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FIRE SAFETY OF MID-RISE BUILDINGS WITH LIGHT TIMBER STRUCTURES – STUDIES OF THE FIRE RESISTANCE OF A NOVEL CONSTRUCTION SYSTEM

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ABSTRACT: A novel construction system with light timber structures is being developed for mid-rise timber buildings. Requirements for the fire resistance of the building elements and structures increase with taller buildings because the consequences of a fire are higher than for small buildings. Mid-rise buildings therefore need fire resistance of 60-90 minutes. Floor elements with light timber structures have been studied with regards to the fire performance. Experimental results for the floor construction designed for large spans are presented here. The experimental results show that it is possible to achieve fire resistance REI 90 or more for the floor. The results indicate that large void cavities in the construction delays the charring of the timber structure. The construction provides fire protection of the main beams throughout the full fire scenario.

KEYWORDS: Light timber frame, construction system, fire resistance, temperature development, void cavity

1 INTRODUCTION

1.1 BACKGROUND

Wood is a renewable resource, light, easily and locally available in most areas, and environmentally friendly. The focus on sustainability therefore makes timber structures attractive and its suitability is now evaluated for all types of buildings. Elements with light timber frames can be prefabricated with a high degree of completion, with insulation, cladding/flooring, etc. Prefabrication ensures high quality, and the work environment is better than outdoors. Installation of the elements is fast, which makes the construction time for a building shorter than with traditional methods, reducing the time-related costs and exposure to wind, rain and frost [1]. An important challenge for mid-rise and tall buildings with light timber structures is the fire safety. The performance-based building regulations developed in Europe and many other countries the 1990s allowed for larger timber buildings than previously. However, the research focus has since mainly been on development of heavy timber structures for large buildings [2].

1.2 A NOVEL CONSTRUCTION SYSTEM

A novel floor construction is developed for spans of approximately 8 m, which is longer than what is possible for traditional light timber floors. The structure is therefore designed to achieve a higher stiffness and strength. A novel solution to enable installation of the noise reducing ceiling in the factory is developed to achieve a higher degree of prefabrication. The construction is also designed to give long fire protection of the main load-bearing structure.

1.3 OBJECTIVES

The main objective of the project is to develop a novel construction system with light timber structures and a high degree of prefabrication, for buildings with 5-8 floors with large open spaces. The main objectives of the experiment presented in this paper were to study; the fire resistance performance of the novel floor construction, whether it is possible to prevent involvement of the main structural members in the full duration of the design fire scenario, if the insulation would fall out during the fire and if the large void cavity would delay the thermal exposure on the timber construction. The fire behaviour during exposure to a "complete" fire development, including the cooling phase, is studied as this is a requirement for mid-rise timber buildings in Norway [3].

2 METHOD

2.1 TEST SETUP

The standard test method described in EN 1365-2 [4] was used. The floor specimen is placed on top of a horizontal furnace with dimensions 3080 mm x 4060 mm, see Figure 1. Siporex elements are used to cover the furnace completely, as the specimen is not wide enough, see pt. 2.2. A few deviations from the test method were made; on the cold side of the floor only the thermocouples for measurements of the average temperature change were installed, external load was not applied on the floor during the test because the span across the furnace is too short to

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test the load bearing capacity for a structure as stiff as this floor. Numerous additional thermocouples were installed inside the construction. The planned temperature-time curve was also different than described in the test method, see pt. 2.4.

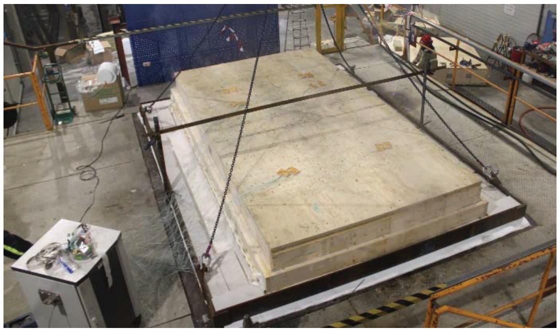

Figure 1: The floor specimen mounted on the horizontal furnace (Photo: RISE Fire Research AS)

2.2 TEST SPECIMEN

The novel floor construction is optimized with respect to the strength and stiffness, and to protect the load-bearing structure. The specimen is 2400 mm wide and 4382 mm long, with free span of 4300 mm. Description of the floor, see also Figure 2:

(1) wooden board
(2) structural timber beams
(3) structural timber flange
(4) ceiling system with 2 x 15 mm fire rated gypsum boards, acc. EN 520 [5]
(5) stone wool insulation, acc. EN13162 [6].

