Daniel Brandon, Pierre Landel, Rune Ziethén, Joakim Albrektsson, Alar Just – RISE, Research Institutes of Sweden

High-Fire-Resistance Glulam Connections for Tall Timber Buildings

SMART HOUSING SMÅLAND

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Foreword

This report provides a brief overview of relevant results as required by one of the project sponsors Smart Housing Småland. The project consists of 4 timber connection fire resistance tests and 4 tests of similar connections at room temperature. A more detailed discussion of the tests of connection 3 and 4 is given in the Master Thesis of Ronstad and Ek (2018).

The research presented in this report was conducted by RISE (Sweden). The study was funded by **Smart Housing Småland** (Sweden), **Formas** (Sweden).

The timber beams used for the tests were sponsored by **Moelven** (Sweden).
Densified veneer wood for tests of connections 3 and 4 were sponsored by **Lignostone BV** (the Netherlands).
The melamine-formaldehyde adhesive used to assemble connections 3 and 4 were sponsored by **Akzo Nobel** (Sweden).

The presented study is part of a multi-disciplinary research project on the conceptual design of two 22-storey timber buildings, named: *Tall Timber Buildings – Concept Studies.*

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Summary

Tall timber buildings generally require fire resistance ratings of 90 minutes, 120 minutes or more. The vast majority of fire tested structural timber connections, however, did not reach a fire resistance that was relevant for these buildings. Commonly timber connections between glued laminated timber members comprise of exposed steel fasteners, such as bolts, screws, nails and dowels. However, it has previously been concluded that connections with exposed steel fasteners, generally do not achieve fire resistance ratings of 30 minutes and are, therefore, inadequate to be implemented in tall timber buildings without fire encapsulation.

The research project presented in this report consists of four connection fire tests that are designed to achieve structural fire resistance ratings of 90 minutes, using different design strategies. This goal was achieved for all tested column-beam connections. A single test of a moment resisting connection did not lead to a fire resistance rating of 90 minutes, due to timber failure at the smallest cross-section after 86 minutes. The low temperature of the steel fasteners and the limited rotation of the connection, however, suggest that the connection would have been capable of achieving a 90 minutes fire resistance rating if larger beam cross-sections would be used.

Background

The maximum height of timber buildings has increased rapidly in the last 15 years, due to changes of building regulations in many European countries and due to the development of mass timber materials, such as glued laminated timber beams and cross-laminated timber (CLT) panels. If their size is sufficient, mass timber members can achieve fire resistance ratings that are relevant for tall timber buildings without the need for fire protective encapsulation. There is, therefore, a potential to expose mass timber members, although it should be noted that there are additional fire safety risks involved. The connections between especially glued laminated timber beams do not, however, always easily obtain a fire resistance rating that is required for realizing tall buildings without the presence of fire protection.

Connections between glued laminated timber members often comprise steel fasteners, such as dowels, bolts, nails and screws, often in combination with steel plates. If steel fasteners and/or plates are exposed to a fire, the fasteners conduct the heat rapidly into the timber connection. This causes timber under high mechanical stresses adjacent to these fasteners to heat up rapidly. At increasing temperatures timber weakens significantly quicker than steel and has no significant strength left at the charring temperature of approximately 300°C. For this reason, timber connections with exposed steel members rarely have fire resistance ratings of 30 minutes or higher (Carling, 1989), while fire resistance ratings of 90 minutes or higher are required for tall timber buildings in Sweden and in many other countries.

Recent architectural trends include having visible timber surfaces in tall buildings. Therefore, there is a need for high fire resistance timber connections without fire protective encapsulation (Gerard et al. 2014).

Literature review of timber connection fire tests

Fire resistance tests of connections between timber beams have been analysed for this study. Table 1 indicates the number of tests performed in previous experimental studies and the nature and direction of the load acting on the connections during the fire test. Figure 1 indicates the frequency of tests that resulted in different fire resistance ratings. The figure also makes a distinction based on the nature of the applied load.

The most common connection type between glued laminated timber members in tall timber buildings is a column-beam connection loaded in shear. To be applicable for implementation in tall buildings a fire resistance of at least 90 minutes is required in most countries. In Figure 1 it can be seen that there are only 2 previous tests that meet both of these descriptions, which strongly indicates that there is a need for fire tests of connections relevant for tall timber buildings.

Table 1: Number of timber connection tests performed for different configurations

Reference	Configuration				
	Tension 0°	Tension 90°	Tension 45°	Bending	Shear
Dhima (1999)	19				
Laplanche (2006)	17				
Frangi and Mischler (2004)	6				
Lau P.H. (2006) & Chuo (2007)	9				
Peng (2010)	15				
Audebert (2010)		4	3	6	
Palma (2016)					19
Barber (2017)					3

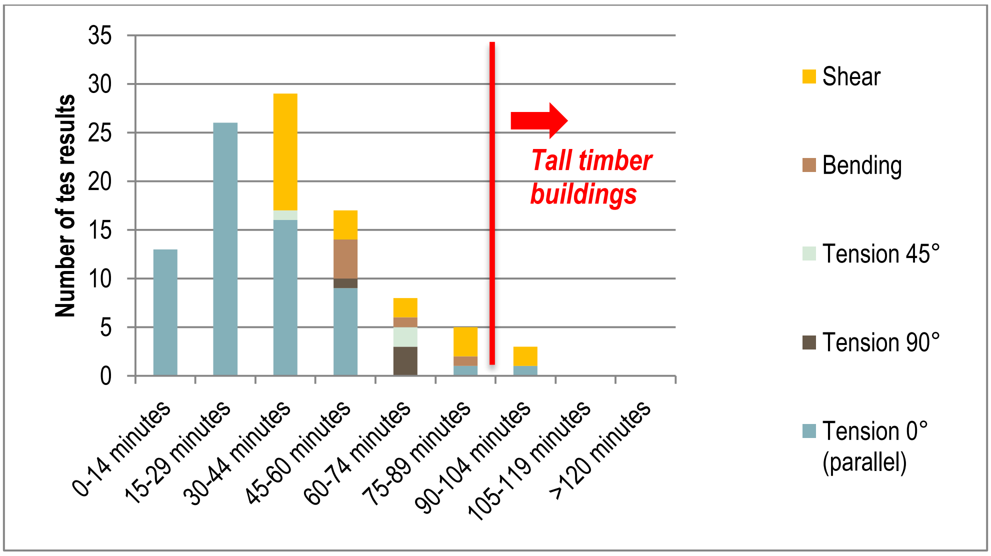

Figure 1: Overview of previous fire resistance tests and fire resistance times of timber connections

In response to the lack of fire resistance tests of glued laminated timber connections with acting shear loads and bending moments, this study includes fire resistance tests of three column-beam connections with shear loads acting upon them. Additionally, the fire resistance of one moment resisting connection is determined in this study. This study also includes destructive tests of all connections performed at room temperature prior to the fire tests, to determine the capacity of all connections.

Method

Three shear connections and a moment connection were designed aiming to achieve a fire resistance rating of 90 minutes while bearing 36% +/- 4% of their initial capacity. To determine the initial capacity, three tests of similar connections were performed at room temperature. The loading procedure of these tests was in accordance with ISO 6891 (1983).

Fire resistance tests of the connections were performed according to EN1363-1 (2012) to determine a fire resistance rating. The tests that were performed first (connection 3 and 4) were performed in an intermediate scale furnace of 1.0 x 1.0 x 1.0m. Due to the complexity of the setup, it was decided to perform the subsequent tests in a large scale furnace of 3.0 x 5.0 x 3.0m (width x length x depth), with the same exposure. Figure 3 and 4 show the setups for the intermediate scale furnace of a shear connection and the moment connection, respectively.

Technical drawings of all specimens can be found in Annex A.

