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FIRE RESISTANCE OF PRIMARY BEAM – SECONDARY BEAM CONNECTIONS IN TIMBER STRUCTURES

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ABSTRACT: Within the German research project “Fire resistance of primary - secondary beam connections in timber structures” solutions for a fire-safe design are being developed. This paper describes a series of small scale fire tests on unloaded specimens, conducted with different joist hangers, full thread screws and dovetail connectors. As a result design recommendations for the subsequent loaded large scale fire tests within the research project and for further practical application will be given.

KEYWORDS: fire resistance, connections, joist hangers, full thread screws, connectors, timber structures

1 INTRODUCTION

Energy and resource efficiency in conjunction with the aspect of sustainability is playing a key role in shaping our future towards a more fossil independent society. Especially bio based construction materials such as wood and wood based products can positively contribute in this development.
In recent years the increasing demand for new, innovative, energy and cost efficient buildings is noticeable all over the world. This is especially true for residential, office and administration buildings as well as for wide span structures, which utilise timber as the primary building material.

There are many benefits of building timber structures, such as visual and tactile attractiveness, high energy efficiency, quick erection time and a low carbon footprint. Despite these advantages, there are substantial concerns and limitations by authorities and design codes related to fire safety for the use of timber as a construction material in modern building.

To consider this aspect appropriately European and international design codes have been developed over the past years to assess the fire safety in buildings. These design rules for fire exposed timber structures such as the ones listed in EN 1995-1-2 [1], NZS 3606 [2], AS 1720-4 [3] or in the U.S. AWC-DCA2 [4] are mostly focused on determining the charring and residual cross section of unprotected and protected linear timber members, like beams and columns.

Traditional timber connections have been successfully used by carpenters in the construction process across generations. However in modern timber engineering these connections are mostly replaced by industrial produced steel and aluminium connectors, screwed connections and CNC manufactured timber to timber connections. These “new” connection systems allow for wider variation in geometry, reduction of overall connection height, transfer of larger loads and a less time consuming manufacture process. The largest proportion of these connections is taken by primary - secondary beam - and joist to column connections.
However, general regulations and design methods to assess the fire safety of these connections do not exist [5] [12]. Furthermore, approved and reliable systems are rare [9], and in addition are not applicable for all geometries. For all other connections including e.g. joist hangers, full thread screws, concealed dovetail connectors and joist ties (see Figure 1), which are currently the most common used systems, a general understanding about fire safe design or technical approvals does not exist. Hence, proving fire safety becomes quite challenging and complex, resulting in different approaches among engineers.

To overcome this gap of knowledge, a German research project has been started in 2013. It seeks to investigate the thermal and structural performance of typical engineered connections for timber structures in the event of fire. The investigations include joist hangers, screwed connections, concealed joist ties and corbels.

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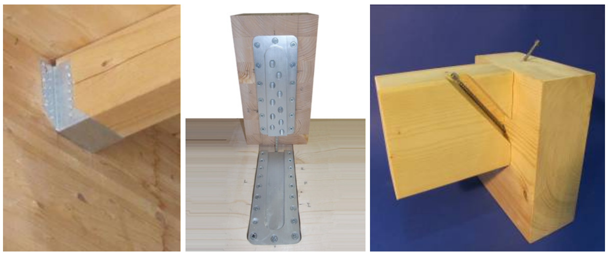

***Figure 1:** typical joist connections for timber structures (from left: joist hanger, dovetail connector, full thread screws)*

2 CONCEPT OF INVESTIGATIOS

The investigations conducted in this research project are based on a three pillar strategy (I – III).

I. small scale fire tests on unloaded specimens: to assess the influence of geometry and material interaction

II. mechanical testing of connections at ambient conditions: under consideration of the results and residual cross sections gained in step I

III. full scale fire tests on loaded specimens for selected and optimised connections: based on the results gained in the previous steps I and II and the associated FE modelling

Since all experimental investigations only allow a limited number of tests, the results will be extended by numerical modelling, for further parametrical studies and optimisation process.

3 EXPERIMENTAL EXAMINATIONS

The following paragraphs provide details about the design and experimental results of the conducted small scale fire tests on unloaded members of step I.

3.1 GENERAL CONFIGURATIONS AND SMALL SCALE TEST SETUP

3.1.1 Testing Facilities

All conducted small scale tests were carried out at the fire tests facility of MFPA Leipzig GmbH in Germany. Each of the unloaded U-shaped specimens was assembled on one CLT floor and two CLT wall panels with a thickness of 100 mm. The 3-layered CLT panels were used as supporting structure, representing the primary beams. At the inner side of the CLT wall panels 300 mm long glulam- as well as sawn timber beam sections were attached with joist hangers, fully threaded screws and aluminium dovetail connectors, 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 for the examined connections.

