

FIRE RESISTANCE TESTS ON STEEL-TO-TIMBER DOWELLED CONNECTIONS REINFORCED WITH SELF DRILLING SCREWS

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1. INTRODUCTION

1.1 Background

The fire performance of timber structures is largely influenced by the behaviour of the connections. Current structural fire design rules for timber connections, according to EN 1995-1-2 [1], are based on a limited number of tests and are only valid for fire resistances up to 30 minutes, for unprotected bolted or dowelled (with $d < 12$ mm) connections with side member of wood.

Improving the fire resistance of timber connections has been the goal of several studies [2–4], which have focused on increasing the thickness of the side members of wood and the end/edge distances of the fasteners or providing additional protection using panels. Another alternative is to overdesign the connections at normal temperature to obtain lower load ratios in fire design, therefore improving the fire resistance. Although effective, these strategies lead to larger cross-sections (compromising the whole design) or might not be aesthetically appealing.

The reinforcement of timber connections with self-drilling screws has also been addressed in numerous studies [5–9], which focused mainly on preventing brittle perpendicular-to-grain and block shear failures. Reinforcement with self-drilling screws can also, in addition to prevent brittle failure modes, increase ductility and the load-carrying capacity of the connections at normal temperature, by reducing longitudinal splitting and embedment of the fasteners.

Since self-drilling screws can be easily inserted and concealed inside timber members, the additional overstrength they provide at normal temperature could be used to improve the fire resistance of timber connections. An experimental campaign was conducted at ETH Zurich and

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Empa, to characterize the behaviour of timber connections reinforced with self-drilling screws at normal temperature and under fire exposure.

1.2 Objectives and scope

The objectives of this study are to assess the influence of reinforcement with self-drilling screws on the fire resistance of timber connections, namely steel-to-timber dowelled connections with multiple shear planes.

The study included two series of experimental campaigns aimed at analysing the behaviour of different connection typologies at room temperature and under ISO 834 fire exposure. The first campaign took place in 2003 and covered tests at normal temperature and under fire exposure of four typologies of unreinforced connections, some of them also tested with additional fire protection (gypsum or timber boards). The results from the first campaign were used to prepare the second campaign, conducted in 2012, comprising tests at normal temperature and under fire exposure of similar and new connection typologies reinforced with self-drilling screws.

2. TEST PROGRAMME

2.1 Previous experimental campaign

The campaign conducted in 2003 [4,10,11] covered steel-to-timber dowelled connections with 2 and 3 slotted-in steel plates, dowels of diameter 6.3 and 12 mm, different dowel layouts, increased end and edge distances of the fasteners, additional protection using wood-based and gypsum panels and different load levels during fire exposure. An overview of the relevant part of this campaign is presented in Table 1.

Table 1: Overview of part of the previous experimental campaign

Connection typology	Number of tests	Type of test	Load ratio	Geometry
D01.1	5	20 °C	Until failure	Cross section: 200×200 mm ² Fasteners: 9 rows with 2 dowels (<i>d</i> = 6.3 mm)
	2	Fire	30% · <i>R</i> _{m,D01.1,20°C}	Steel plates: 3 (thickness 5 mm)
D03.1	5	20 °C	Until failure	Cross section: 200×200 mm ² Fasteners: 3 rows with 3 dowels (<i>d</i> = 6.3 mm)
	2	Fire	30% · <i>R</i> _{m,D03.1,20°C}	Steel plates: 3 (thickness 5 mm)
D04.1	5	20 °C	Until failure	Cross section: 200×200 mm ² Fasteners: 4 rows with 2 dowels (<i>d</i> = 12 mm)
	2	Fire	30% · <i>R</i> _{m,D04.1,20°C}	Steel plates: 2 (thickness 5 mm)

2.2 New experimental campaign

The recently conducted campaign focused on the typologies presented in Table 1, and a new connection typology with only one slotted-in steel plate (D05.1) was introduced (Table 2). This campaign included 15 tests at normal temperature and 10 fire resistance tests.