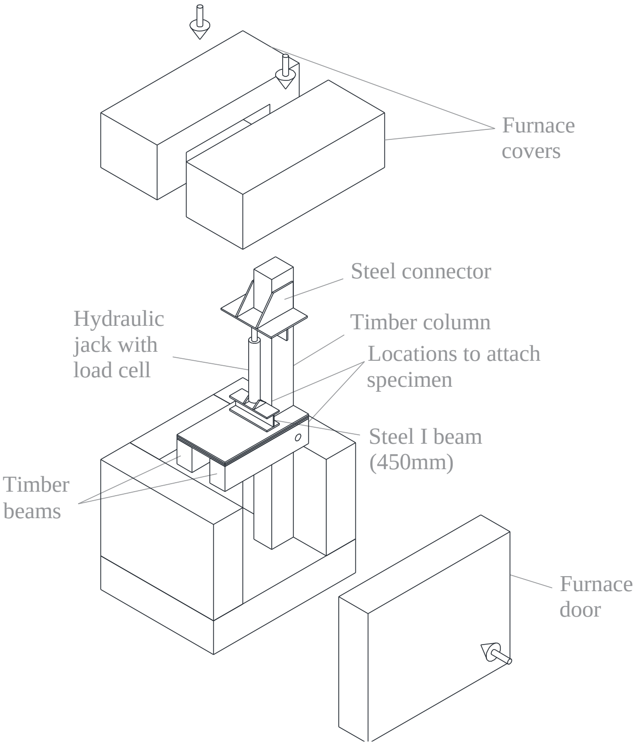

Figure 2: Fire resistance test setup of a shear connection

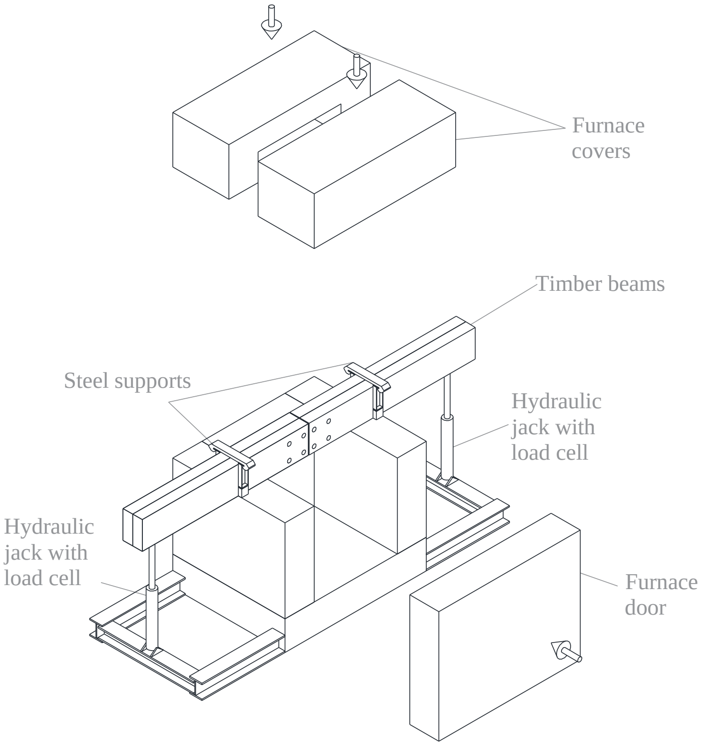

Figure 3. Fire resistance test setup of the moment connection

Most important results

The connection details and results are summarised in this section. In addition, specific information is given in the annexes. The master thesis by Ronstad and Ek (2018) discuss the background, preparation, tests and results corresponding to connection 3 and 4 in detail.

Connection 1 – Steel shoe connection

Connection 1 was included on request of practitioners and partners of the project. This connection has been applied in practice and comprises of a steel shoe that is screwed onto the column and bears the beam. High fire resistance is achieved by encapsulation with 2 layers of 15mm type F gypsum board around the beam and steel shoe and 1 similar layer around the column. Fire sealant *Bostik Fire Bond Silmax Pro* was used to seal the gypsum joints around the steel shoe. Figure 4 shows an exploded view of Connection 1 next to the drawing of the assembled connection. An overview of results is given in Table 2.

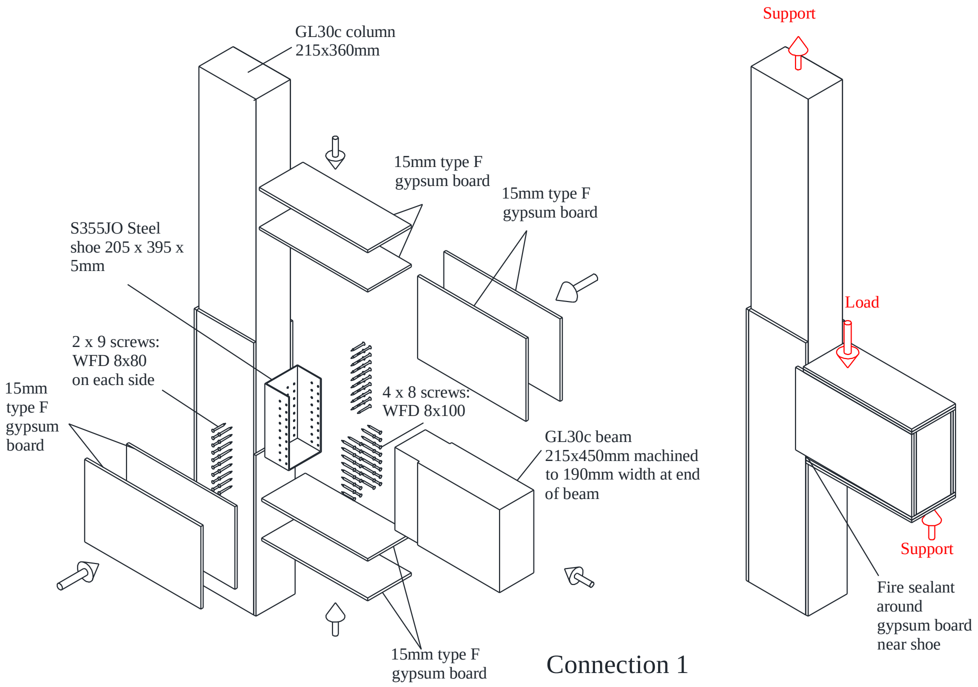

Figure 4: Exploded view of connection 1 (left) and assembled connection 1 (right)

Table 2: Overview of results of tests of connection 1 (calculated shear force in the connection)

Room temperature test				Fire test results			
Ultimate shear force	Yield shear force	Stiffness, K_i, ISO 6891	Failure mode	Applied shear force	Failure mode	Failure time	**Fire resistance**
232.3 kN	130.3 kN	19.7 kN/mm	Embedment of screws & tensile failure perp. to grain in column	82 kN (35%)	Embedment of screws in column	122min	**R120**

The measured temperatures of the steel members at the time of failure ranged between 350 and 480°C, indicating that the timber around the steel screws was close to these temperatures and started to char. The picture of the beam cross-section (Figure 7) shows that also in the beam, the screws started to cause charring deeper in the timber. This indicates that embedment failure occurred, which is confirmed by video evidence. Pictures taken after the room temperature test and the fire test are shown in Figure 5 and 6, respectively. Annex A shows the technical drawings deflection and steel temperatures of connection 1.

Figure 5: Connection 1 after room temperature test

Figure 6: Connection 1 fire test 10 minutes after failure

Figure 7: Photo of cross-section of beam with charred screw holes.

Connection 2 – Dowelled flitch plate connection

Connection 2 was based on connections implemented in existing buildings. The connection comprises of a protected 8mm thick steel flitch plate in a 12mm thick slot and ten 12mm dowels (hammered in 12mm holes) in each timber member to transfer shear loads from the beam to the column. High fire resistance is achieved by 53mm long timber plugs protecting the dowel and two approx. 2cm wide barriers of fire sealant around the steel plate between the beam and the column (Figure 9). Figure 8 shows an exploded view of Connection 2 next to the drawing of the assembled connection. An overview of results is given in Table 3. The first failure occurring during the fire test was at the end support of the beam (not in the connection).

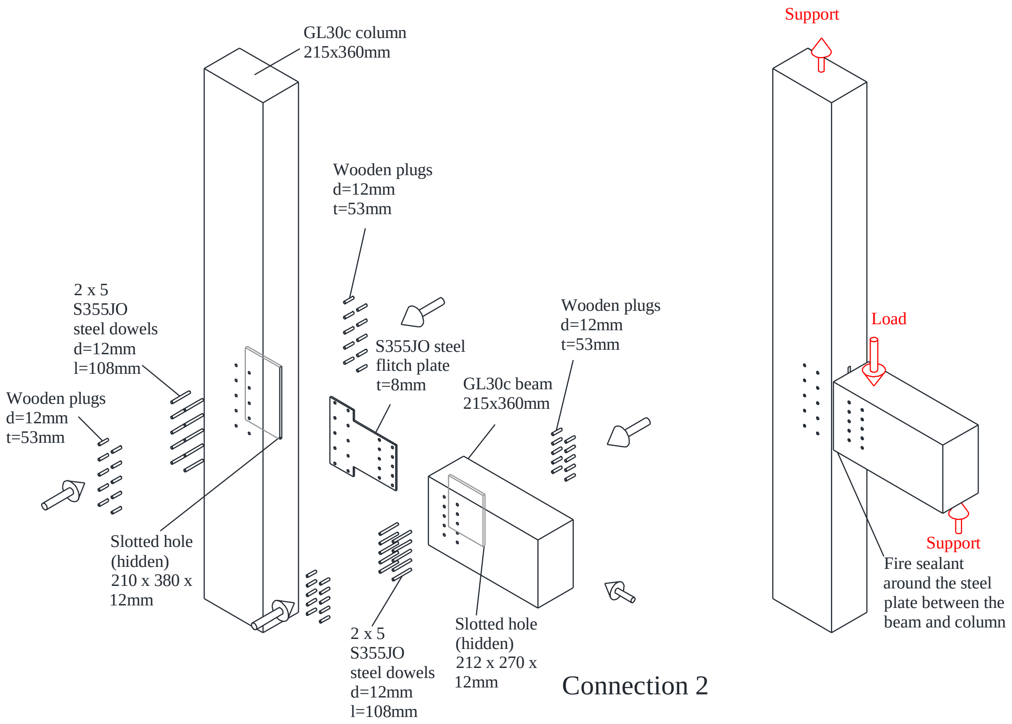

Figure 8: Exploded view of connection 2 (left) and assembled connection 2 (right)