All timber members were of spruce with a moisture content of approximately 12 %.

The resulting U-shaped specimens were placed in a diesel fired furnace, as shown in Figure 3, and exposed to the standard fire curve in accordance with EN 1991-1-2 [7] for 30 and 60 minutes.

3.1.2 Instrumentation

Type-K thermocouples were applied inside the timber members at the connectors and fasteners to measure the increase in temperature and identify critical configurations. For selected nails and screws thermocouples were welded to the head and tip as presented in Figure 6, to ensure a precise measurement at the fasteners. These specific fasteners were placed in predrilled holes with 3 mm diameter. The attached thermocouples were also fed through the holes to the fire unexposed side. The remaining areas of the holes were sealed with mastic afterwards.

To control the furnace temperatures four plate thermocouples were installed in accordance with EN 1363 - 1 [6]. In addition, four sheath thermocouples were installed to measure local temperatures close to the surfaces of the connections.

***Figure 2:** assembled specimen with measurement equipment before placed into the furnace*

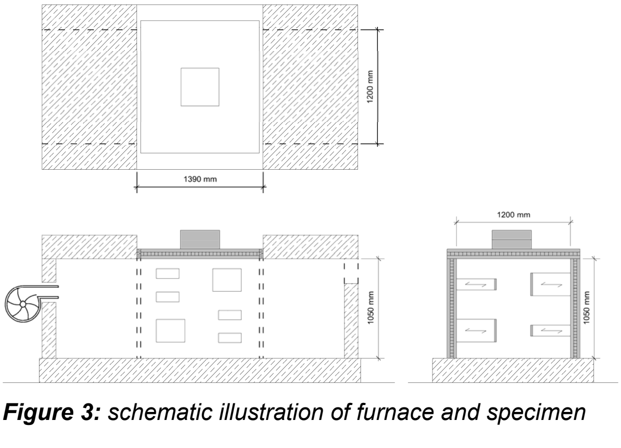

***Figure 3:** schematic illustration of furnace and specimen*

3.2 INDIVIDUAL TEST SETUP

In order to cover a wide spectrum of configurations the tests were carried out with variation of beam dimensions, type of connectors, fasteners and joint design.

3.2.1 Joist Hangers

In the conducted fire tests two sizes of joist hangers for beam dimension of W x H = 100 mm x 240 mm and 200 mm x 300 mm were investigated, each for internal and external wings. The Joist hangers were made of galvanized zinc coated 2 mm thick steel sheets. To fasten the joist hangers to the beam sections and CLT wall elements rink shank nails with diameter of 4 mm and screws with nominal diameter d_n of 5 mm (core diameter 3.3 mm) were used. Both types of fasteners had a length of 50 mm and 70 mm. For all setups, the 50 mm long fasteners were applied at the right side and the 70 mm long fasteners at the left side of the symmetrical joist hangers. An exception was made for the 100 mm wide beams, where only 50 mm long fasteners were used to fasten the beam to the joist hangers. Either screws or nail were used per joist hanger. Therefore in total eight different combinations were assessed. To measure the increase in temperature, thermocouples were installed for each configuration at fastener heads and tips, in the joint between connector wings and timber members, and in the gap between beam sections and wall elements as illustrated in Figure 4. In order to ensure practical conditions the beam sections were fastened in all setups with a gap of 7 mm to the CLT elements (steel sheet thickness + fastener head). No further protection measure was applied to these gaps.

The fire tests with joist hangers were carried out for 30 minutes.

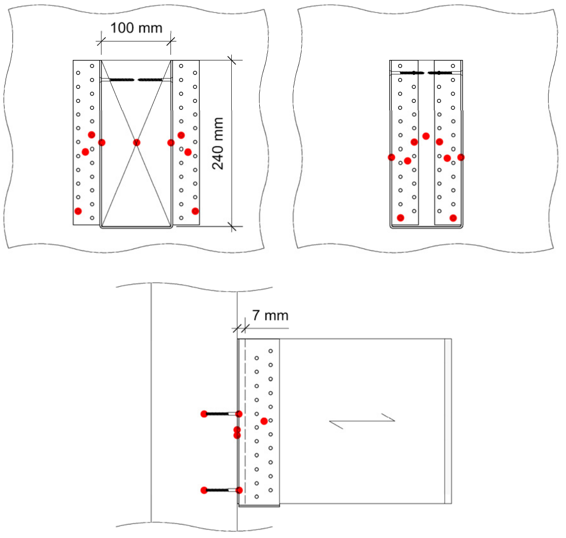

Figure 4: *exemplary test setup for joist hangers*

3.2.2 Full Thread Screws

In order to investigate the effect of screw length, diameter, shape of screw head and type of steel on the temperature development and charring rate of timber, nine screws were installed into each CLT ceiling element, as presented in Table 1, and examined in 30 and 60 minute lasting fire tests. To enable the assessment of up to 300 mm long screws the CLT ceiling elements were backed by two additional CLT panels with100 mm thickness each (see Figure 5).