Table 2: Overview the new experimental campaign

Connection typology	Number of tests	Type of test	Load ratio	Geometry	
D01.1.R	3	20 °C	Until failure	Geometry:	same as D01.1
	2	Fire	$30\% \cdot R_{m,D01.1,20^\circ\text{C}}$	Reinforcement:	2 self-drilling screws ($d = 7$ mm)
D03.1.R	3	20 °C	Until failure	Geometry:	same as D03.1
	2	Fire	$30\% \cdot R_{m,D03.1,20^\circ\text{C}}$	Reinforcement:	8 self-drilling screws ($d = 7$ mm)
D04.1.R	3	20 °C	Until failure	Geometry:	same as D04.1
	2	Fire	$30\% \cdot R_{m,D04.1,20^\circ\text{C}}$	Reinforcement:	4 self-drilling screws ($d = 9$ mm)
D05.1	3	20 °C	Until failure	Cross section:	160×160 mm ²
	2	Fire	$30\% \cdot R_{m,D05.1,20^\circ\text{C}}$	Fasteners:	2 rows with 2 dowels ($d = 12$ mm)
D05.1.R	3	20 °C	Until failure	Steel plates:	1 (thickness 5 mm)
	2	Fire	$30\% \cdot R_{m,D05.1,20^\circ\text{C}}$	Geometry:	same as D05.1
D05.1.R	3	20 °C	Until failure	Reinforcement:	4 self-drilling screws ($d = 7$ mm)
	2	Fire	$30\% \cdot R_{m,D05.1,20^\circ\text{C}}$		

Note: d is the outer thread diameter.

Unlike in the previous campaign, the load level during the fire tests of the reinforced connections was not 30% of the average load-carrying capacity of the reinforced connection at normal temperature, but 30% of the average load-carrying capacity of the corresponding unreinforced connection. Using the same load in both cases allows isolating and assessing the effect of the reinforcement in the fire resistance.

3. TEST SPECIMENS

3.1 Materials

The connection specimens in both campaigns were produced with spruce glued laminated timber, strength class GL 24h according to EN 1194 [12].

The steel plates were manufactured with grade S355 steel, according to EN 10025-2 [13], and the steel dowels with grade 11SMnPb37 steel, in accordance with EN 10087 [14], as in the previous campaign.

Full threaded self-drilling screws were used for reinforcement. They were made from carbon steel, with characteristic tensile resistances of 15.4 and 25.4 kN, respectively for $d = 7$ and $d = 9$ mm screws [15].

3.2 Geometries

The geometries of the tested steel-to-timber connections are presented in Figs. 1 to 4.

The steel plates were 5 mm thick and were inserted in 6 mm wide slots. The diameter of the dowels was 6.3 mm in connections D01.1.R and D03.1.R, and 12 mm in connections D04.1.R and D05.1.R. The outer thread diameter and length of the self-drilling screws was 7×140 mm in connections D01.1.R, D03.1.R and D05.1.R, and 9×160 mm in connections D04.1.R. The 9 mm screws were inserted in pre-drilled holes with a diameter of 6 mm.

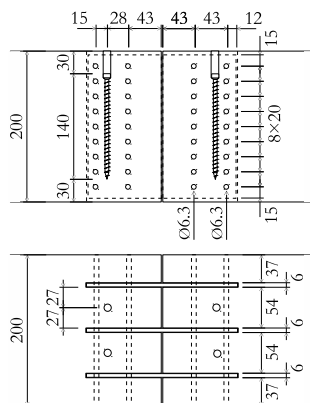


Figure 1: Connections D01.1.R.

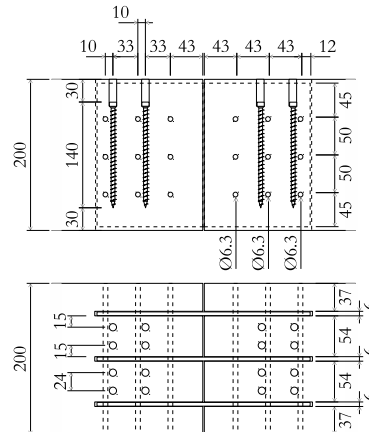


Figure 2: Connections D03.1.R.

Slight variations of the position of the screws were made in the fire tests specimens of connections D04.1.R and D05.1.R. These variations consisted of placing the screws closer to the dowels and/or the steel plates (Figs. 3 and 4). The consistency and repeatability of the fire resistance obtained in the previous campaign [11] allowed to introduce these small variations without compromising the accuracy of the results.