The cavity between the gypsum boards and timber structure is larger than 50 mm deep. The three main beams in the specimen are numbered BA1, BA2 and BA3.

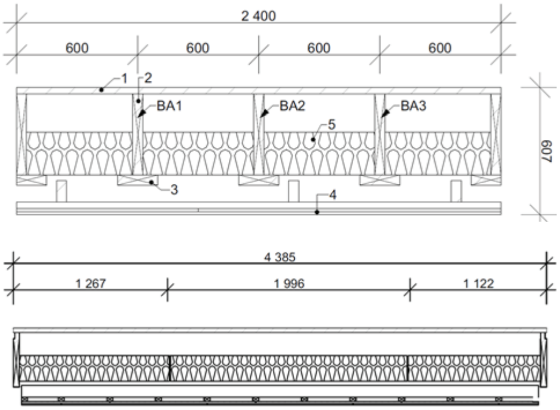

Figure 2: Floor construction, cross-section (top) and longitudinal section (bottom). Measurements in metre (m) (Ill.: Støren Treindustri AS)

The gypsum boards in the ceiling, the flanges and the insulation between the beams are, among other factors, designed to maximize the performance during fire. The load-bearing structure is made of structural timber. The specimen was stored inside the lab for 6 days before testing, at approximately 21°C. The moisture content in the components was not measured.

2.3 INSTRUMENTATION

Instrumentation of the floor was partly according to the test standard EN 1365-2 [4], but with additional instrumentation at three locations inside the construction to gain more knowledge and information about the temperature development inside the floor. The three locations are on/near beam BA1 at distance 966 mm from one end of the floor, on/near beam BA2 at distance 2193 mm from one end of the floor, and on/near beam BA3 at distance 1092 mm from the other end of the floor. Thermocouples of the type Quick-Tip were installed on and inside the beams, and at several other positions at the three locations. Figure 3 shows the positions on the surfaces of the flanges and beams, and the positions on/between each layer.

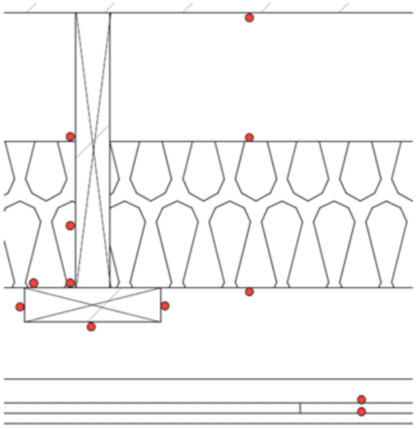

Figure 3: Instrumentation on the surfaces inside the construction (Ill.: Støren Treindustri AS)

Thermocouples were also drilled into the flanges from the top, see Figure 4. To measure the temperatures in the vertical direction, thermocouples are positioned at a distance of 10 mm to the side of the beam, see Figure 5. Depths from the underside of the flanges are 8, 18, 28, 38 mm. Horizontal measurements are positioned 10 mm below the top surface of the flange, at depths from the lateral side 10, 20, 30, 40, 50 mm.

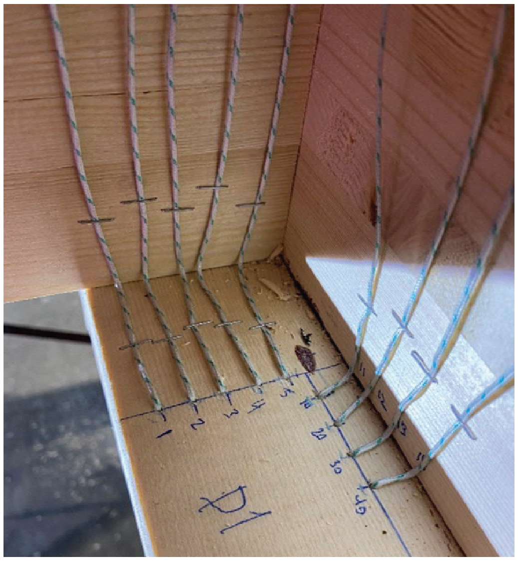

Figure 4: *The TCs inside the flange were drilled into the wood from the top of the flange*

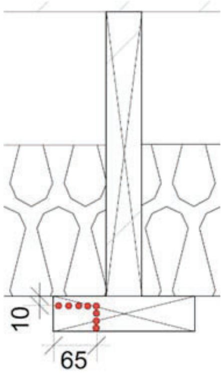

Figure 5: *Instrumentation inside the flange of the main beams (instrumentation group D) (Ill.: Støren Treindustri AS)*

2.4 TEST CONDITIONS

The furnace temperature followed the standard temperature-time curve given in EN 1991-1-2 [7] for 90 minutes. After 90 minutes the temperature was planned to decrease, with a cooling rate of 20°C/minute to represent the cooling phase of a complete fire, see the blue curve in Figure 6. Cooling was planned to be achieved by reducing, and eventually turning off, the gas burners, and removing the Siporex elements on the sides of the specimen.

