8th International Conference on Structures in Fire
Guo-Qiang LI, Venkatesh K. R. KODUR, Shou-Chao JIANG, Jian JIANG, Su-Wen CHEN, Guo-Biao LOU (Eds.)
Shanghai, China, June 11-13, 2014

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

Veronika Hofmann*, Martin Gräfe*, Norman Werther* and Stefan Winter*

* Ingenieurfakultät Bau Geo Umwelt
Technische Universität München, Arcisstrasse 21, 80333 München, Germany
e-mails: veronika.hofmann@tum.de, m.graefe@tum.de, n.werther@tum.de, winter@tum.de

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

Abstract. *This research project deals with the fire resistance of primary beam - secondary beam connections in timber structures. The main objective concerns the fire safety design of joist hangers, full thread screws and dovetail connectors. This paper describes a series of small scale furnace fire tests in different configurations of these types of connectors. In conclusion design recommendations are given.*

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 special constructions. The benefits of building in timber are visual and haptic 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 EN 1995-1-2 [1], NZS 3606 [2] or in the U.S. AWC-DCA2 [3] 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 [4]. Approved and reliable systems are rare.

To overcome this gap of knowledge a German research project has been started early in 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 and dovetail connections (see Figure 1).

Figure 1. Typical joist connections for timber structures. From the left: joist hanger, dovetail connector, full thread screw.

2 CONCEPTION OF INVESTIGATIONS

2.1 Methodical approach

Since 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 process.

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),
(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 FE modelling.

3 EXPERIMENTAL TESTING

3.1 General configurations and setup of small scale tests

3.1.1 Testing Facilities

The unloaded U-shaped specimens were assembled each of one CLT floor and two CLT wall panels with a thickness of 100 mm. The 3-layered CLT panels were used as support structure representing the primary beams. At the inside 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 aluminum dovetail connectors, respectively, as illustrated in Figure 2. All beams were orientated in such a way that each bottom side was facing to 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 fuel fired furnace, as shown in Figure 2 and exposed to ISO 834 fire for 30 and 60 minutes, respectively. The tests were carried out under variation of beam dimension, type of connectors and fasteners as well as joint dimension to cover a wide spectrum of configurations.

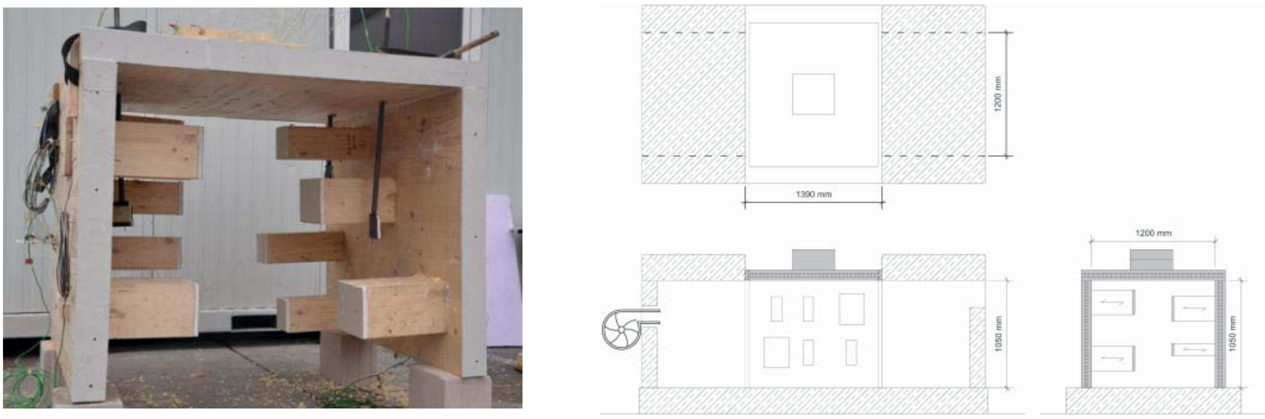


Figure 2. Left: assembled specimen with measurement equipment, right: drawing of furnace and specimen.

3.1.2 Instrumentation

Temperature measurements during the fire tests were realized by 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 predrilled holes in the timber members and sealed at the fire unexposed side with mastic.