Table 1: *Assessed full thread screws*

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

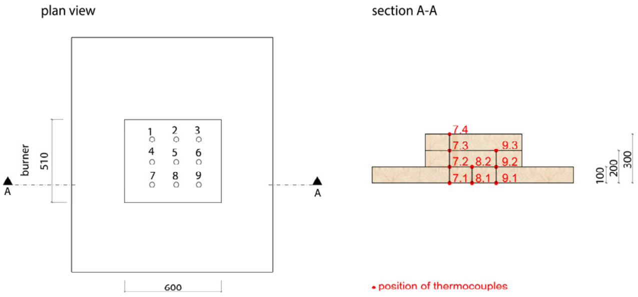

Figure 5: *position of full thread screws in the CLT ceiling element with corresponding measuring points*

Thermocouples were attached to all heads and tips of the screws, as depicted in Figure 6. In addition, the temperatures for the 200 mm long screws were measured at half-length, and for the 300 mm long screws at 1/3 and 2/3 of the total length, as illustrated in Figure 5.

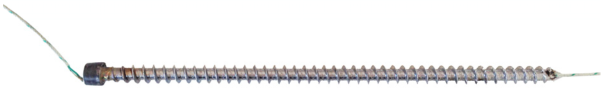

Figure 6: *laser welded thermocouples attached to a full thread screw*

Furthermore the interaction of edge distance $a_{4,c}$ and the thermal influence of the unprotected screw heads were of special interest and examined in the fire tests. Therefore beam sections were attached to the CLT wall panels by crosswise installed pairs of screws. Six beam sections have been tested for 30 minutes and ten for 60 minutes. The screws used in the fire tests had dimensions (d_n x length) of 6 mm x 160 mm and 12 mm x 300 mm and screwed were in under 45°.

Following edge distances were examined as protecting wood covering:

a) $a_{4,c} = 3 \cdot d_n$ [mm] (in accordance with EN 1995-1-1)

b) $a_{4,c} = 3 \cdot d_n + \beta_n \cdot t + d_0$ [mm] (according to EN 1995-1-2)

c) $a_{4,c} = 3 \cdot d_n + (\beta_n \cdot t + d_0)/2$ [mm] (half between a) and b))

Furthermore the influence on the temperature development of different gap sizes between primary and secondary beams was assessed.

The position of thermocouples attached to each setup can be seen in Figure 7.

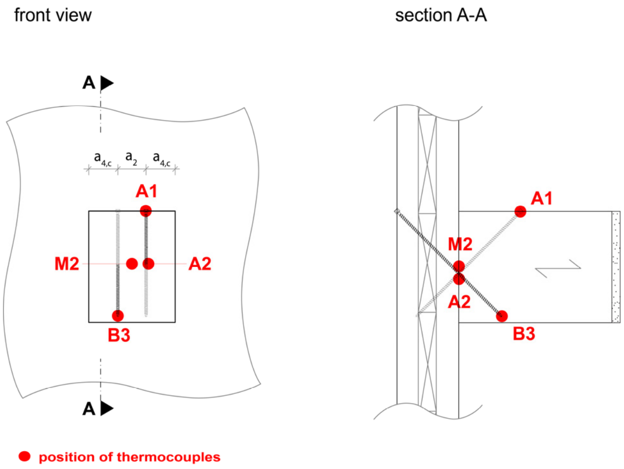

***Figure 7:** crosswise installed full thread screws and position of thermocouples in the connection*

3.2.3 Dovetail Connectors

In a third series of tests concealed aluminium dovetail connectors were investigated under variation of edge distance (protective side cover, a_{fi}) with 30 and 60 minutes fire exposure. Here, three different sizes of side covering were examined, each for the smallest (type G: W x H = 45 mm x 60 mm) and the largest (type F: W x H = 75 mm x 200 mm) size of the tested dovetail connectors. A summary of the assessed setups is given in Table 2. The connectors were installed without a gap between beam sections and wall panels by placing the connectors into milled notches in the timber members, as shown in Figure 8. The influence of gap sizes and further protection methods were examined in additional fire tests [10].

