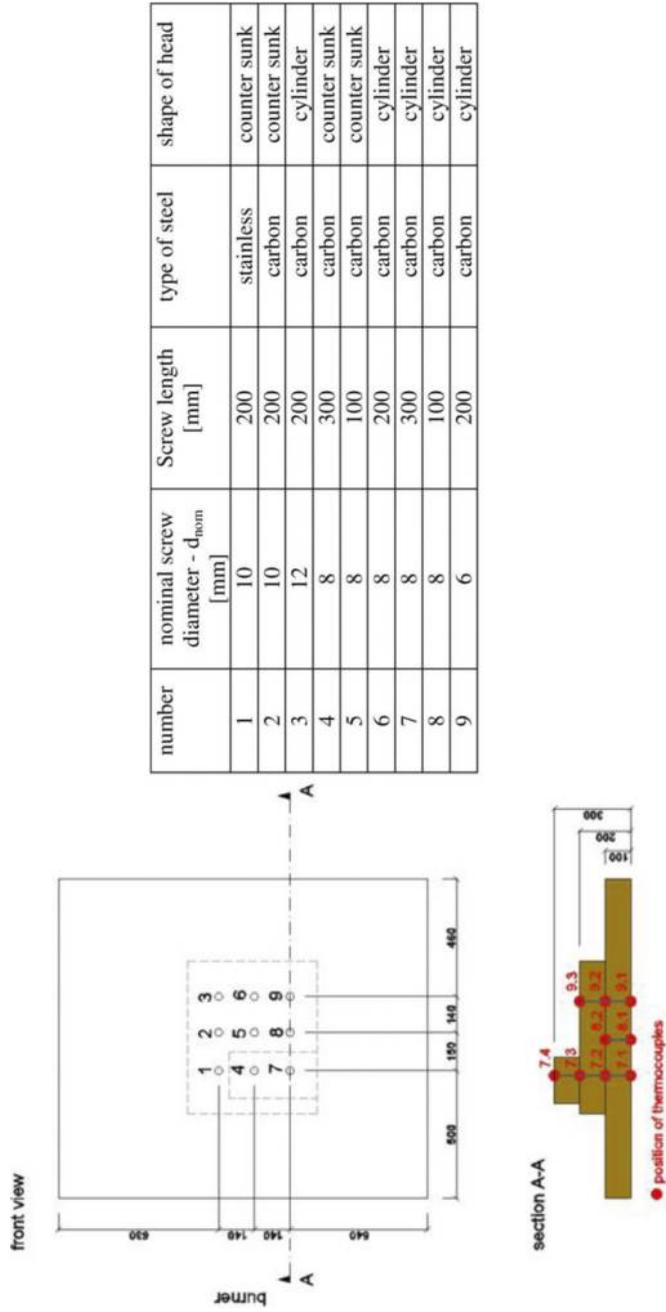| number	nominal screw diameter - d_{nom} [mm]	Screw length [mm]	type of steel	shape of head
1	10	200	stainless	counter sunk
2	10	200	carbon	counter sunk
3	12	200	carbon	cylinder
4	8	300	carbon	counter sunk
5	8	100	carbon	counter sunk
6	8	200	carbon	cylinder
7	8	300	carbon	cylinder
8	8	100	carbon	cylinder
9	6	200	carbon	cylinder

Figure 4.
Position of full
thread screws in the
CLT ceiling element
with corresponding
measurement points

clamps at the main beam. The relative vertical displacement at the connection was measured by two displacement transducers fixed on the primary and secondary beam.