3.2 Individual setup

3.2.1 Joist Hangers

In the conducted fire tests two sizes of joist hangers for beam dimensions of W × H = 100 mm × 240 mm and 200 mm × 300 mm have been investigated, each for internal and external wings. The joist hangers were made of 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 nominal diameter of 5 mm (core diameter 3.3 mm) have been used as fasteners. Both types were 50 mm 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 beams to the joist hangers. Either screws or nail were 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. In order to ensure practical conditions the beam sections were fastened with a gap of 7 mm to the CLT elements (thickness of steel sheet + fastener head) in all setups. No further protection measure was applied to these gaps. The fire tests with joist hangers were conducted for 30 minutes.

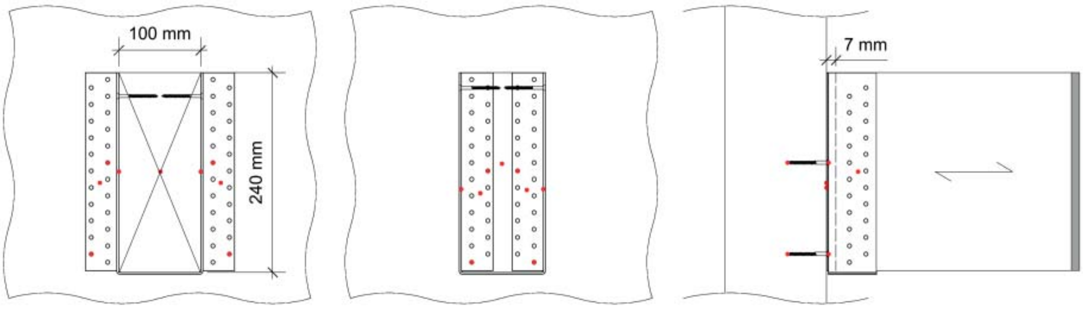


Figure 3. Exemplary fire test setup for joist hangers.

3.2.2 Full Thread Screws

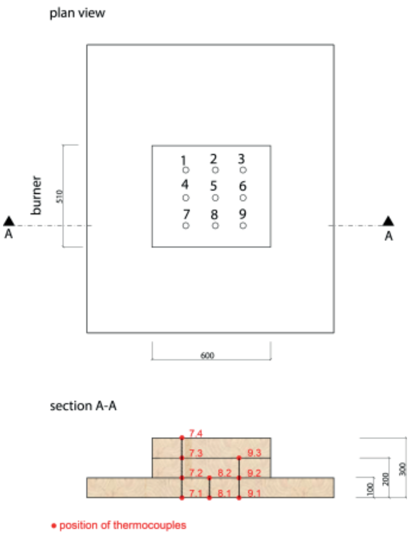
In order to investigate the effect of screw length, diameter, shape of screw head and steel type to the temperature development and charring rate of timber, nine screws have been installed into each CLT ceiling element, as presented in Figure 4 and examined in 30 and 60 minutes fire tests. To enable 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 (see Figure 4).

To all heads and tips of the screws thermocouples were attached. 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 4.

The interaction of edge 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. Six beam sections were tested for 30 minutes tests and ten for 60 minutes. The screws used in the fire tests had dimensions ($d_{nominal}$ x length) of 6 mm x 160 mm and 12 mm x 300 mm respectively and screwed in under 45°. Following edge distances were examined as protecting wood covering:

a) $a_{4,c} = 3*d_{nominal}$ (in accordance with EN 1995-1-1)
b) $a_{4,c} = 3*d_{nominal} + \beta_n*t + d_0$ (according to EN 1995-1-2)
c) $a_{4,c} = 3*d_{nominal} +(\beta_n*t + d_0)/2$ (half between a) and b))

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



number	nominal screw diameter - $Ø_n$ [mm]	screw length [mm]	steel type	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.