Table 3: Overview of results of tests of connection 2 (calculated shear force in the connection)

Room temperature test				Fire test results			
Ultimate shear force	Yield shear force	Stiffness, K_i, ISO 6891	Failure mode	Applied shear force	Failure mode	Failure time	**Fire resistance**
133.5 kN	66.8 kN	22.3 kN/mm	Splitting failure of column	54 kN (40%)	Failure not in connection (at support)	100min	**(≥)R90**

Pictures taken after the room temperature test and the fire test are shown in Figure 10 and 11, respectively. The average 1-dimensional charring rate determined by thermocouples was 0.7mm/min. And the measured temperatures of the steel members at the time of failure ranged between 95 and 150°C at the moment of failure, with the majority of measurements around 100°C. Due to the rate of temperature increase near the end of the test, it is however, not expected that the connection would have remained intact for another 20 minutes to achieve a higher fire resistance rating than 90 minutes if the support would not have failed.

Figure 9: outer 2cm wide fire Sealant in the gap of the connection

Figure 10: Connection 1 after room temperature test

Figure 11: Connection 2 fire test 6 minutes after failure

Connection 3 – DVW-Reinforced connection with a steel tube fastener

Connection 3 has been used in buildings in the Netherlands and is commercially known as Lignoforce. The connection was studied before and was shown to have an evidently improved stiffness, load bearing capacity (Leijten 1998) and seismic performance (Bakel et al. 2017) in comparison with traditional dowel type connections. At the shear plane the timber members are reinforced with a densified veneer wood (DVW) plate that can be glued in the factory on the members. At the building site a tube can be compressed using a hydraulic jack as discussed by Ronstad and Ek (2018) to achieve a tight fit and a high initial stiffness. It was chosen only to implement one single tube in the connection, not to exceed the loading capabilities of the fire test rig. High fire resistance is achieved by protection of the tube fasteners with a 70mm long timber plug. The dimensions of the timber members are and can be significantly smaller than those of connections 2 and 3, while achieving a loadbearing capacity and fire resistance class that is in the same range. Figure 5 shows an exploded view of Connection 3 next to the drawing of the assembled connection. An overview of results is given in Table 4. The first failure occurring during the fire test was at the end support of the beam as a screw of the setup snapped.

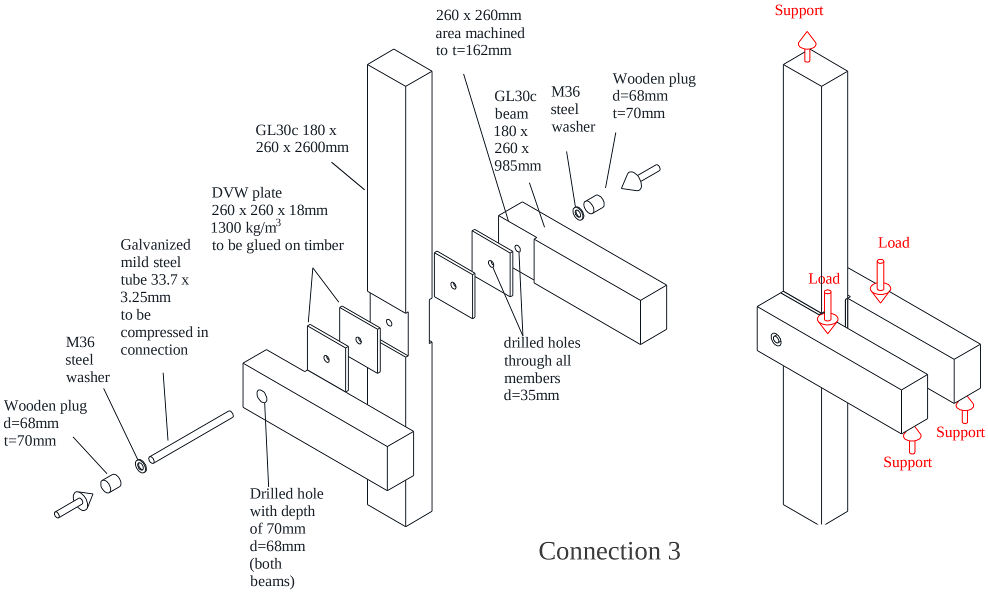

Figure 12: Exploded view of connection 3 (left) and assembled connection 3 (right)

Table 4: Overview of results of tests of connection 3 (calculated shear force in the connection)

Room temperature test				Fire test results			
Ultimate shear force	Yield shear force	Stiffness, K_i, ISO 6891	Failure mode	Applied shear force	Failure mode	Failure time	**Fire resistance**
181.4 kN	139.4 kN	58.2.3 kN/mm	Bond line failure due to beams rotating away from column	57.4kN (32%)	Not in connection (at support)	113min	**(≥)R90**

The connection itself did not fail at the end of the test. Therefore, it is relevant to discuss the likelihood of the connection having a higher fire resistance based on analysis. Three different types of failure modes are assessed:

- Embedment failure caused by weakening of the timber around the tube fastener.
- Brittle timber or densified veneer wood failure caused by reduction of the uncharred cross-section.
- Timber column or beam failure

Temperatures measured in the tube at the shear plane at the end of the test were approximately 80°C. If the test were to continue there would have been a plateau at approximately 100°C in which the heating rate stalls due to the energy needed to evaporate moisture of the timber and DVW material. The temperatures at 120 minutes (only 6 minutes after the end of the test) would therefore likely not have exceeded 100°C. Brandon et al. (2015) showed that the embedment strength of DVW does not drop substantially under 200°C. Therefore, embedment failure before 120 minutes is deemed very unlikely.

The average one dimensional charring rate determined from thermocouple measurements was 0.65mm/min for the first 62 minutes and 0.53mm/minutes for 112 minutes (almost the entire duration of the test). Using this rate, at 120 minutes the edge distance can be estimated as approximately 65mm from the lower side. However, due to the downwards (realistic) direction of the load, timber or DVW failure modes should be expected in the beam material above the tube fastener. The protection of the floor and wall on the top and the end of the beams lead to practically unchanged end-and upper edge distance. In addition, the char line would not have surpassed the protective plug at 120 minutes, indicating still significant beam thickness at the location of the connection. Therefore, brittle failure modes, such as shear plug failure or splitting failure would very unlikely occur within 6 minutes if the fire test were continued.

The weakest link in the tested structure (apart from the end support that failed) is the column. Being exposed form 3-sides, the reduced cross section of the column reduces rapidly. Depending on the structural design, the column will likely fail before the connection fails.

Annex D shows drawings, pictures and data of the tests of connection 4.

Figure 13: Specimen after the fire test (end support failed)

Connection 4 – DVW-Reinforced connection with a steel tube fastener

Connection 4 is a moment-bearing variant of the DVW-reinforced tube connection, Connection 3. Also the moment connection of this type (commercially known as Lignoforce) has been used in buildings in the Netherlands, mainly to realise portal frame structures. This is possible due to the high rotational stiffness, moment capacity (Leijten 1998) and, if needed, high energy absorption under seismic loads (Bakel et al. 2017). Leijten and Brandon (2013) have shown that the flitch plate connection can have the same rotational stiffness and moment capacity as the earlier studied 3-member connection. High fire resistance is achieved by protection of the tube fasteners with a 70mm long timber plug, protection of the steel plate by a 62mm wide DVW strip and fire sealant around the steel at the gap. Figure 6 shows an exploded view and of the assembled connection.