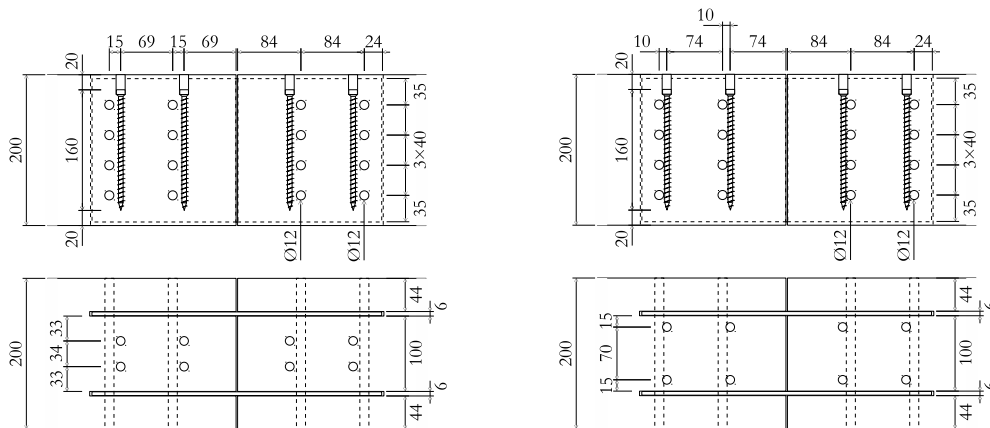


Figure 3: Connections D04.1.R-1 (left) and D04.1.R-2 (right)

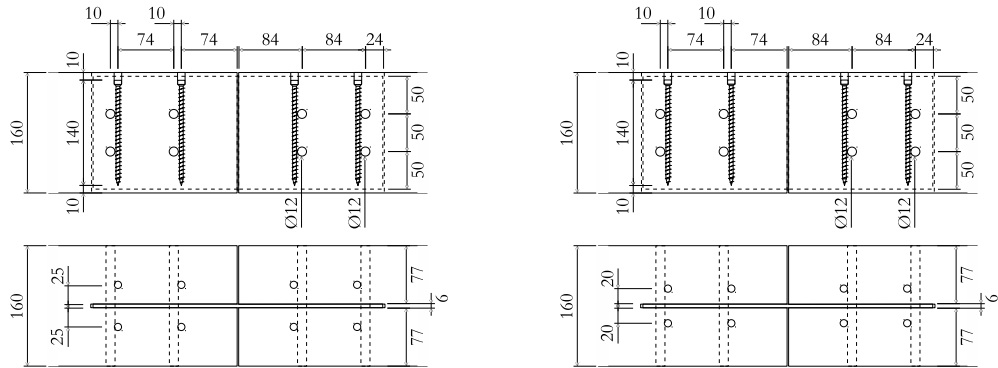


Figure 4: Connections D05.1.R-1 (left) and D05.1.R-2 (right)

In both the fire tests and in the tests at normal temperature two connections were tested simultaneously. The specimens for the fire tests were composed by two timber members and the connections to be tested were located in the centre of the specimen (Fig. 5); in the specimens for the tests at normal temperature the connections were located in the ends of the timber member (Fig. 6).

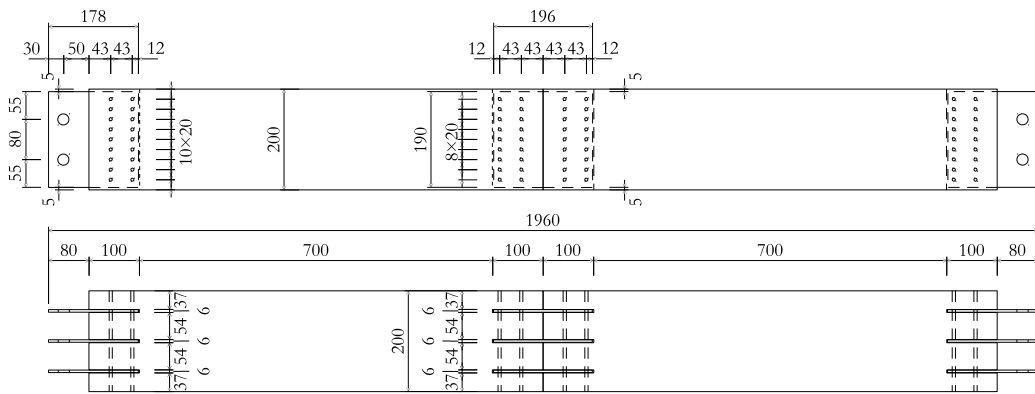


Figure 5: Geometry of a test specimen for the fire resistance tests (connections D01.1)

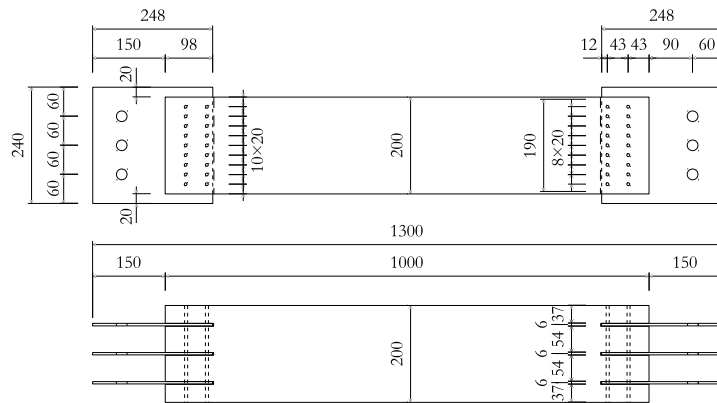


Figure 6: Geometry of a test specimen for the tests at normal temperature (connections D01.1)