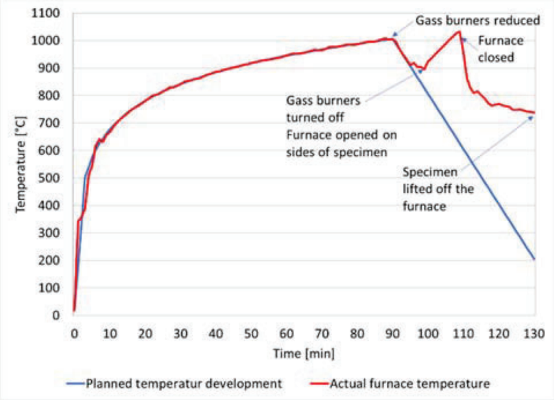

Figure 6: *Planned (blue) and achieved (red) temperature-time development in the furnace*

3 RESULTS AND DISCUSSION

3.1 TEMPERATURE MEASUREMENTS

The temperatures in the furnace and inside the floor were not registered during the time-period 100-109 minutes, because the logging stopped when the gas burners were turned off after 100 minutes. In the figures showing the results, a straight line is drawn between these two points. However, this might not be the actual temperature development. This does not affect the analysis of the results where charring of the wood has started, but can give a few minutes error for the reading of when charring temperatures of 300°C were reached on the top of the flange and inside the flanges. The error is less than 9 minutes.

Before lifting the specimen off the furnace after 130 minutes, the cables for the thermocouples had to be cut because they were too short. The temperatures in the specimen were therefore not measured after this.

The specimen was left outside the furnace until 255 minutes, i.e. 125 minutes after lifting it off the furnace. No flaming combustion was observed during this period, only glowing. It was then cooled with water to stop the combustion.

3.2 FURNACE TEMPERATURE

The planned temperature development in the furnace was difficult to achieve, and the cooling phase became different than planned, see Figure 6. The gas burners were reduced after 90 minutes to decrease the temperature, and turned off after 100 minutes when the cooling no longer followed the planned curve. At the same time, the Siporex elements on the sides of the specimen were removed. However, cooling at the planned rate was still not possible, mainly due to the free surfaces of flanges and other combustible material. After 130 minutes, the floor was therefore lifted off the furnace for continued cooling, but without external extinguishment, see Figure 7. The presence of combustible materials such as the flanges

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made it difficult to decrease the temperature in the furnace after the gypsum board fall-off, and removing the Siporex increased the supply of Oxygen. These are the main reasons the planned cooling was not achieved.

Figure 7: Lifting the floor off the furnace to achieve cooling

The temperature development inside the cross-section and flanges might be affected by the elevated temperatures during the cooling phase, with a quicker temperature increase than if the cooling had evolved as planned. It is not possible to determine the scale of this.

3.3 TEMPERATURE DEVELOPMENT INSIDE THE FLOOR

Temperatures between all layers and on the surfaces were measured with thermocouples, as described in pt. 2.3. Figure 8 shows the average of the temperature development at each position, based on three measuring points. Observed fall-off of the gypsum boards and measurements of start of charring of the flanges are given in Table 1. The charring temperature of wood is defined to be 300°C in EN 1995-1-2 [8]. Time to start of charring is therefore determined by the time at which the temperature on the surface of the wood reaches 300°C.