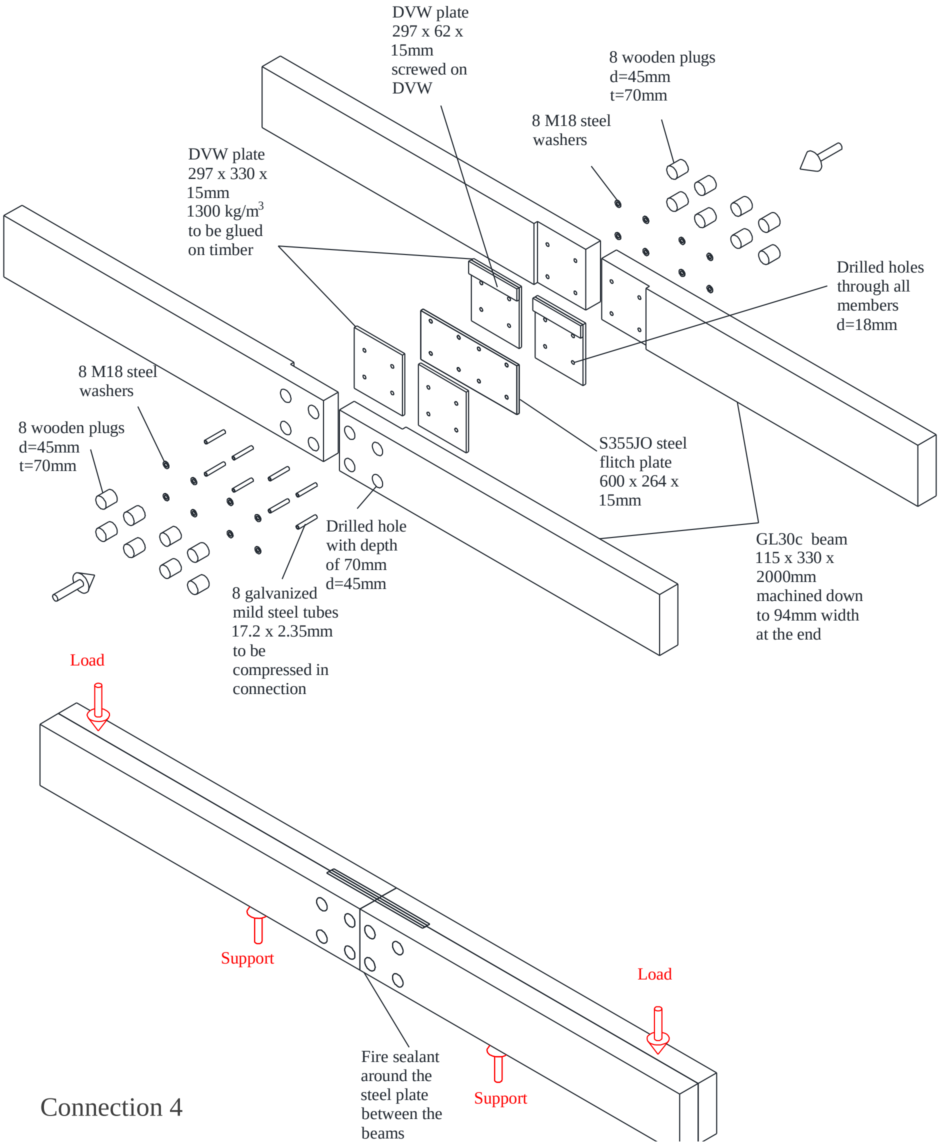

Figure 14: Exploded view of connection 4 (top) and assembled connection 4 (bottom)

Table 5 shows an overview of results. The first failure occurring during the fire test at the smallest cross-section of the beam but did not involve the connectors, DVW plates or the flitch plate. It is therefore expected that a small increase of the beam cross-section would have resulted in a fire resistance classification higher than R60. The temperature of the tubes near the shear plane was 50 to 70°C, indicating no embedment failure occurred or would occur within the next few minutes.

Table 5: Overview of results of tests of connection 3 (calculated shear force in the connection)

Room temperature test				Fire test results			
Ultimate bending moment	Yield bending moment	Stiffness, K_i, ISO 6891	Failure mode	Applied bending moment	Failure mode	Failure time	**Fire resistance**
39.5 kNm	24 kNm	2319 kNm/rad	Tube def. & DVW splitting	15.8 kN (40%)	Bending failure of timber at the smallest cross-section	86min*	**R60***

*Due to a technical problem the furnace temperatures were too high for the first 12 minutes and subsequently too low for approximately 5 minutes.

Figure 15: Two strips of fire sealant at the gap.

Figure 16: Specimen after the fire test – failure mode: bending failure at the minimum cross-section

Summary and conclusions

An analysis of previous fire tests of glued laminated timber connection showed that there is a shortage of tested connections that are relevant for tall timber buildings.
Four significantly different connections have been tested at a fire testing furnace to determine their structural fire resistance. During the fire tests, a load equal to 36% +/-4% of the connections' ultimate load bearing capacity was implemented. To determine their load bearing capacity, similar connections were tested to failure at room temperature prior to the fire tests.

Connection 1 was a shear connection of gypsum protected glued laminated timber. The load was transferred from the beam to the column using a steel shoe designed by Moelven. The steel shoe was protected using two 15mm thick layers of type F gypsum boards. The connection failed after 122 min due to embedment failure of the screws that attached the steel shoe to the column, achieving a fire resistance R120.

Connection 2 was a shear flitch plate connection. All steel members including the dowels were protected with at least 52mm of timber. At the gap between the column and the beam, fire sealant was applied to protect the steel plate. During the fire test, the initial failure occurred outside of the connection at 100 minutes, achieving a fire resistance of R90. The analysis indicates that the connection would be able to bear the loads longer if the failure mode outside of the connection did not occur. However, due to the char line in the proximity of the steel connection members, it is **not** expected that this connection would have achieved a fire resistance rating of R120.

Connection 3 was a three-member shear connection with a tube fastener, designed in agreement with previous studies (Leijten, 1998). To achieve high strength and stiffness while being able to have relatively small cross-sections of timber members the connection was reinforced using densified veneer wood plates, commercially known as Lignostone. The only measure to ensure a high fire resistance of Connection 3, was the implementation of two timber plugs at both sides of the dowel. During the fire test, one of the supports from the setup failed after 113 minutes achieving a fire resistance of R90. The temperatures of the steel tube near the shear plane were still relatively low, which indicates the connection would not have taken place for a significant time if the setup would not have failed. In the connection design, the shear plane at the dowel was protected by a significant amount of timber in all directions for the entire test duration. Therefore, it is not expected that connection failure would be the governing failure mode and that the beams or the column would failure first.

Connection 4 was a bending moment flitch-plate connection with steel tube fasteners, designed in agreement with previous studies (Leijten and Brandon 2013). Similarly to Connection 3, to achieve high strength and stiffness while being able to have relatively small cross-sections of timber members, the connection was reinforced using densified veneer wood plates, commercially known as Lignostone. Measures to achieve a high fire were similar to those of Connection 2: the implementation of timber plugs protecting the dowels; protection of the steel flitch plate and; fire sealant at the gap of the connection to protect the steel plate. Failure occurred at 86 minutes achieving a fire resistance of R60. The failure, however, did not occur in the connection, but in the smallest cross section of the beam. This was the predicted failure mode. However, the failure occurred a few minutes to be relevant for tall timber buildings in Sweden. A slight increase of the timber cross-section would very likely have led to a higher fire resistance.

Figure 17 indicates the fire resistance of connections tested in this study versus, fire resistance ratings of previously tested connections.

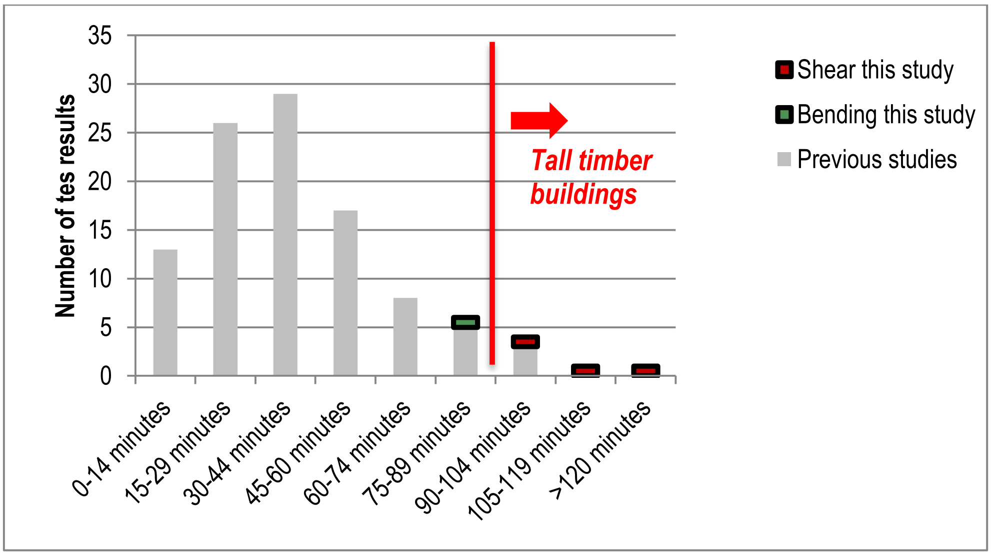

Figure 17: Overview of previous connection fire resistance tests and connection fire resistance tests of this study

Continuation of research

This study only focused on connections between glued laminated timber members. Connection fire tests relevant for CLT structures and light timber frame structures have not been studied substantially and require research. A new study funded by the US governmental department of agriculture and performed by RISE will look into connection performance in detail. Partnership with two of the largest CLT manufacturers will help the project to come up with practicable and relevant solutions.
In addition, reparation of fire damages in tall timber buildings has been an upcoming question as buildings grow taller. Restoring connections after a fire will likely be the most challenging part of the structure and requires research. The US funded project will also look at possibilities for restoration.