***Table 2:** Configuration of assessed parameters in fire tests with dovetail connectors*

configuration	1.1	1.2	2.1	2.2	3.1	3.2
type	G	F	G	F	G	F
duration of fire exposure [min]	30		30		90	60
protective side coverage a_{fi}	according to technical approval $a_{fi\ (above,\ below)} \geq$ 15 mm $a_{fi\ (left,\ right)} \geq$ 12,5 mm		at all sides $a_{fi} \geq 31$ mm		at all sides $a_{fi} \geq 55$ mm	
selected beam W/H [mm]	70/90	100/230	120 /120	140 /260	160 /180	180 /300
installation of connector	concealed no gap between primary beam and secondary beam					

In all setups thermocouples were attached to both aluminium plates of each connector at various positions, as depicted in Figure 9. The temperatures of screws, connecting the aluminium plate to the timber members were not measures in this test series.

The tests aimed to determine the appropriate dimension of side coverage a_{fi} with timber, which protects the connectors on all sides from direct fire exposure and avoids an temperature increase in the aluminium members up to a critical level (according to EN 1999-1-2 [8]).

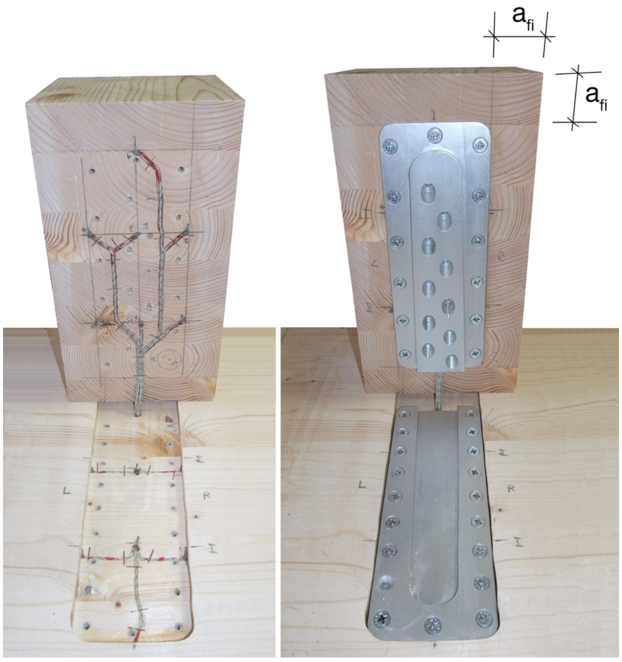

***Figure 8:** dovetail connector and installed thermocouples*

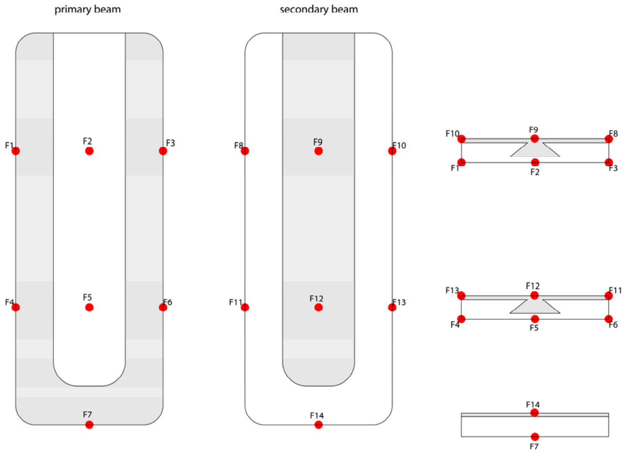

Figure 9: *position of thermocouples on dovetail connectors*

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, which is in contact with the metal fasteners is mainly influenced by the type of fastener. The unprotected fasteners conducted the heat from the surface into the interior of the timber members, resulting in a larger charring depth compared to free undisturbed areas of the beams not adjacent to the fasteners (see Figure 10).