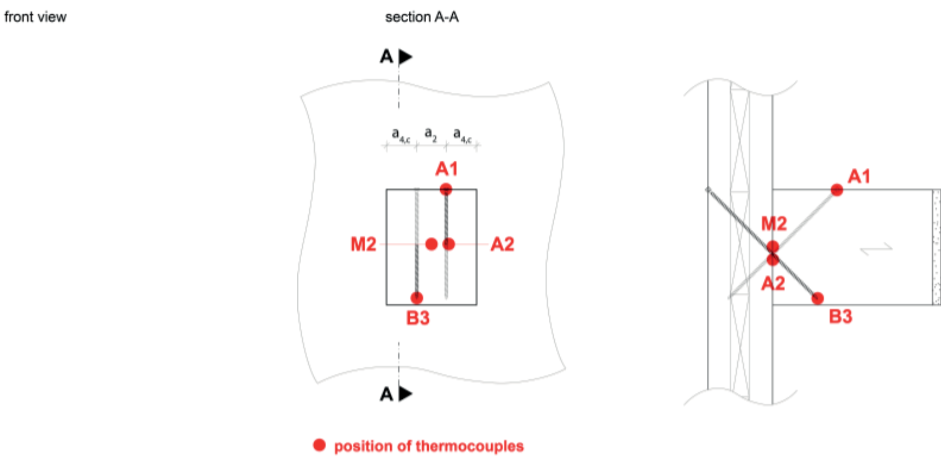


Figure 5. Crossed screws and position of thermocouples in the connection (schematic illustration).

3.2.3 Dovetail Connectors

In a third series of tests concealed aluminum dovetail connectors were assessed under variation of edge distance (protective side cover, a_{fi}) for 30 and 60 minutes fire exposure. Here three different sizes of side covering were examined, each for the smallest (type G: W × H = 45 mm × 60 mm) and the largest (type F: W × H = 75 mm × 200 mm) size of dovetail connector used in this test series. A summary of the assessed setups is given in Table 1. The connectors were installed without a gap between beam sections and wall panels by inserting the connectors into milled notches in the timber members. The influence of gap sizes and further protection methods were examined in additional fire tests [7].

In all setups thermocouples were attached to both aluminum plates of each connector at various positions. The temperatures of screws connecting the aluminum plate to the timber members were not measured.

The tests were conducted to determine the appropriate dimension of side cover by timber, which protects the connectors from direct fire exposure and avoids a critical temperature level of the aluminum (according to EN 1999-1-2 [5]).

Table 1. setup for fire tests with dovetail connectors.

configuration	1		2		3	
type G: 45 mm × 60 mm F: 75 mm × 200 mm	G	F	G	F	G	F
duration of fire exposure	30 minutes		30 minutes		90 minutes	60 minutes
protective side cover a_{fi}	according to technical approval $a_{fi\ (above,\ below)} \geqslant 15$ mm $a_{fi\ (left,\ right)} \geqslant 12{,}5$ mm		at all sides $a_{fi} \geqslant 31$ mm		at all sides $a_{fi} \geqslant 55$ mm	
selected beams W/H [mm]	70/90	100/230	120 /120	140 /260	160 /180	180 /300

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 type of fastener mainly influences the charring of wood in contact with the fasteners. The unprotected fasteners conducted the heat from the surface into the interior of the timber members resulting in larger charring depth than for the free undisturbed area of the beams. The examined screws with nominal diameter of 5 mm performed better than the 4 mm nails with same length. This is evident from the more slowly heating curve of the screw tips and can be also visualized 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 bright up to a length of 35 mm from the tip while the nails were colored black along their entire length. By dismantling the specimens it turned out that the gripping capacity of screws was much higher than for the corresponding rink shank nails, due to 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 was used. For example the tip temperatures of the 4 × 50 mm rink shank nails reached 450°C whereas only 230°C arose for the 4 × 70 mm nails after 30 minutes fire exposure.

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 must therefore be classified as too narrow for further examination. 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.

Connections 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) 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 to the charring behaviour of the connection. Larger gaps 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 this area and consequently maintain the load bearing capacity of the connection the gap size should be as small as possible or supplemented with sealing or top side covering.

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 minutes fire exposure as depicted in Figure 6.