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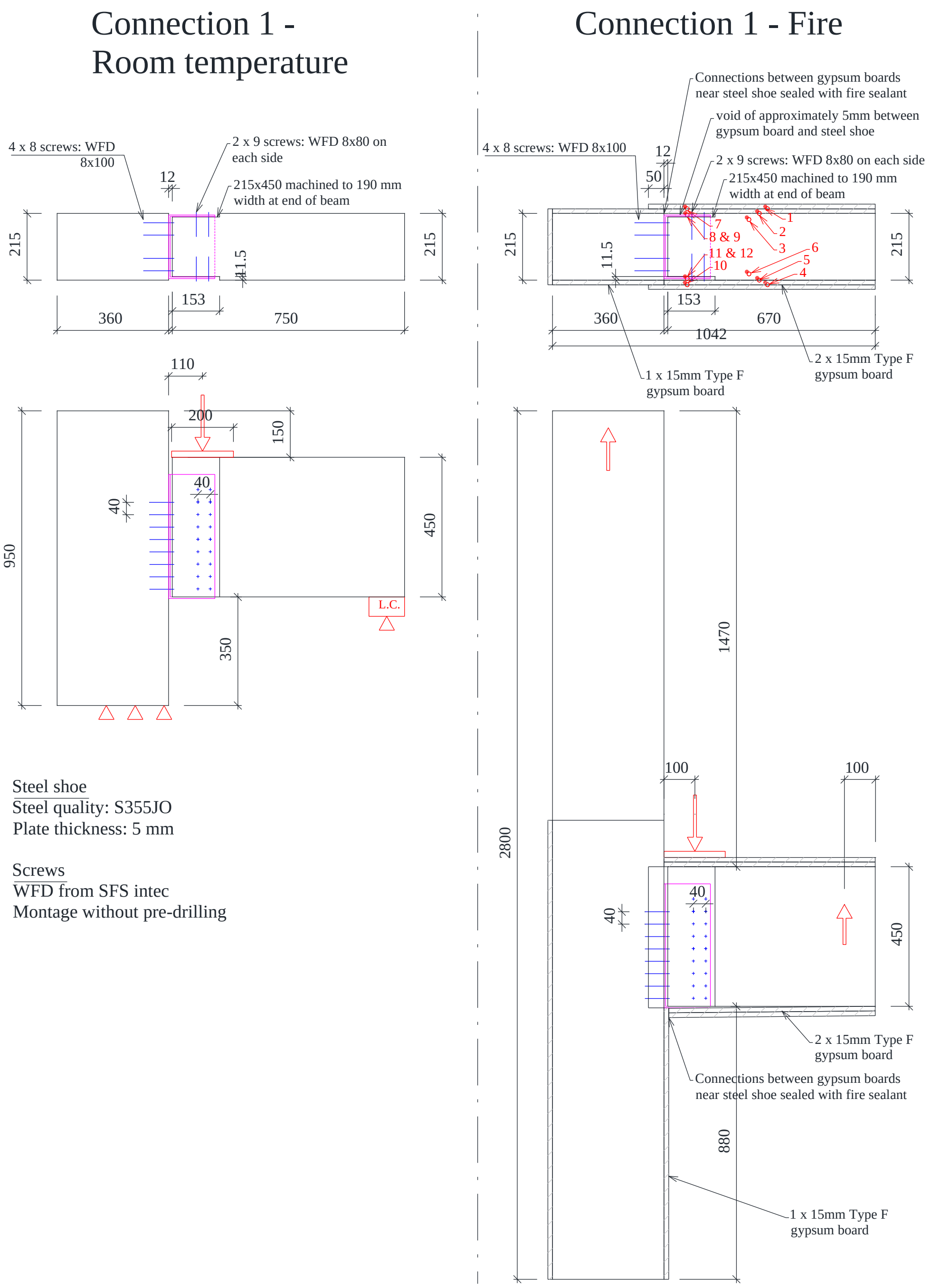
Annex A: Connection 1 drawings, photos, results


Connection 1 - Room temperature

Connection 1 - Fire

Steel shoe
Steel quality: S355JO
Plate thickness: 5 mm

Screws
WFD from SFS intec
Montage without pre-drilling

Connections between gypsum boards near steel shoe sealed with fire sealant

void of approximately 5mm between gypsum board and steel shoe

Figure A1: Drawings of connection 1

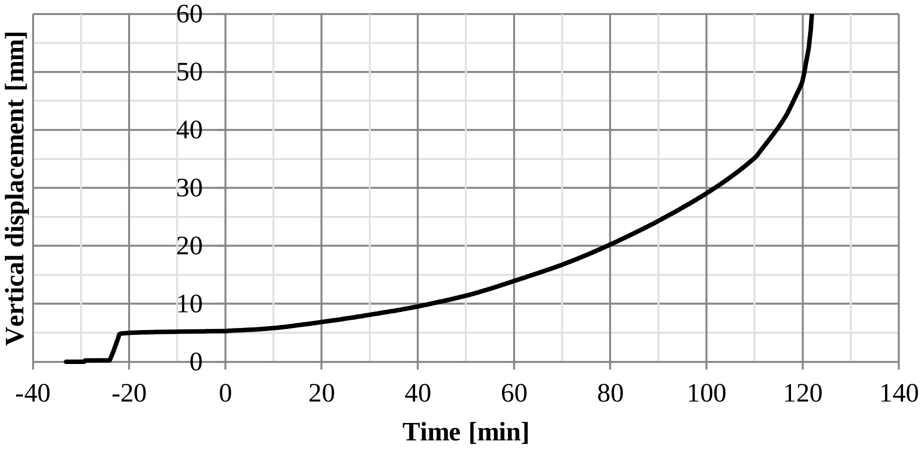


Figure A2: Downward displacement on top of the beam at 180mm from the column.

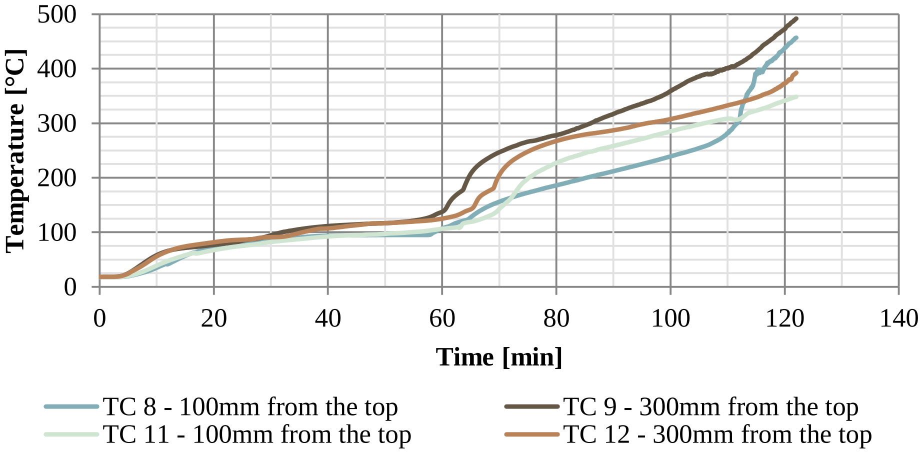
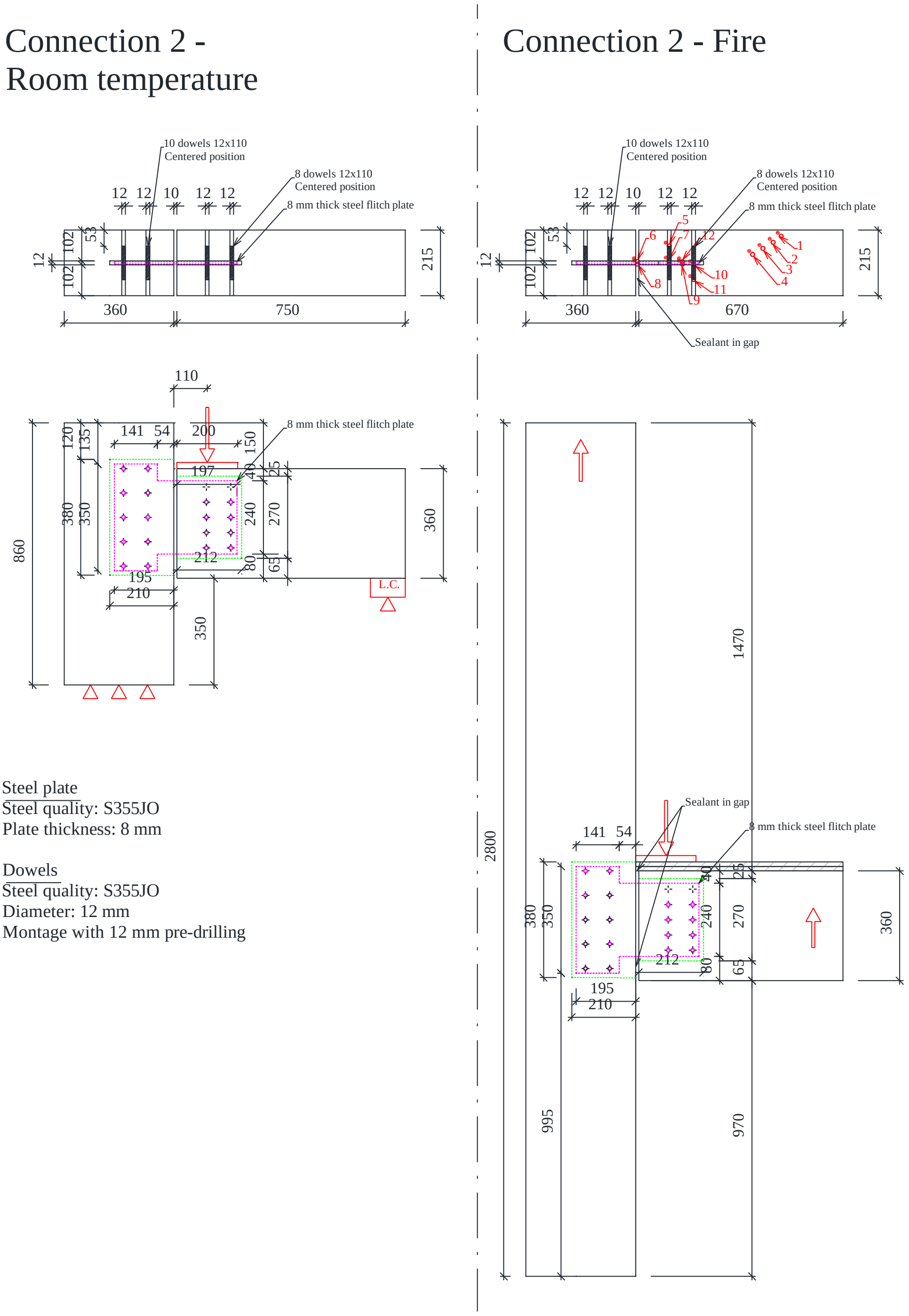