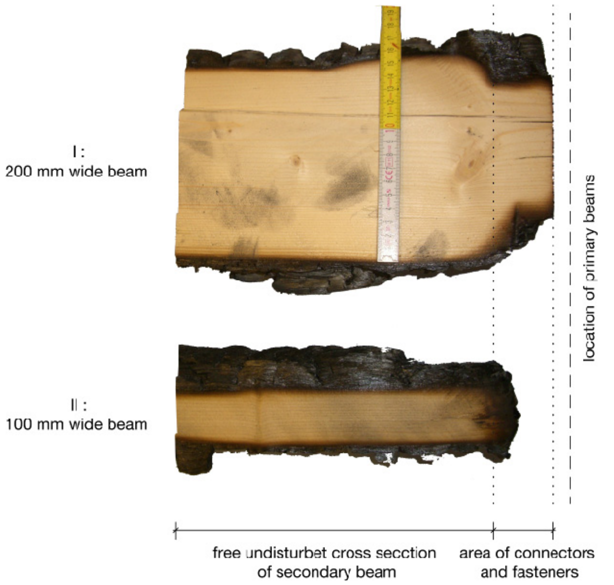

Figure 10: *horizontal section through fire exposed secondary beams – influence of fasteners visible on the right side of the beams*

The examined screws with a nominal diameter of 5 mm (3.3 mm core diameter) performed better than the 4 mm nails with same length, resulting in more slowly heating curves within the temperature measurements of the screw tips. A less charring of wood in contact with the screws and the magnitude of discolouration alongside the removed fasteners confirmed this result too, see Figure 11. The 70 mm long screws showed no change in colour and were still metallic bright up to a length of 35 mm from the tip, while the nails were coloured black along their entire length.

According to the observations during the dismantling of the specimens, the gripping capacity of screws could be assumed to be much higher than for the corresponding rink shank nails, due to their threads and less charring.

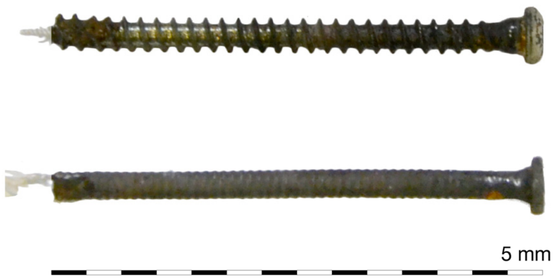

Figure 11: *removed screw 5x70 and rink shank nail 4x70*

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 was used. For example the tip temperatures of the 4 x 50 mm rink shank nails reached 450 °C whereas only 250 °C occurred for the 4 x 70 mm nails after 30 minutes fire exposure, see Figure 12. In contrast, the nail heads showed significant lower differences in temperature with values between 700 °C and 730 °C.

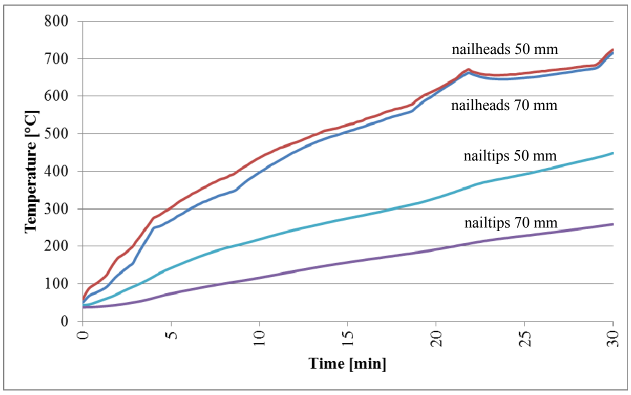

Figure 12: *temperature development in rink shank nails 4x50 and 4x70 (mean values)*

4.1.2 Influence of Joist Hanger Geometry

The 100 mm wide secondary beams showed either no or only little residual cross sections in the area of the joist hangers, and therefore were classified to be too slender for further examination, see Figure 10 (II: 100 mm wide beam). Some of these 100 mm wide beam sections already fell down after the fire test, as a result of the extra time it took to remove the complete specimen from the furnace.

Connectors with internal wings showed significant lower temperatures (up to 200 °C) than those with external wings on the surface of the CLT wall element (primary beam). A similar difference was not recorded in the measured temperatures between connector and secondary beams. In this area the surface temperatures and charring was governed by the influence of the direct fire exposure.

The gaps between the wall elements (primary beam) and the beam sections (secondary beam) had significant influence to the charring behaviour of the connections. Larger gap sizes led to an additional exposure at the end grain side of the attached beam sections and increased the charring due to “the almost five-sided fire exposure”. To reduce charring in these areas and consequently maintain the load bearing capacity of the connections, the gap size should be as small as possible or supplemented with a fire retardant sealing or covering on the top side.

4.2 FULL THREAD SCREWS

4.2.1 Influence of Screw Dimension

The length of the full thread screws had a great influence on the measured temperatures if exposed on the unprotected head side. This effect is confirmed by the previously presented results of fasteners for joist hangers.