3.3 Reinforcement

The reinforcement screws were concealed inside the timber members and placed between the steel plates to delay as much as possible their exposure to elevated temperatures. Clearance holes for the head of the screws were made before driving the screws into the timber members, and wooden plugs were afterwards inserted in the clearance holes (Fig. 7).



Figure 7: Reinforcement with self-drilling screws: unreinforced connection, boring the clearance holes, driving the screws, and inserting the wooden plugs (connection D05.1)

4. TESTS AT NORMAL TEMPERATURE

4.1 Procedure

The tests at normal temperature were conducted in accordance with EN 26891:1991 [16]. This standard prescribes a loading procedure based on the estimated load-carrying capacity F_{est} of the connection (established based on the results of the previous campaign): the load is increased up to $0.4 \cdot F_{est}$, then reduced to $0.1 \cdot F_{est}$, and thereafter increased until failure. The load and the displacements of the steel plates (relative to the timber member) on both connections (Fig. 6) were continuously measured throughout the tests.

4.2 Results

The results of the tensile tests at normal temperature of both experimental campaigns are presented in Table 3, and the effect of the reinforcement is shown in Table 4.

A detailed analysis of the tests at normal temperature is outside the scope of this paper, but a few remarks should be considered. In the connections with multiple shear planes (D01.1.R, D03.1.R and D04.1.R), the minor influence of the reinforcement on the load-carrying capacity is mainly because these connections are already highly optimised [17] and the need to conceal the screws reduces their effectiveness (commercially available shorter screws have smaller diameters). In the D01.1.R connections, for instance, the reduced net cross-section due to the high number of holes and slots is further reduced by the screws and therefore earlier brittle net-section tension and block-shear failures were observed (confirming the results by Stapf et al [9], who reported that screws did not prevent block shear failures). In connections D04.1.R, the wood member between the two steel plates was wide enough to induce plastic hinges in the dowels and the reinforcing screws were not fully exploited. On the other hand, in connections D05.1 (only one steel plate), the screws reduce the embedment of the bent dowels in the wood next to the steel plate, therefore improving both load-carrying capacity and ductility.

Table 3: Results of the tests at normal temperature

Connection typology	Load-carrying capacity		Slip modulus	Ductility
	R_{mean} [kN]	R_k [kN]	$k_{s,\text{mean}}$ [kN/mm]	D_{mean} [mm/mm]
D01.1	482 (8%)	425	369 (24%)	14 (26%)
D01.1.R	439 (2%)	375	218 (16%)	5 (48%)
D03.1	230 (3%)	204	369 (13%)	8 (16%)
D03.1.R	234 (5%)	200	218 (16%)	12 (15%)
D04.1	414 (2%)	366	154 (14%)	4 (36%)
D04.1.R	420 (2%)	359	150 (16%)	4 (23%)
D05.1	103 (1%)	88	257 (11%)	7 (27%)
D05.1.R	129 (4%)	110	219 (17%)	14 (16%)

Note 1: Coefficient of variation of the test results shown in parentheses.

Note 2: Characteristic 5-percentile value R_k determined according to EN 14358:2006 [16].

Note 3: Ductility is defined as the ratio between the ultimate and the yield displacements $D = d_u / d_y$, according to EN12512:2001+A1 [17]. Yield displacement d_y calculated by fitting two linear segments to the load-displacement curve using the least squares method (assuming the slope of the elastic segment is the experimental joint slip value k_s).

Table 4: Effect of the reinforcement at normal temperature (reinforced/unreinforced ratio)

Connection typology	Load-carrying capacity		Slip modulus	Ductility
	R_{mean}	R_k	k_s	D_{mean}
D01.1	0.91	0.88	0.59	0.33
D03.1	1.02	0.99	0.98	1.56
D04.1	1.02	0.98	0.85	1.02
D05.1	1.26	1.26	1.14	2.04

Note: If the ratio is higher than 1, then the reinforced connection exhibits higher values than the unreinforced connection.