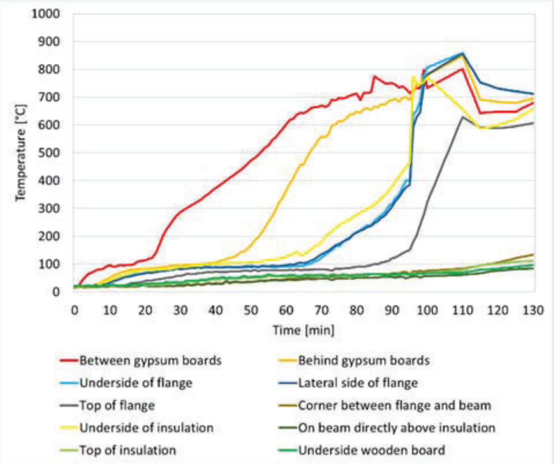

Figure 8: Temperature development through the floor at different positions, average of the three measuring locations in the floor

Table 1: Time until fall-off of gypsum boards and start of charring of wooden battens and flanges

Measuring point	Results
Temperature behind gypsum boards >300°C	57 min
Temperature on underside of insulation >300°C	83 min
Temperature on underside of flanges >300°C	88 min
Temperature on lateral sides of flanges > 300°C	89 min
Fall-off second gypsum board layer	95 min

Figure 8 shows a considerable difference between the temperature behind the gypsum boards and on the undersides and lateral sides of the flanges. The temperature on the unexposed surface of the gypsum boards increased fast after evaporation of the moisture in the boards, while on the other surfaces the heating rate was considerable slower. At its maximum the difference is approximately 370°C. This is probably caused by the large void cavity, which delays the temperature development considerably.

Charring temperatures behind the gypsum boards were reached after 57 minutes, but on the flanges, charring only started after 88-89 minutes. Charring of the flanges was, in other words, delayed by approximately 31 minutes. As mentioned above, this is probably mainly due to the large void cavity between the gypsum boards and flanges. The positive influence of a void cavity of a certain depth has been reported by Schleifer [9], and is included in design models for determination of the fire resistance of light timber frame assemblies [10]–[12].

3.4 FIRE PROTECTION PROVIDED BY THE GYPSUM BOARDS

Charring temperature 300°C was reached behind the gypsum boards in the ceiling after 57 minutes. Both gypsum board layers had fallen down after 95 minutes. The combination of fire protection provided by the boards and the large void cavity contributed greatly to prevent charring of the wooden structure before 88 minutes into the fire exposure.

The gypsum boards provided fire protection longer than expected based on guidance given in [10], [11], where 2 x 15 mm fire rated gypsum prevents charring for 46 minutes and falls down after 57 minutes. The design methods, developed to calculate the fire resistance of load-bearing timber structures and fire separating building elements, are meant to be conservative to cover most products on the market. Based on the results, the gypsum boards used in this experiment had better fire properties.

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3.5 CHARRING

Charring of the timber structure in the floor element started at approximately 88 minutes, when the undersides and lateral sides of the flanges reached 300°C, see Table 1. This is 31 minutes after the temperature behind the gypsum boards in the ceiling reached 300°C. As described in pt. 3.1, this indicates that the large void cavity in the floor element significantly delayed the start of charring behind the gypsum boards in the ceiling. Calculations based on the design methods given in [10], [11] do not account for an effect of this magnitude from void cavities.

The temperature development in the flanges measured by the thermocouples drilled into the wood is shown in Figure 9 for vertical direction, and in Figure 10 for horizontal direction. See Figure 5 for the positions of the thermocouples.

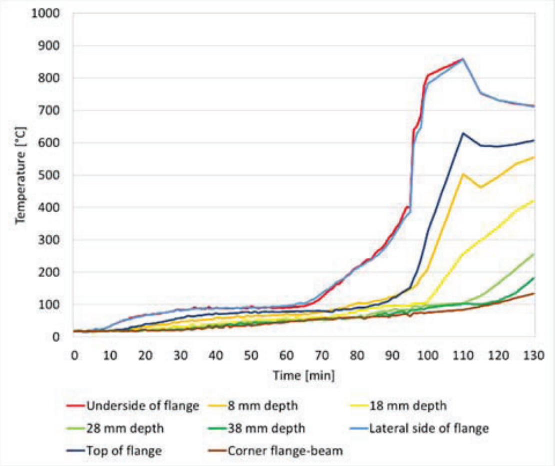

Figure 9: *Temperature development inside the flanges at depths 8, 18, 28, 38 mm from the underside, average of the three measuring locations in the floor*

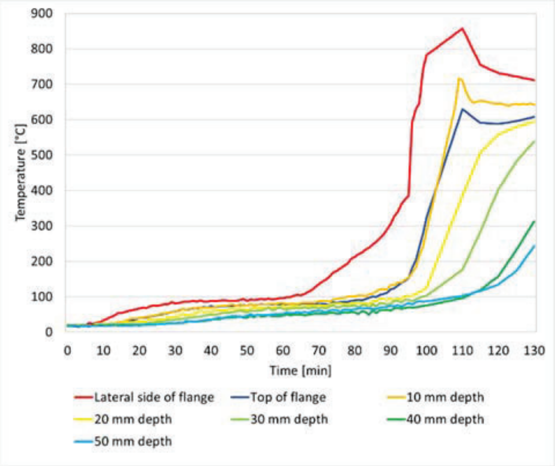

Figure 10: *Temperature development inside the flanges at depths 10, 20, 30, 40, 50 mm from the lateral side, average of the three measuring locations in the floor*

The average char depths of the flanges after 90 and 130 minutes, based on the temperature measurements inside the flanges, are given in Table 2.