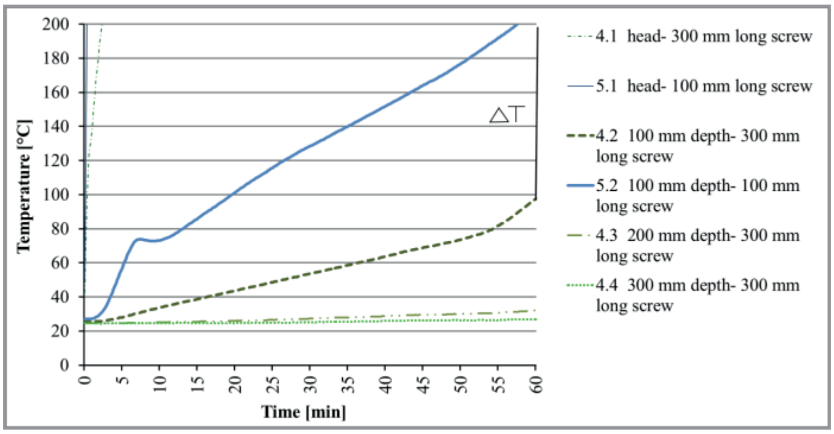


Figure 6. Temperature development for two counter sunk head full thread screws $Ø_n$ 8 mm.

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. Further on 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 $Ø_n$ 6 mm screws showed higher temperatures at the screw heads than those with $Ø_n$ 12 mm. After about 20 minutes these head temperatures were comparable to each other again. Contrary to this all temperatures along the $Ø_n$ 6 mm screws lay below the corresponding temperatures of $Ø_n$ 12 mm screws as shown exemplarily in Table 2.

Table 2. temperature distribution along 200 mm long full thread screws after 60 minutes fire exposure.

	head (0 mm)	mid length (100 mm)	tip (200 mm)
$Ø_n$ 6 mm	900°C	60°C	35°C
$Ø_n$ 12 mm	900°C	110°C	60°C

This temperature distribution can be explained by the fact that the peripheral surface increases linear while the cross section area increases quadratic with the diameter of the screw. The shape of screw head did not have any significant influence to the temperature distribution in the screws.

4.2.2 Influence of steel types 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 have been about 80° C higher than at stainless steel screws. The screw tips only showed a temperature difference of about 30°C after 60 minutes. This behavior is caused by the different thermal conductivity of the screws. Carbon steel has a significant higher conductivity as stainless steel at ambient temperature. Therefore, the heat is better conducted in greater depth, resulting in higher temperatures within the screw and at the timber. With increasing temperature both thermal conductivities are approaching and behave in the same way from 800°C onwards, whereby the resulting temperatures equalize again.

4.2.3 Edge Distance

The temperature profile of full thread screws and the surrounding timber in primary – secondary beam connections is substantially influenced by the edge 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 edge distance, the temperature in the screw is mainly influenced by the fire exposed head. The temperatures of the screw heads in the secondary beams showed a linear increase in the beginning, until after 20 minutes 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 for 30 minutes to the fire with an edge distance of $a_{4,c} = 3*d_{nominal} + (\beta_n*t + d_0)/2$ [mm] showed at the measuring point in the middle (A2) temperatures below 160 °C. Screws with a 60 minutes exposure required an edge distance of $a_{4,c} = 3*d_{nominal} + (\beta_n*t + d_0)$ [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 significant difference. The differences can be explained with the additional influence caused by the head exposure.

4.3 Dovetail connectors

4.3.1 Influence of Dimension

Timber beams with dovetail connectors exposed 30 minutes to the fire and mounted with a wood coverage of 15 mm at all sides showed remaining sections which were partially smaller than the connector, which led to directly exposed fasteners. A further test with the smallest and biggest connector and a larger wood coverage of 31 mm at all sides showed temperatures which gives reason to expect a sufficient strength for a practical use. At the test specimen “4” with 60 minutes fire exposure and wood coverage of 55 mm the remaining thickness of uncharred timber seemed big enough for a sufficient load bearing capacity for practical application. At test specimen “3” with a wood coverage of 55 mm the temperature measurements after 60 minutes reached temperatures between 170 and 215 °C. Aluminum has remaining strength of about 42 % at 215 °C (according to [5]) compared to the strength in cold condition, which is not sufficient for the load bearing capacity in the case of fire. After 75 minutes a significant increase in the temperature measurements was registered, this can be explained by the end of the steam generation due to the moisture content in the timber. The chosen coverage of 55 mm for an exposure of 60 minutes may be reduced due to the results of the tests “3” and “4”. As the temperature didn’t significantly increase until 75th minute in the 90 minutes test, the charring which took place between 60 and 75 minutes may be subtracted from 55 mm. A subtraction of 0.8 mm/min * 15 minutes = 12 mm leads to a minimum coverage of 43 mm.