The load was applied by a force-controlled hydraulic cylinder mounted on a steel frame. A constant load of $0.4 \times R_{fi,estimated}$ was applied during the time of classification (ISO 834 fire for 30 resp. 60 min). $R_{fi,estimated}$ is the load-bearing capacity after 30-min fire exposure, what could be expected with regard to literature, and that for joist hangers, it was a level of 30 to 40 per cent of $R_{k,20°}$. For the full thread screws, the level of $R_{fi,estimated}$ was determined by numerical calculations. At the end of the time of fire exposure, the load was increased until the connection reached failure. "Failure" was reached when the connection was no longer able to bear the applied load in the force-controlled test without regard to the displacement. The load was measured by a load cell and logged during the test time.
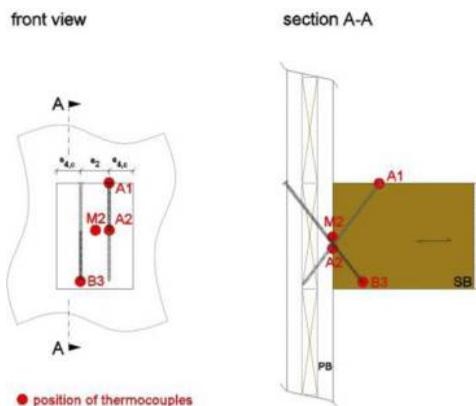

Figure 5.
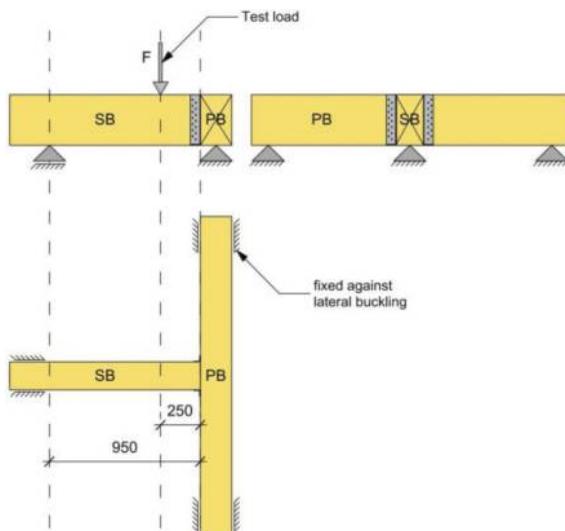Crossed screws and position of thermocouples in the connection (schematic illustration)

Figure 6.
General layout of test specimen

This proceeding enables the identification of the load-bearing capacity of the connection after an aspirated time of fire exposure. Based on that data, reduction factors for the load-bearing capacity under fire exposure can be calculated.

3.2.1.1 Joist hangers. The selection of sizes and types of joist hangers was made based on the results of the unloaded fire tests described in section 3.1 and loaded tests at ambient conditions. All joist hangers used in the fire tests had external wings (see Figure 8), as that during the critical configuration. Rink shank nails and screws were used as fasteners, each 75 resp. 70 in length. The gap between primary and secondary beam was reduced to 4 mm in all configurations because a higher load-bearing capacity was expected compared to a gap of 7 mm.

Joist hangers are often produced with surplus holes, but not all holes are needed to get a full nailing pattern, according to ETA (2013), reaching the maximum of load capacity under ambient temperatures. In contrast to ETA, two joist hangers were assessed using all holes. All joist hangers were tested for 30 min. Every primary beam had the cross section 200×320 mm.

3.2.1.2 Full thread screws. A screw angle of 45° results in the maximum shear force resistance for the connection and was used for the pairwise crossed screws. Thereby, one screw is screwed in the primary beam and the other screw in the secondary beam (cf. Figure 9). The edge distances ($a_{4,c}$, a_3 Table II) and the distance between the screws ($a_2 = 1{,}5 \times d_{nom}$) were chosen as small as possible to reach an expected shear force resistance under fire exposure of 50 per cent to 60 per cent of $R_{k, 20°}$.

4. Experimental results

4.1 Joist hangers

4.1.1 Influence of fasteners. The conducted series of fire tests with joist hangers showed that the charring of wood in contact with the fasteners is mainly influenced by the type of fastener. The unprotected fasteners conducted the heat from the surface into the

No.	Type of joist hanger	Cross-section secondary beam (mm)	Fasteners (mm)	Nailing pattern
B1	Type 04 120 × 160	120 × 160	Rink shank nails 4 × 60	Full according to ETA
B2	Type 05 120 × 240	120 × 240	Screws 5 × 60	Full according to ETA
B3	Type 05 140 × 200	140 × 200	Screws 5 × 70	Full according to ETA
B3a	Type 05 140 × 200	140 × 200	Screws 5 × 70	All holes are used
B4	Type 05 140 × 200	140 × 200	Rink shank nails 4 × 75	All holes are used