On top of the flange the temperature approximately 20 mm in from the corner, see Figure 3, follows the temperature at depth 10 mm in the flange from lateral side. This indicates that there is some air leakage between the flange and the insulation. This leakage is negligible in the corner between the flanges and beams, at distance 75 mm from the lateral side of the flanges.

The residual cross-sections of the flanges were also measured physically after the fire experiment at three positions, see Figure 11 and Table 2. These are not at the same positions as the thermocouples. Residual height and width, plus width of the "shelf" of the flange for insulation to rest on, are similar to the last readings before the thermocouples were disconnected after 130 minutes, see Table 2. The cooling phase continued after this for approximately 125 minutes, but the charring of the timber stopped early in the cooling phase or the charring rate decreased considerably.

Figure 11: *The residual cross-sections of the flanges after the fire experiment. The main load-bearing beam is discoloured but not charred*

Table 2: *Average char depth at 90 minutes, when the specimen was lifted off the furnace at 130 min, and after the experiment*

Measuring point	**Char depth at 90 min**	**Char depth at 130 min**	**Char depth after experiment**
Flange height	5 mm	31 mm	27 mm
Flange width	7 mm	48 mm	49 mm

The char depth varied considerably between the measuring locations, between 2-25 mm, with largest variation for the height of the flange.

Charring after the specimen was lifted off the furnace and the surrounding temperature dropped to around 20°C, during the 2 hours before extinguishment, was negligible.

The charring rates during the different phases of the charring of the flanges are given in Table 3. The phases are:
Phase 2 – before fall-off of gypsum boards
Phase 3 – after fall-off of the gypsum boards
Phase 4 – after the char layer has reached a thickness of 28-30 mm.

Table 3: *Charring rates during different phases*

Charring phase	**Vertical direction**	**Horizontal direction**
Phase 2, before fall-off	0.60 mm/min	0.89 mm/min
Phase 3, after fall-off	0.74 mm/min	1.38 mm/min
Phase 4, char layer min. 28-30 mm	0 mm/min	0.70 mm/min

Charring on the lateral sides of the flange is faster than on the underside, with 10 mm larger char depth at 130 minutes. This is due to the simultaneous heating from the underside.

3.6 FIRE PROTECTION OF THE MAIN LOAD-BEARING STRUCTURE

The novel design of the floor, with 2 x 15 mm fire rated gypsum boards, large void cavity and flanges under the beams, protected the main load-bearing beams and prevented charring of them for the duration of the fire experiment. In addition to the fire protection given by the gypsum boards and the cavity reported above, the flanges prevented charring of the beams from below. The flanges also held the insulation in place and prevented charring from of the lateral sides of the beams.

3.7 FIRE RESISTANCE

Fire resistance of the floor is at least 90 minutes for both the load-bearing and fire separating properties. No external loading was applied on the floor in the experiment. This is because the structure has high strength and stiffness, and it would therefore not be possible to apply a sufficiently large load to cause noticeable deflections. The floor will have little deflection also with a span of 8 m. It can therefore be assumed that the fire protection with gypsum boards will remain intact also in a real building.

4 CONCLUSIONS

An experiment has been performed to study the fire behaviour of a novel floor construction with light timber structure during a "complete" fire development, including cooling phase. The main findings are:

- it is possible to achieve fire resistance of 90 minutes or more for the floors load-bearing and fire separating properties,
- the large void cavity between the gypsum boards and wooden surfaces of the structure delays the charring of the timber structure,
- the construction provides fire protection of the main load-bearing beams throughout the fire,
- the experimental results were significantly better than results from design methods, mainly due to longer fire protection provided by the gypsum board and the effect of the large void cavity,
- the insulation is held in place by the flanges throughout the fire experiment,
- the charring stopped when the specimen was lifted off the furnace.

Achieving a cooling phase in the furnace was difficult due to the large surfaces of the combustible elements in the specimen.

The effect of the void cavity should be studied further, and design methods improved to account for this effect.

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