Figure A3: Temperatures measured on steel shoe.

Annex B: Connection 2 drawings, photos, results



Connection 2 - Room temperature

Connection 2 - Fire

Steel plate
Steel quality: S355JO
Plate thickness: 8 mm

Dowels
Steel quality: S355JO
Diameter: 12 mm
Montage with 12 mm pre-drilling

Figure B1: Drawings of connection 2

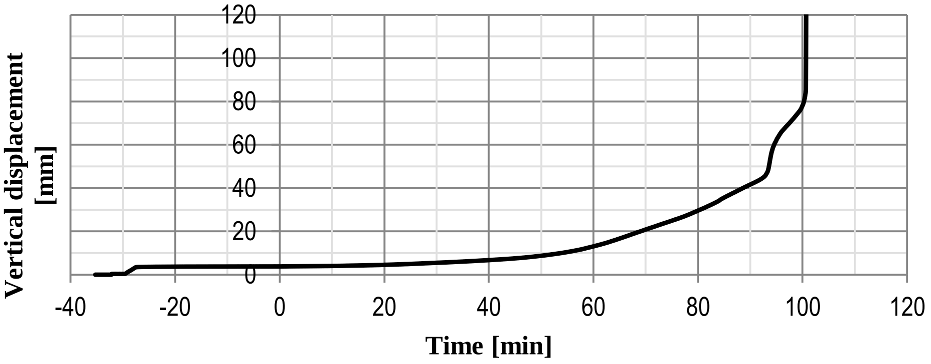


Figure 6: Downward displacement on top of the beam at 180mm from the column

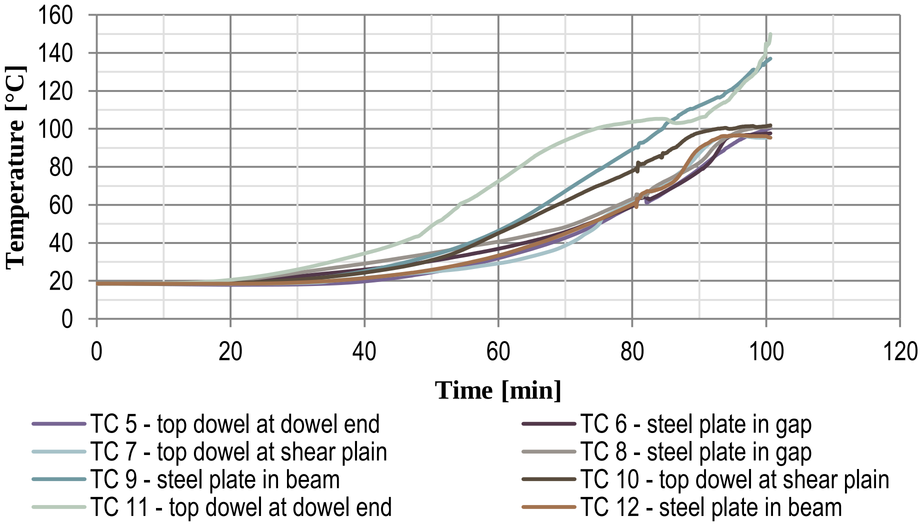
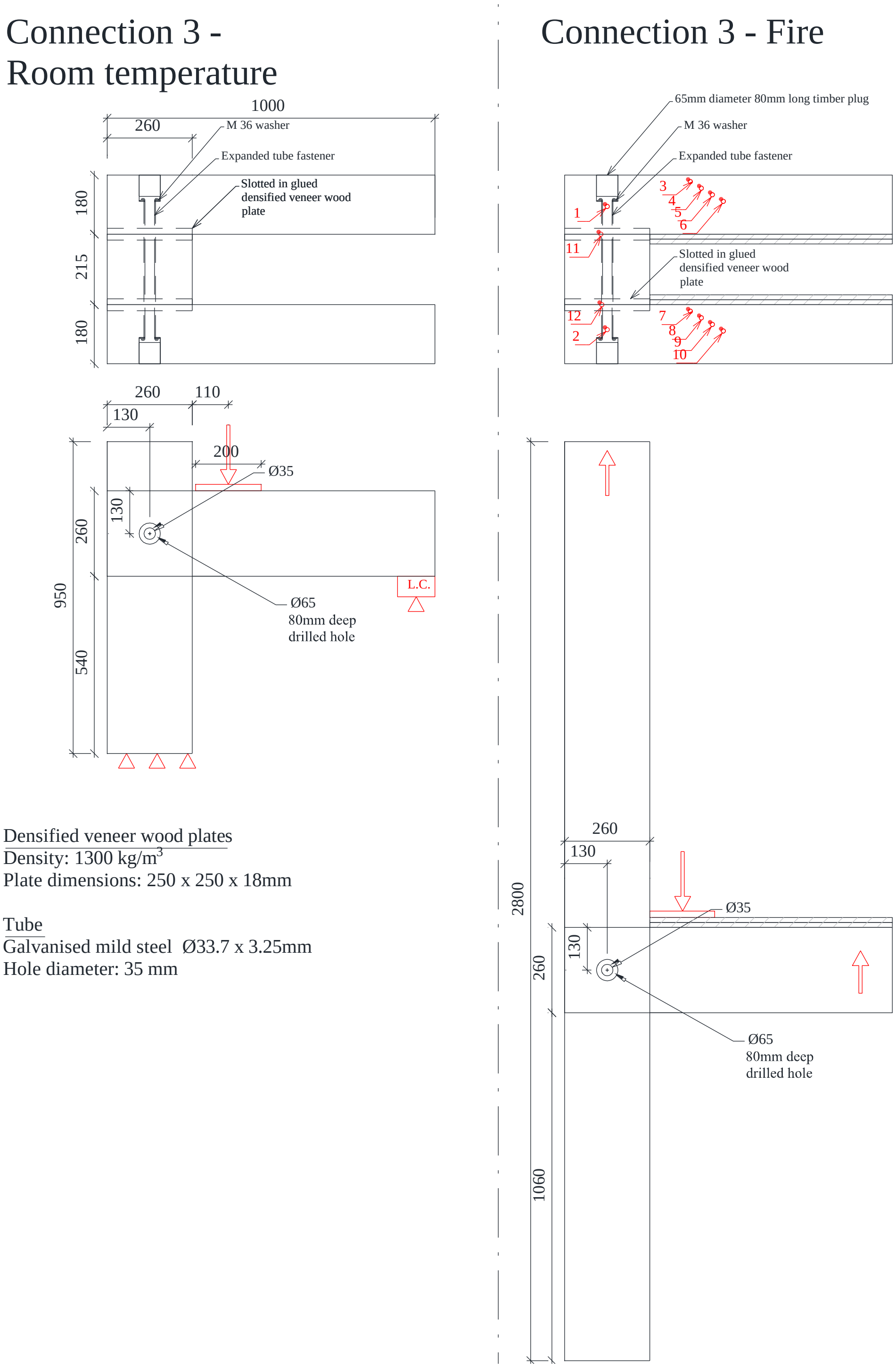


Figure 5: Temperatures of steel members

Figure 5: Temperatures in timber at different depths

Annex C: Connection 3 drawings, photos, results


Connection 3 - Room temperature

Connection 3 - Fire

Densified veneer wood plates
Density: 1300 kg/m^3
Plate dimensions: 250 x 250 x 18mm

Tube
Galvanised mild steel Ø33.7 x 3.25mm
Hole diameter: 35 mm

Figure C1: Room temperature test

Figure C2: Room temperature test

Figure C3: the failure mode for high shear forced.