5. FIRE RESISTANCE TESTS

5.1 Procedure

The fire resistance tests were conducted in the small furnace of the Laboratory for Fire Testing at the Swiss Federal Laboratories for Materials Science and Technology (Empa), in Dübendorf, Switzerland. The test specimens were attached to a steel frame, on top of the furnace, and enclosed in an insulated outer covering (Fig. 8). The specimens were then loaded up to the target load level ($0.3 \cdot R_{\text{mean,unreinforced},20^\circ\text{C}}$) a few minutes before being exposed to the standard ISO 834 fire curve. The target load level was kept constant throughout the fire test. After failure, the specimens were promptly removed from the furnace and cooled with water.

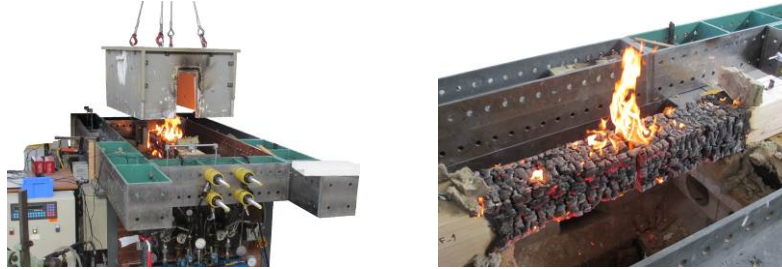


Figure 8: End of a fire test in the small furnace at Empa.

5.2 Results

The main results of the fire resistance tests are presented in Table 5 and the effect of the reinforcement in Table 6.

Table 5: Results of the fire resistance tests

Connection typology	Fire resistance	Load
	$t_{fi,mean}$ [min.]	E_{fi} ($0.3 \cdot R_{mean,unreinforced,20^\circ C}$) [kN]
D01.1	33.0 (32.0; 34.0)	145
D01.1.R	32.0 (32.0; 32.0)	
D03.1	32.5 (32.0; 33.0)	69
D03.1.R	41.5 (42.0; 41.0)	
D04.1	34.8 (34.5; 35.0)	124
D04.1.R	34.0 (34.0; 34.0)	
D05.1	34.0 (34.0; 34.0)	30
D05.1.R	39.5 (40.0; 39.0)	

Note: Test results shown in parentheses.

Table 6: Effect of the reinforcement on the fire resistance (reinforced/unreinforced ratio)

Connection typology	Fire resistance $t_{fi,mean}$
D01.1	0.97
D03.1	1.28
D04.1	0.98
D05.1	1.16

The reinforcement was effective in significantly increasing the fire resistance in connections D03.1.R and D05.1.R, but not in connections D01.1.R and D04.1.R.

As in the tests at normal temperature, the failure mode of connections D01.1.R and D04.1.R was not influenced by the reinforcement. In the first case the screws did not prevent block shear failures in the internal timber members (Fig. 9, left), and in the second case screws were not effective, as internal timber member were wide enough (and protected by the outer steel plates) to impose a plastic hinge in the dowels even without screws (Fig. 9, right).



Figure 9: Failure modes of connections D01.1.R-1 (left) and D04.1.R-1 (right) in the fire tests.

Regarding connections D03.1, fire resistance increased approximately from 30 to 40 minutes with the reinforcement. The screws induced plastic hinges in the fasteners and delayed the splitting failures reported in the unreinforced connections (Fig. 10, left). It should be noted that the screws did not improve the load-carrying capacity of these connections at normal temperature, but significantly increased their ductility.

In the D05.1 connections, the reinforcement successfully increased the embedment resistance (which was the observed failure mode in the unreinforced connections in fire), but, as the screws were too long and prematurely exposed to fire, higher fire resistances might have been achieved if the screws were more protected (Fig. 10, right).



Figure 10: Failure modes of connections D03.1.R-1 (left) and D05.1.R-1 (right) in the fire tests.

6. CONCLUSIONS

Steel-to-timber dowelled connections reinforced with self-drilling screws were tested at normal temperature and under ISO 834 fire exposure.

The tests at normal temperature show that the reinforcement had a small influence on the load-carrying capacity of the tested connections with multiple steel plates, but can have a major influence on ductility. The fire resistance tests showed that the reinforcement with screws increased the fire resistance of some of these connections and, if their fire performance is to be derived from the behaviour at normal temperature, not only the load-carrying capacity but also ductility and the failure mode have to be taken into account.

Regarding the behaviour of the connection with a single steel plate (two shear planes), the reinforcement increased both the load-carrying capacity and ductility at normal temperature and also the fire resistance, by effectively locally increasing the embedment properties. Further

investigations will be conducted to study this and other techniques to improve the fire resistance of these connections.

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