4.3.2 Gaps

The connectors may be mounted with gaps or completely covered by the timber. If the connector is mounted with a gap, a gap in the thickness of the connector remains between the timber beams. From the standpoint of fire safety the gap is unfavourable, as the aluminum parts are directly subjected to the flames and therefore heat up rapidly. Result will be a faster softening of the aluminum and an increased charring rate alongside the fasteners. In the production process this option is faster and easier to fabricate, as milling in notches in the main beam. Optimization for the fire safety can be realized by intumescent fire protection materials placed in the remaining gap (cf. [7]).

For the option without gap the connector is placed in a corresponding notch in the main beam. Therefore it is surrounded at all sides by timber, which acts as an insulation material. The direct exposure to the fire at the top may be excluded by a fitting in piece of timber, which leads to a complete coverage. A protection of such kind leads to a significant lower heating rate and accordingly an increased timespan of sufficient strength.

5 CONCLUSIONS

Based on the results the connection of joist hanger to the secondary beam appears as 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 minutes 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 affecting the strength of the connection at the main beam positively. In the interest of a maximum in strength at fire exposure, the gap between the timber beams should be as small as possible. For practical reasons a compromise is necessary, appropriate seems a gap size of 7 mm like in the tests conducted. A width of secondary beams of at least 140 mm, i. e. the double of 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 reached. For reasonable cross sections heights of about 180 mm can be recommended.

Favourable for the charring depth and the temperature of full thread screws is the use of long screws with small diameters. Screws made of stainless steel performed better than carbon steel screws. The type of head is irrelevant for the temperature alongside the screws. The bigger the edge distance $a_{c,4}$ the smaller is the influence on the temperature of the screw by the fire exposed sides of the cross section. Temperatures lower than 220 °C in the middle of the screws are resulted by side distances of $a_{4,\,c} = 3{*}d_{nominal} + (\beta_n{*}t + d_0)/2$ for a 30 minute exposure and $a_{4,\,c} = 3{*}d_{nominal} + (\beta_n{*}t + d_0)$ (according to EN 1995-1-2) for a 60 minute exposure respectively.

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 for 30 min fire exposure and 43 mm for 60 min fire exposure. Connectors mounted with gap should be protected be means of intumescent materials alongside the sides of the connector.

ACKNOWLEDGEMENTS

The authors would like to acknowledge both the students and technicians at TU München for their help assembling the specimens, thank GH-Baubeschläge GmbH, SPAX International GmbH and Merk Timber GmbH for the fasteners and beam specimens, and thank the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) and the Federal Office for Building and Regional Planning (BBR) for funding this research project in the German research program “Zukunft Bau”.

REFERENCES

[1] European Committee for Standardisation (CEN). Eurocode 5. *Design of timber structures. Part 1-2: General – Structural fire design, EN 1995-1-2*. Brussels, Belgium, 2004.

[2] Standards Council New Zealand. NZ 3603. *Timber Structures Standards*, 1993

[3] American Wood Council: Design for Code Acceptance, *Design of Fire - Resistive Exposed Wood Members*, 2010

[4] Deutsche Gesellschaft für Holzforschung, *Holz Brandschutz Handbuch, 3*. Auflage Ernst & Sohn Verlag, 2009

[5] DIN EN 1999-1-2: 2007 Bemessung und Konstruktion von Aluminiumtragwerken – Teil 1-2: Tragwerksbemessung für den Brandfall

[6] Bauaufsichtliche Zulassung, Z-9.1-550, „ET-Passverbinder als Holzverbindungsmittel“

[7] Stöckl, U.: Verhalten von standardisierten Systemverbindern im Brandfall, Institut für Brandschutztechnik und Sicherheitsforschung GmbH AT-Linz, 2013