Table I.
Setup with joist hangars

No.	Duration of fire exposure (min)	Dimension of full thread screws $d_{nom} \times l$ (mm)	Covering the head of screws	$a_{4,c}$ (mm)	a_3 (mm)
S1	30	6 × 180	25-mm-solid spruce board	36	33
S2	60	6 × 180	25-mm-solid spruce board + 15-mm gypsum plasterboard	64	61
S3	30	6 × 180	25-mm solid spruce board	32	29
S4	30	12 × 350	–	73	67

Table II.
Setup with fully threaded screws
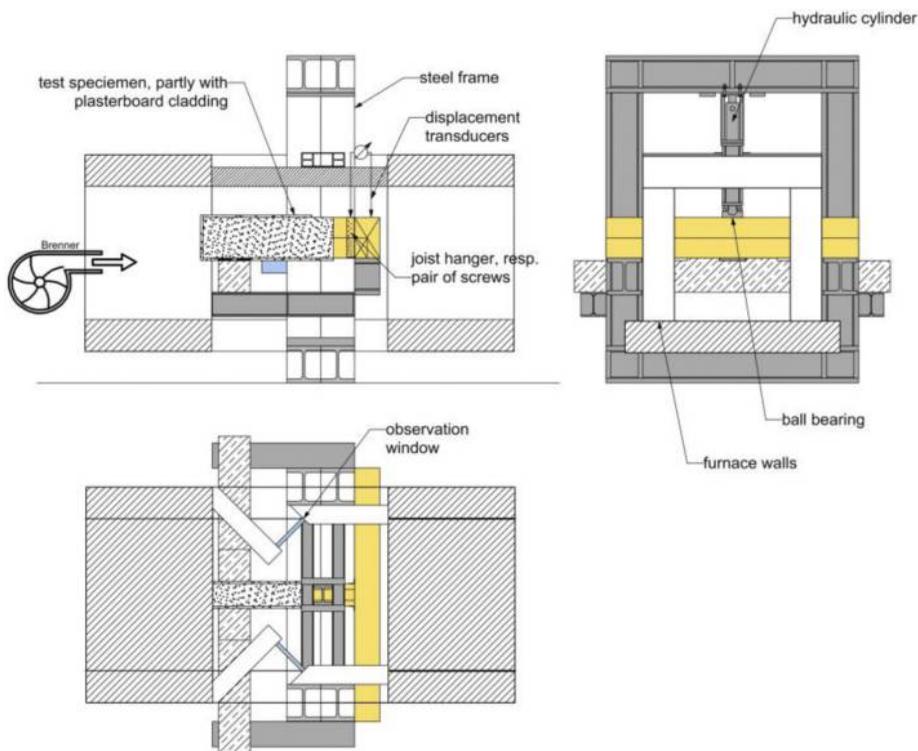
Figure 7.
Setup of the furnace
complete with load
frame

Figure 8.
Left: joist hanger
Type 04, right: joist
hanger Type 05 [GH
Baubeschläge]

interior of the timber members, resulting in a larger charring depth than for the free undisturbed area of the beams. The examined screws with a nominal diameter of 5 mm performed better than the 4 mm nails with the same length. This is evident from the more slowly heating curve of the screw tips and can be visualized equally by less charring of wood in contact with the screws and by the magnitude of discoloration alongside the removed fasteners. The 70-mm-long screws were still clean up to a length of 35 mm from the tip while the nails were colored black along their entire length. By
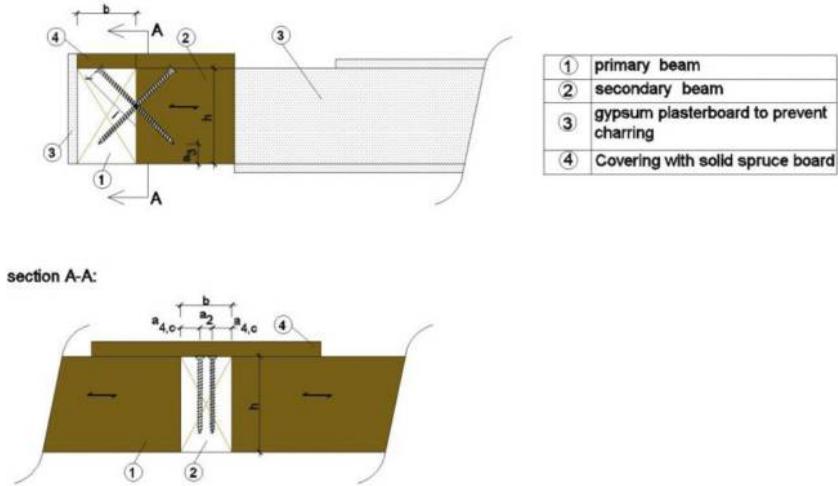
Figure 9.
Primary beam –
secondary beam
connection with
pairwise crossed full
thread screws