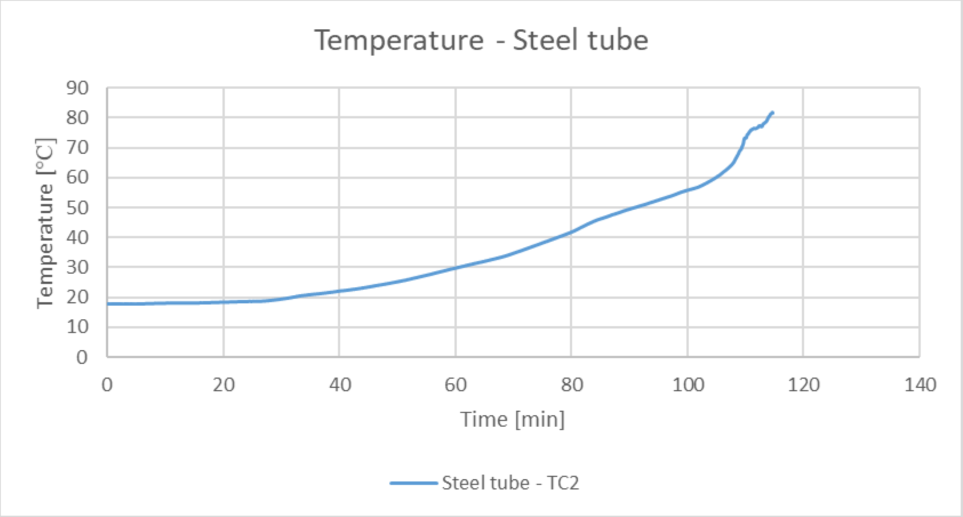


Figure C4: Temperature of the steel tube at the shear plane (TC2).

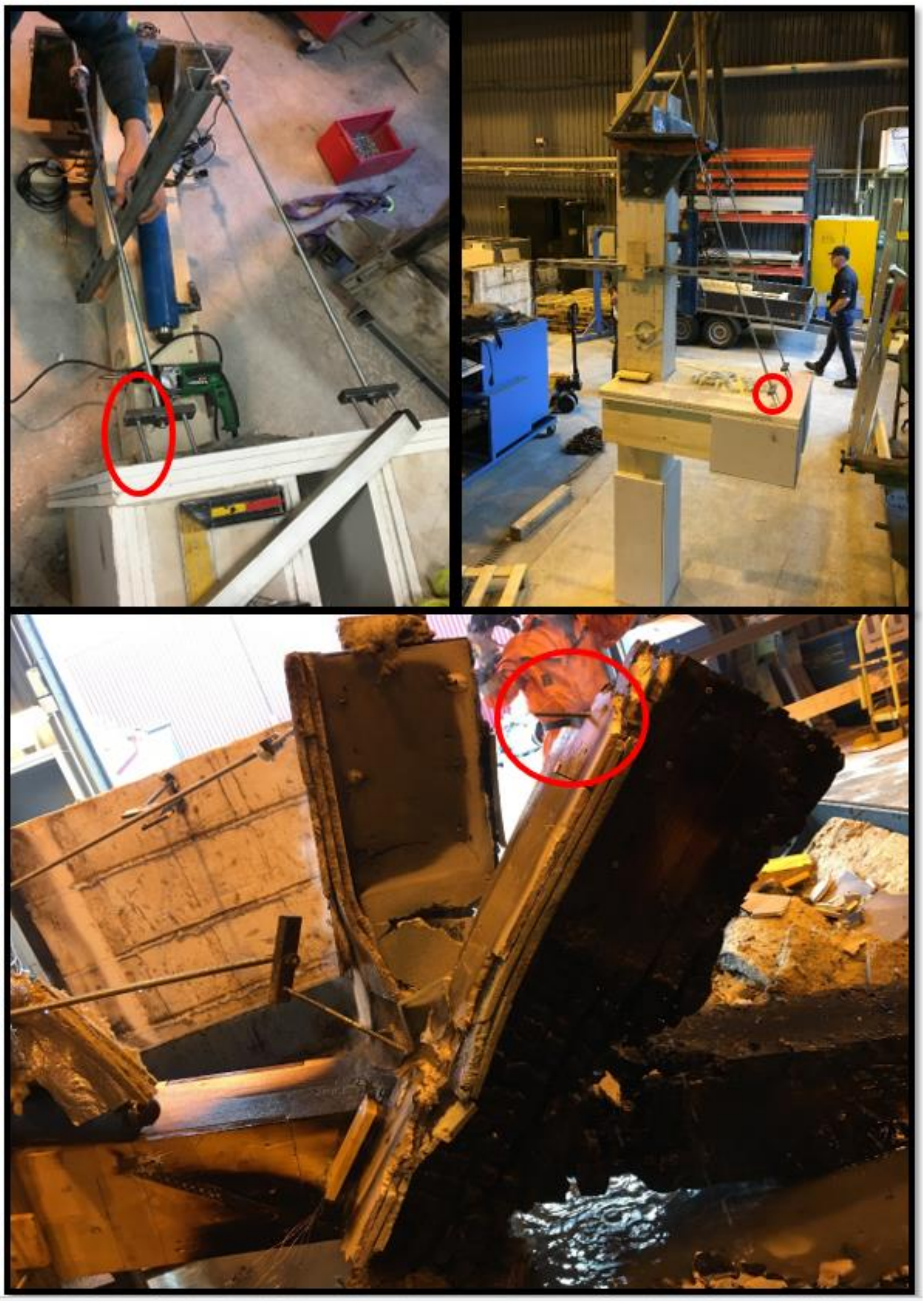
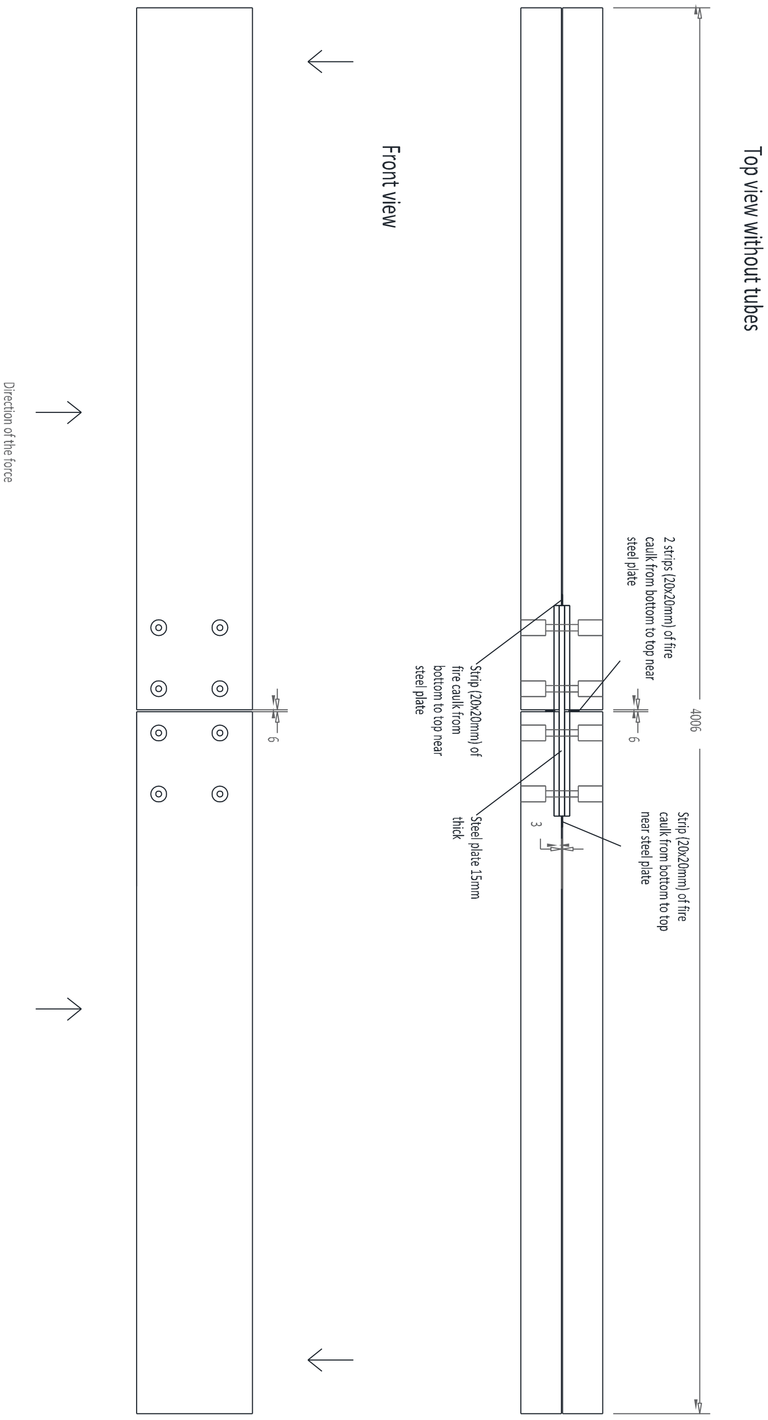