The comparison of the temperatures in the same embedment depth of 100 mm and 300 mm long full thread screws, with same diameter, shows lower temperatures for the longer screws. This difference in temperature ΔT rises with increasing distance from the exposed surface. In a depth of 100 mm the measured difference was about 100°C after 60 minutes fire exposure, as depicted in Figure 13. This difference was caused by the larger contact surface and the ability of the longer screw to penetrate with its tip in more distant and cooler timber. Further the larger thermal capacity of the longer screw also has some influence.

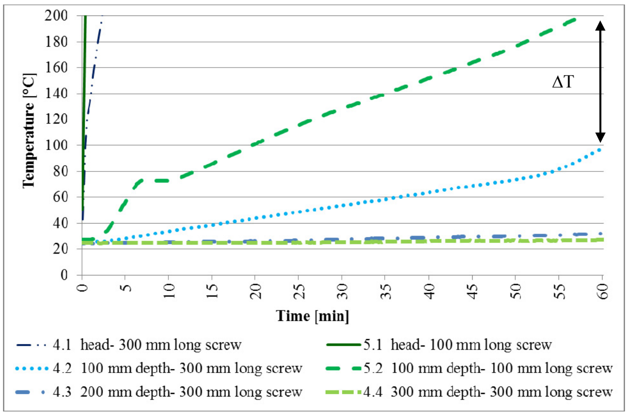

Figure 13: *temperature development for two counter sunk head full thread screws (d_n = 8 mm)*

The results obviously reveal that the screw diameter is influencing the temperature at the screws too.

In the early stages of fire exposure the screws with 6 mm diameter showed higher temperatures at the screw heads than the one with 12 mm diameter. After about 20 minutes the head temperatures were comparable to each other again. In contrast all temperatures along the screws with 6 mm diameter lay below the corresponding temperatures of screws with 12 mm diameter as shown exemplarily in Table 3.

Table 3: *Temperature distribution along a 200 mm long full thread screw after 60 minutes fire exposure*

nominal diameter d_n	head (0 mm)	mid length (100 mm)	tip (200 mm)
6 mm	~ 900°C	60°C	35°C
12 mm	~ 900°C	110°C	60°C

The temperature distribution in Table 3 can be explained by the fact that the peripheral surface increases linearly, while the cross section area increased quadratic with the diameter of the screw.

The examined variations in screw head shape showed no significant influence on the temperature distribution in the screws.

4.2.2 Influence of Steel Type

The assessed screws made of stainless steel performed better than the carbon steel screws with same dimensions. This was evident from lower temperatures along the screws and less charred wood in contact with the screws.

The temperature measurements of the screw heads showed similar results for both stainless and carbon steel screws over the entire duration of fire exposure. At the beginning of the tests (until minute 20), however about 10 - 20°C higher temperatures were recorded on the stainless steel screws. In contrast, the temperatures along the screws showed an opposite behaviour during the entire fire test, as presented in Figure 14. The measured temperatures in the middle of the carbon steel screws were about 80°C higher than at the stainless steel screws. The screw tips showed only a temperature difference of about 30°C after 60 minutes.

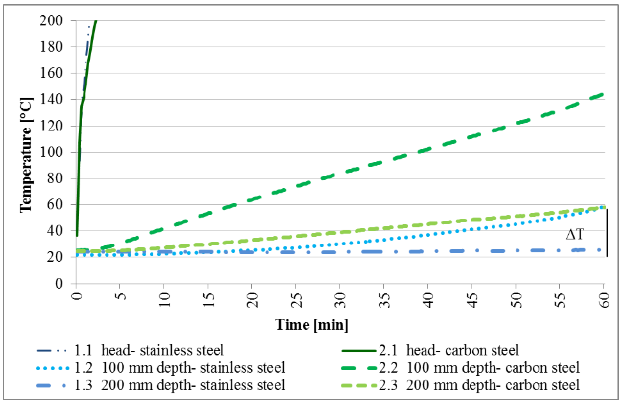

***Figure 14:** temperature development in 200 mm long stainless- and carbon steel screws (d_n = 10 mm)*

This behaviour is caused by the different thermal conductivity of the screw types. Carbon steel has a significant higher conductivity as stainless steel at ambient temperature. Therefore, the heat is better conducted into greater depth, resulting in higher temperatures within the screws and in the timber members. With increasing temperatures both thermal conductivities approach and behave in the same way from 800°C onwards, whereby the resulting temperatures equalize again.

4.2.3 Edge Distance

In addition to the dimension and type of screw the temperature profile of full thread screws in a primary - secondary connections is also affected by the edge distance a4,c.