dismantling the specimens, it turned out that the gripping capacity of screws was much higher than that of the corresponding rink shank nails because of their threads and less charring. A comparison of the temperatures at the fastener tips showed that the 50-mm-long fasteners heated up more quickly than the 70-mm-long fasteners, if the same fastener type and diameter were used. For example, the tip temperatures of the 4×50 mm rink shank nails reached 450°C, whereas only 230°C were measured for the 4×70 mm nails after 30-min fire exposure.

4.1.2 Influence of joist hanger geometry. The 100-mm-wide secondary beams showed no or only little residual cross sections in the area of the joist hangers and must therefore be classified as too narrow for further examination. Some of these 100-mm-wide beam sections had already fallen off after the fire test as a result of the extra time it took to remove the complete specimen from the furnace.

Connections with internal wings showed lower temperatures (up to 200°C) than those with external wings on the surface of the CLT wall element (primary beam) between the wings. This difference was not recorded in the measured temperatures between connector and secondary beams. The influence of the direct fire exposure governed the surface temperatures and charring.

The gaps between the wall elements (primary beam) and the beam section (secondary beam) had a great influence on the charring behavior of the connection. Larger gap sizes led to an additional exposure at the end grain side of the attached beam sections and increased the charring because of "the almost five-sided fire exposure". To reduce charring in this area and consequently maintaining the load-bearing capacity of the connection, the gap size should be as little as possible or reinforced with sealing or top side covering.

4.1.3 Load-bearing capacity and load bearing behavior. The typical mechanical behavior of joist hangers under fire exposure can be described as follows:

After a few minutes, the connections start to deform; after approximately 15 min, the deformation velocity starts to increase. All specimens showed relative displacements of about 30 mm toward the end of the fire exposure; failure occurred at about 40-mm

displacement. The fasteners had been considerably deformed, the connections failed after pulling out of the fasteners. The sheet metal itself failed in no case (Figures 10-12).

The figures of the maximum load-bearing capacity are shown in Table III. The load-bearing capacity $R_{k,20°}$ at ambient conditions was calculated using the methods given in the ETA (2013), regarding the actual densities of each specimen. The load F_{fi} after the fire exposure at the connection in the moment of failure was measured.

The specimens B1 and B2 almost entirely lost their load-bearing capacity. The load-bearing capacities of B3, B3a and B4 reach up to a level, which is suitable for use in practice. It can be seen clearly that connections using rink shank nails retain lower load levels than connections using screws, provided that other parameters are identical.

Connections using the number of fasteners required in the according ETA reach a lower load-bearing capacity than connections with the maximum number of fasteners possible by the number of punched holes.
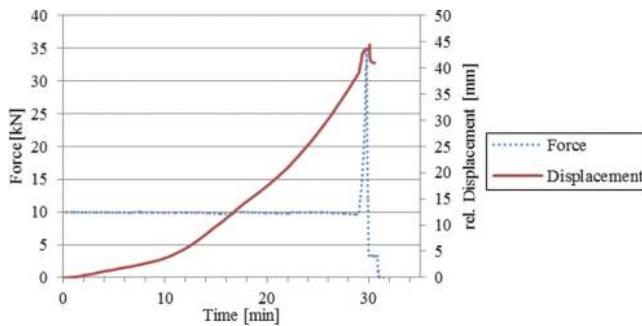

Figure 10.
Typical load-time
and
displacement-time
curve of a joist
hanger connection
(Test B3a)