Figure C5:Location of support failure (from Ronstad and Ek, 2018)

Annex D: Connection 4 drawings, photos, results



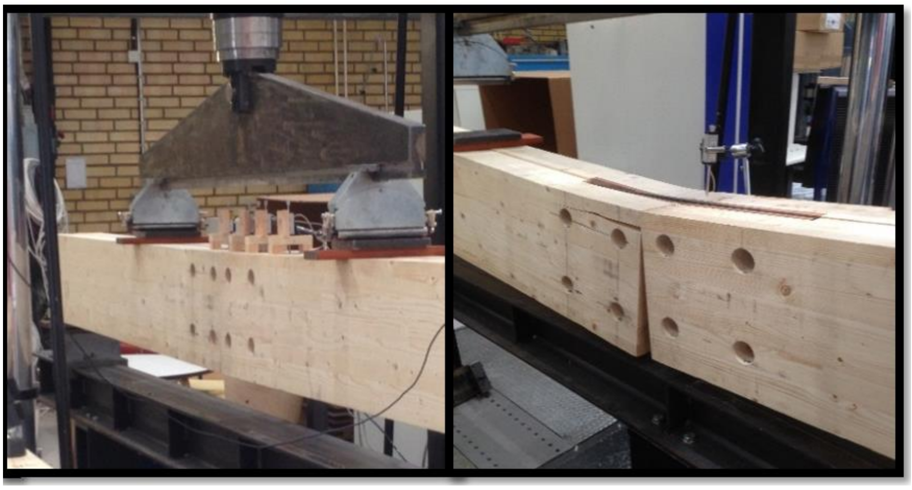


Figure D2. Photos during and after test

Figure D3. Preparation for the fire test of the moment connection.

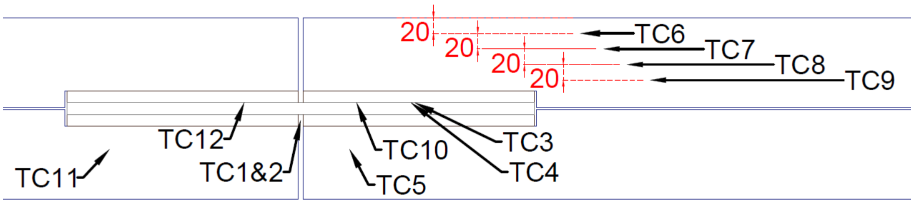


Figure D4. Thermocouple positions (top view)

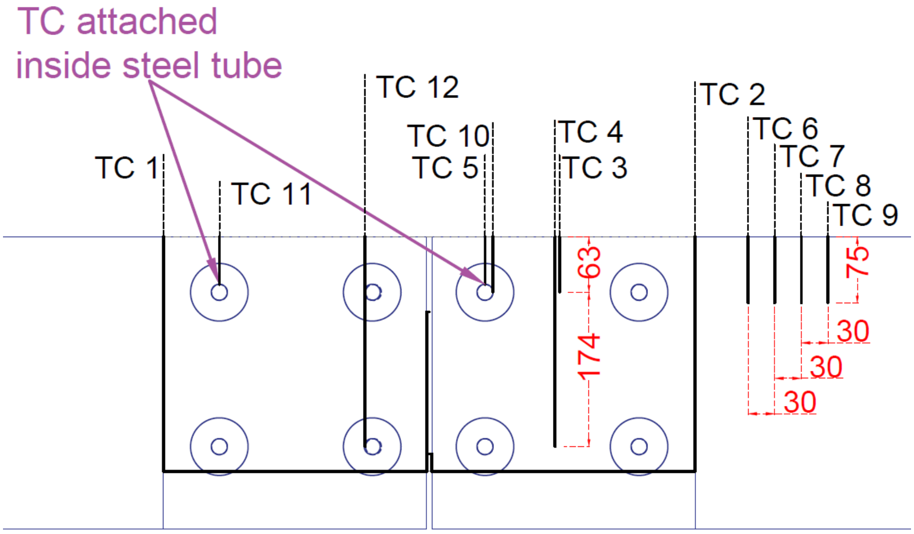


Figure D5. Thermocouple positions (front view)

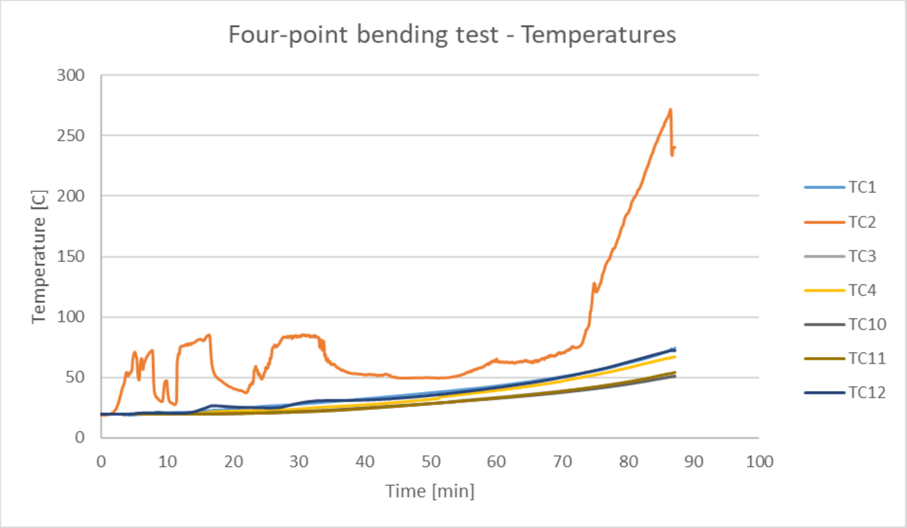


Figure D6. Thermocouple teadings of TC1-4 and 10-12

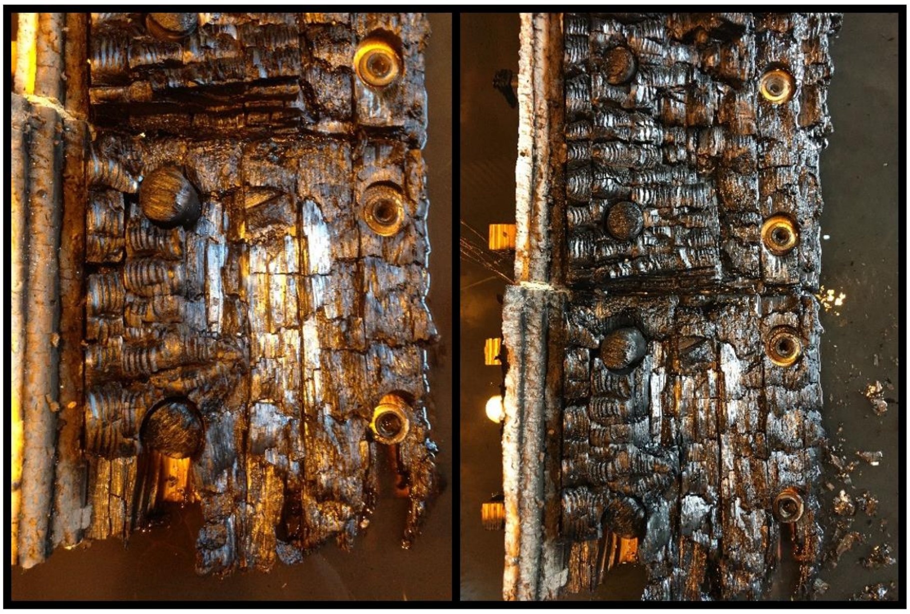


Figure D7. Tubes after the test without a sign of damage

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