The screws are protected against heat by the wooden side coverage, which is continuously converted into charcoal and therefore reduced during fire exposure. If sufficient edge distance $a_{4,c}$ is provided at all sides, the temperature in the screws are mainly influenced by the fire exposed head.

The temperatures of the unprotected screw heads in the secondary beams showed an almost linear increase during the beginning (until minute 30), and with increasing time approached slowly the furnace temperature. In both test series the screw heads showed a maximum temperature of approximately 800 - 900°C after 30 and 60 minutes exposure, respectively.

Screws exposed for 30 minutes to the fire, with an edge distance of $a_{4,c} = 3 \cdot d_n + (\beta_n \cdot t + d_0)/2$ showed temperatures below 160 °C at the measuring point – A2 (see Figure 7) in the middle of the screw length. The screwed connections with 60 minutes exposure required an edge distance of $a_{4,c} = 3 \cdot d_n + (\beta_n \cdot t + d_0)$ to keep the temperatures below 220 °C.

A comparison of temperatures at measuring point - A2 with temperatures which can be expected under one-dimensional fire exposure in the same depth (see annex B [1] or [9]) showed significant differences. The differences in temperature can be explained with the additional thermal influence caused by the head exposure. The influence of the screws on temperature development and charring was more pronounced in the 60 minutes fire tests as in the 30 minutes tests.

The measuring points – M2 in the centre of the connections recorded temperatures of about 100 °C for a considerable long period of time, which can be explained by the migration of moisture and following phase change reaction.

The tests with gap sizes of up to 1 mm between primary and secondary beam showed no additional impact on the temperature development within the connection.

4.3 DOVETAIL CONNECTORS

4.3.1 Influence of Dimension

Timber beams with dovetail connectors exposed 30 minutes to fire and mounted with a wood coverage a_{fi} of 15 mm at all sides (configuration 1.1 and 1.2 in Table 2) showed remaining cross sections which were partially smaller than the connector (see Figure 15), which led to directly exposed fasteners. Consequently temperatures of more than 300 °C were recorded at the aluminium connectors.

***Figure 15:** remaining cross section after 30 minutes fire test with insufficient wood coverage (connector type G)*

Further tests with a wood coverage a_{fi} of 31 mm at all sides showed temperatures at the connectors between 96 °C and 104 °C after 30 minutes.

Similar results were obtained in the 60 minutes test (specimen 3.2) with and wood coverage a_{fi} of 55 mm.

For these tests the recorded temperatures, remaining cross sections (see Figure 16) and thickness of uncharred timber give reason to expect a sufficient load bearing capacity for practical application under fire conditions.

For test specimen “3.1” with a wood coverage a_{fi} of 55 mm maximum temperatures of 100 °C were measured up to 75 minutes. After 75 minutes a significant and almost linear increase in temperature was recorded up to 90 minutes. This can be explained by the ending of moisture vaporization contained in the timber. The temperature reached values between 170 and 215 °C after 90 minutes.

Aluminium shows a temperature dependent reduction in strength down to about 42 % at 215 °C (according to [5]) compared to the strength in cold condition, which is not sufficient in terms of load bearing capacity in the case of fire.

The chosen coverage a_{fi} of 55 mm for an exposure to fire of 60 minutes may be reduced due to the results of the 90 minutes tests (specimen 3.1). As the temperature didn't increase significantly until the 75th minute in the 90 minutes test, the charring which took place between minute 60 and 75 may be subtracted from 55 mm wood coverage. A subtraction of 0.8 mm/min · 15 min = 12 mm leads to a minimum coverage of 43 mm.

A similar optimisation for the specimens with 31 mm wood coverage is aspired, but has to be verified in further tests.