Note: The deformation is clearly visible

Figure 11.
View of a joist
hanger connection in
the furnace during
the test after
approximately
15 min

Figure 12.
Joist hanger after the fire test

Note: Typical failure mode in terms of withdrawal of the fasteners (Test B4)

No.	Fire exposure (min)	F_{fi} (kN)	$R_{k,20°}$ (kN)	Proportion η $F_{fi}/R_{k,20°}$
B1	30	0	39.9	0
B2	30	7.7	94.6	0.08
B3	30	17.8	85.4	0.21
B3a	30	26.2	79.0	0.33
B4	30	14.9	76.6	0.19

Table III.
Load-bearing capacities of joist hangers

4.2 Full thread screws

4.2.1 Influence of screw dimension. The length of the full thread screws shows a great influence on the measured temperatures, if exposed from the unprotected head side. This effect is confirmed by the previously discussed results of rink shank nails. The comparison of the temperatures in the same depth of a 100-mm- and a 300-mm-long full thread screw shows lower temperatures at the longer screw. This difference ΔT rises with increasing distance from the exposed surface. In a depth of 100 mm, the measured difference was about 100°C after 60-min fire exposure, as depicted in Figure 13.

This difference was caused by the larger skin surface and the ability of the longer screw to penetrate with their tip in more distant and cooler timber. Furthermore, the larger thermal capacity of the longer screw has some influence. It is obvious from the results that the screw diameter is influencing the temperature at the screws as well. In the early stages of fire exposure, the $d_{nom} = 6$ mm screws showed higher temperatures at the screw heads than those with $d_{nom} = 12$ mm. After about 20 min, these head temperatures were comparable to each other again. Contrary to this, all temperatures along the $d_{nom} = 6$ mm screws lay below the corresponding temperatures of $d_{nom} = 12$ mm screws, as shown exemplarily in Table IV.

This temperature distribution can be explained by the fact that the peripheral surface increases linear, whereas the cross-section area increases quadratically with the diameter of the screw. The shape of screw head did not have any significant influence on the temperature distribution in the screws.
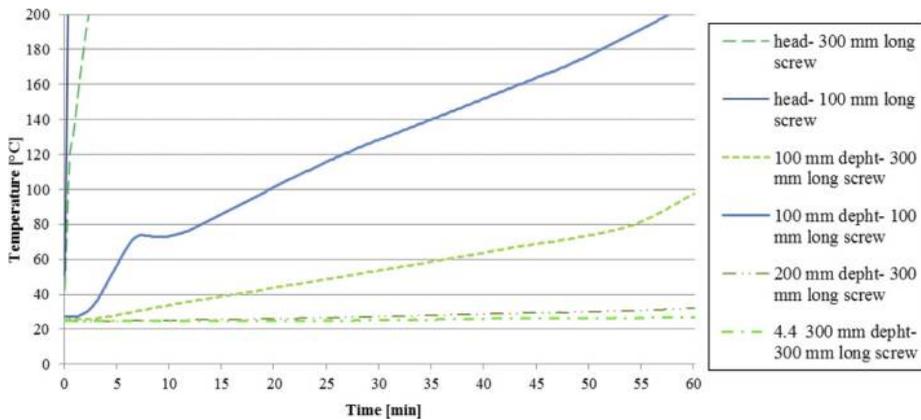
Figure 13.
Temperature
development for two
counter sunk head
full thread screws
d_{nom} 8 mm

Table IV.
Temperature
distribution along
200 mm long full
thread screws after
60 min fire exposure

	Head (0 mm)	Mid length (100 mm)	Tip (200 mm)
d_{nom} = 6 mm	900°C	60°C	35°C
d_{nom} = 12 mm	900°C	110°C	60°C

No.	Fire exposure (min)	F_{fi} (kN)	$F_{k,calculated}$ (kN)	Proportion η $F_{fi}/F_{k, calc.}$
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

Table V.
Load-bearing
capacities of full
thread screws

4.2.2 Influence of steel grades to temperature distribution. The assessed screws made
from stainless steel performed better than the carbon steel screws. The better
performance was shown by lower temperatures along the screws and less charring of
wood in contact with screws.

Temperature measurements in the middle of the carbon steel screws were about 80°C
higher than in stainless steel screws. The screw tips only showed a temperature
difference of about 30°C after 60 min. This behavior is caused by the different thermal
conductivity of the screws. Carbon steel has a significantly higher conductivity than
stainless steel at an ambient temperature. Therefore, the heat is better conducted in
greater depth, resulting in higher temperatures within the screw and timber. With
increasing temperature, both thermal conductivities are approaching and behave in the
same way from 800°C onward, whereby the resulting temperatures equalize again.

4.2.3 Side distance. The temperature profile of full thread screws and the
surrounding timber in primary–secondary beam connections is substantially influenced
by the side distance $a_{4,c}$. The screw is protected from heat by the wooden side coverage,
which is steadily converted into charcoal and, therefore, reduced during the fire
exposure. If there is a sufficient side distance, the temperature influence on the screw is

mainly influenced by the head exposure. The temperatures of the screw heads in the secondary beams showed a linear increase in the beginning, until after 20 min a maximum temperature of about 800°C was reached and held to the end of the test (measuring point A1, see. Figure 5). Screws exposed to the fire for 30 min with a side distance of $a_{4,c} = 3 \times d_{nom} + (\beta_n \times t + d_0)/2$ [mm] showed temperatures below 160°C at the measuring point in the middle (A2). Screws with a 60-min exposure needed a side distance of $a_{4,c} = 3 \times d_{nom} + (\beta_n \times t + d_0)$ [mm] (according to EN 1995-1-2) to keep the temperatures below 220°C. The comparison between the A2 temperatures with the temperatures which have to be expected in the same depth at one-dimensional heat flux shows a clear difference. The differences can be explained with the additional influence caused by the head exposure.

4.2.4 Load-bearing capacity and load-bearing behavior. Connections using full thread screws deform only marginal during the time of fire exposure, provided that sufficient side coverage of the screws exists. The deformation behavior may be described as brittle, similar as under ambient conditions (see Figure 14). Failure occurs by pulling out the screws. The relative displacement of about 35 to 40 mm occurs only after 30 resp. 60 min by increasing the load until failure.

The load ratios $\eta = F_{fi}/F_{k,\ calc.}$ of test no. S1 and S3 are nearly identical (see Table V), although a lower load-bearing capacity of S3 has been anticipated because of the smaller side coverage. Generally, the load ratios reached in the fire tests have been higher than calculated, according to DIN EN 1995-1-2. A side coverage of 29 mm (as in S3) leads to a calculated $\eta = 0.50$, the test measurement is 0.59. Test S4 resulted in the best load ratio of $\eta = 0.84$ because of low charring along the screw. The large side cover of the screw contributed that heat fed in the uncovered screw head could be thoroughly distributed in the surrounding timber by the length of the screw.

5. Conclusion
5.1 General
Based on the results, the connection of joist hanger to the secondary beam appears as a critical area in fire tests and will govern the failure. The results showed that unprotected 50-mm-long fasteners are not long enough to embed in the residual timber cross-section after 30 min and not recommendable for further fire tests with joist hangers. In contrast, fasteners with 70 mm length seem appropriate. For that reason, the position of the wings has no essential influence, although internal wings are positively affecting the strength
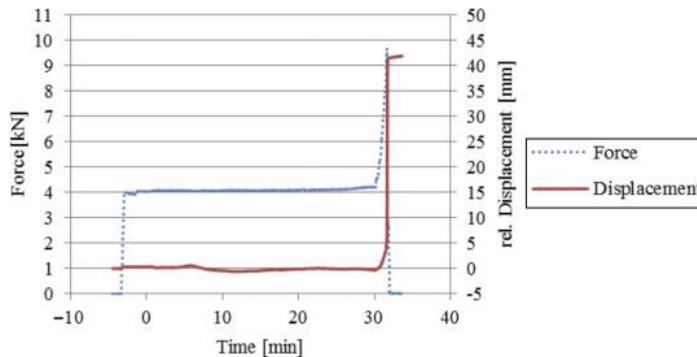
Figure 14.
Typical load-time and displacement-time curve of a full thread screw connection

of the connection at the main beam. In the interest of a maximum in strength during fire exposure, the gap between the timber beams should be as small as possible. For practical reasons, a compromise is necessary, a gap size of 4 mm like in the tests conducted seems appropriate. A width of at least 140 mm for the secondary beams, i.e. the double of the minimum length of the fasteners of 70 mm seems to be advisable. Therefore, a sufficient remaining cross-section in the area of the connection can be reached. For reasonable cross-sections heights of about 180 mm can be recommended.