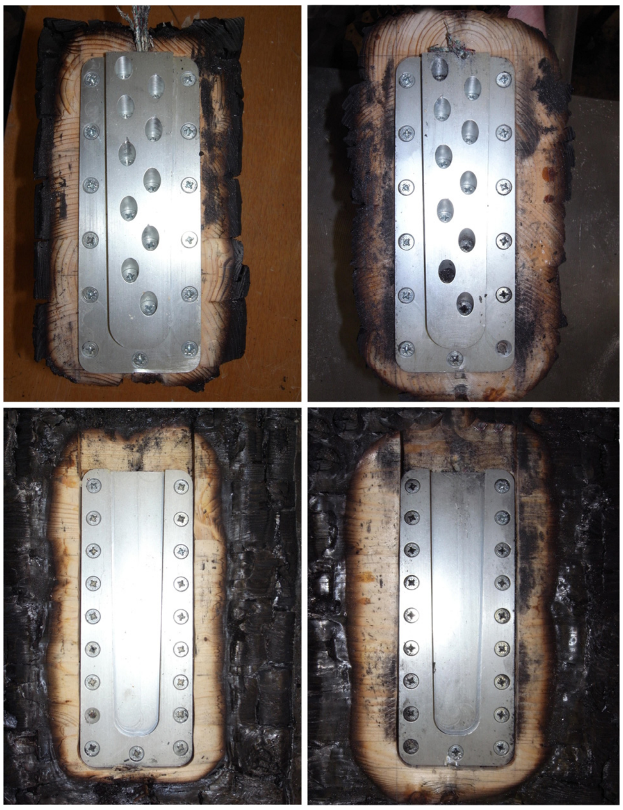

Figure 16: *remaining cross sections after 30 minutes (left) and 60 minutes (right), connector type F*

4.3.2 Gaps and Joints

According to technical approvals the connectors may either be mounted with (face mounted) or without (milled in) a gap between the primary- and secondary beam. All test results presented so far were obtained with a gap less than 1 mm.

For comparative tests to investigate gap influence connectors were placed in notches milled in the main beams. In case of fire the all-sided wood coverage a_{fi} hereby acts as insulation for the aluminium connectors. The direct topside exposure of the connector to fire may be avoided by inserting piece of timber into the remaining notch, which leads to a complete coverage.

For face mounted connectors, a gap with the thickness of the connector remains open between the timber members. From the standpoint of fire safety, this gap is unfavourable, as the aluminium parts are directly subjected to the flames, and therefore heat up rapidly. In the production process, however, this option is faster and easier to fabricate, as milling in notches into the main beam. An optimisation regarding fire safety can be realised by inserting intumescent materials in the remaining gap, which expand and close the gaps under fire exposure [10].

5 CONCLUSIONS

This paper describes a series of small scale furnace tests under standard fire exposure on unloaded primary beam secondary beam connections with joist hangers, full thread screws and concealed aluminium dovetail connectors. The examinations have shown that bare metal fasteners and connectors influence the behaviour of the connections significantly, by increasing the heat conducted into the connection and the charring of timber. The obtained results, as first step in the ongoing research project, confirm and extend the existing knowledge [12] - [18] about fire resistance of connections in loadbearing timber structures.

Pin Shaped Fasteners

Metal fasteners such as nails and screws without any protection at the heads act as „thermal bridges" and conduct the heat inside the connection rapidly. The results have shown that larger diameters stimulate the charring of the surrounding timber especially in the later stage of the exposure. The use of long and skinny fasteners results in lower temperatures and charring of wood in contact with the fasteners.

Joist Hangers

Based on the results, the joint of joist hanger to the secondary beam appears as a critical area under fire conditions, and will govern the failure. The results have shown that unprotected 50 mm long fasteners are not long enough to still embed in the residual timber cross section after 30 minutes and therefore are not recommendable for further fire tests with joist hangers. In contrast, fasteners with 70 mm length seem sufficient and thus appropriate. For that reason the position of connector wings has no essential influence, although internal wings are positively affecting the strength of the connection at the main beam. In the interest of a maximum fire resistance, the gap between the timber beams should be as small as possible. For practical reasons a compromise is necessary. A gap size of 7 mm as in the conducted tests seems appropriate for the further examination. A width of secondary beams of at least 140 mm, i.e. double the minimum length of the fasteners of 70 mm, seems to be advisable. Thereby a sufficient remaining cross section in the area of the connection can be achieved. For reasonable cross sections a beam height of about 180 mm may be recommended.

Full Thread Screws
Favourable for minor charring depth and low temperature of full thread screws is the use of long screws with small diameters. Screws made of stainless steel heat up more slowly than carbon steel screws. The assessed types/shapes of screw heads are irrelevant for the temperature alongside the screws. The greater the edge distance $a_{c,4}$, the smaller is the influence of the fire on the screw temperature. Temperatures below 220 °C in halfway embedment of the screws can be reached by edge distances of $a_{4,c} = 3 \cdot d_n + (\beta_n \cdot t + d_0)/2$ and $a_{4,c} = 3 \cdot d_n + (\beta_n \cdot t + d_0)$ for a 30 minute exposure and for a 60 minute exposure, respectively.

Concealed Connections
Dovetail connectors made of aluminium and mounted without a gap (≤ 1 mm) should be covered by timber at all sides, with minimum thickness of 31 mm and 43 mm for 30 and 60 minutes fire exposure, respectively. Connectors mounted with gap should be protected be means of intumescent materials alongside the bare sides of the connector.

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