To minimize the charring depth and the temperature profile along full thread screws, when directly exposed at the screw head, the use of long screws with small diameters is favorable. Screws made of stainless steel performed better than carbon steel screws. The type of head is irrelevant for the temperature alongside the screws.

Temperatures lower than 220°C in the middle of the screws are resulted by side distances of $a_{4,c} = 3 \times d_{nom} + (\beta_n \times t + d_0)/2$ (according to EN 1995-1-2) for a 30-min exposure and $a_{4,c} = 3 \times d_{nom} + (\beta_n \times t + d_0)$ for a 60-min exposure, respectively.

5.2 Load-bearing capacity and recommendations for the structural design process
5.2.1 Joist hangers. Connections with joist hangers exposed to fire over 30 min are able to bear loads of $0.33 \times F_{k,20°}$, when designed, according to the following recommendations:

- joist hangers Type 05, according to ETA 08/0264, or equivalent;
- minimum cross-section of joist of 140×200 mm;
- use of full thread screws 5×70 mm in all holes, in two rows over the entire height of the joist hanger;
- gap between joist and header max 4 mm;
- position of the wings possible for both inside and outside; and
- a/h > 0,7 (according to DIN EN 1995-1-1).

Identical connections, but made up with ring shank nails 4×70 mm instead of screws, are able to bear loads up to $0,19 \times F_{k,20°}$. The lower load-bearing capacity can be explained by the lower pull-out resistance of the nails.

It is assumed, that bigger cross-sections of joists lead to a better load-bearing ratio because side influences from the upper and lower edge are relatively smaller, and the calculated load-bearing capacity increases linearly with the height of the joist. Protection measures, e.g. fire protecting coating, cladding, and partial exposure to fire are suitable for reaching higher load-bearing ratios. Smaller cross-sections cannot be recommended to be used for load-bearing structures under fire exposure.

5.2.2 Full thread screws. Connections made with full thread screws are able to bear load ratios $F_{fi}/F_{k,20°}$ after 30-min fire exposure of 50 per cent using glued laminated timber, when designed according to the following recommendations:

- sufficient coverage of the screw head;
- side distance $a_{4,c} = \max(\beta_n \times t + 1.6 \times d_{nom}; 29 \text{ mm} + d_{nom}/2)$;
- coverage of the screw tip a_3 of min 29 mm; and
- side distance between screws $a_2 = 2,5 \times d_{nom}$.

To reach the same load ratio over 60 min of fire exposure connections have to be designed as follows:

- sufficient coverage of the screw head;
- side distance $a_{4,c} = 61$ mm $+ d_{nom}/2$;
- coverage of the screw tip a_3 of min 61 mm; and
- side distance between screws $a_2 = 2,5 \times d_{nom}$.

The head coverage is considered as sufficient if the head temperature does not exceed the temperature alongside the screw. The temperature in a certain depth of a timber member can be calculated as follows:

$T(d) = 20 + 180 \times (\beta_n \times t/d)^{0,025 \times t+1,75}$, with

where $T(d)$ is the temperature in depth d due to one-dimensional heat flux induced by ISO time temperature curve; β_n is the design value of fire loss rate; T is the time of ISO fire exposure; and D is the depth of measuring point/timber coverage.

The test specimens where designed to reach a maximal temperature of 150°C at the screw heads. Considering this, a head coverage of 25 mm for 30-min fire exposure is appropriate and has been chosen for the tests, whereas ca. 45 mm is needed for an exposure of 60 min. In the tests with 60-min fire exposure, a coverage of 25-mm timber and 15-mm gypsum plasterboard was used with the same protective effect.

If the screw heads are not protected and equivalent load-bearing capacities are desired, side distances $a_{4,c}$ need to be increased substantially. Recommendations, based on test results and numerical simulations for the design of connections with unprotected screw heads, will be subject of further research and publications by the authors.

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