



Fire Performance of Steel-Timber Hybrid Beam Section

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Abstract. Slim-floor-type of steel-timber hybrid floor systems which use steel beams contained within the depth of the cross-laminated timber (CLT) floor slab offer many benefits, but there is still very little research available on the fire resistance performance of these systems. In the study presented in this paper two furnace tests and numerical simulations have been conducted to investigate the thermal profiles of the steel member and CLT slabs and to obtain information on the temperature development and charring of the hybrid beam section when it is exposed to standard fire conditions. Also, the effects of intumescent fire protection on temperatures and charring performance were investigated. Numerical 2D thermal simulations for unprotected and protected cases were conducted using SAFIR software, and the agreement between experiments and numerical-analysis predictions were in general very good. The results show that intumescent protection reduces the temperatures of the steel and CLT components as well as charring depth significantly, and the start of charring at CLT slab support may be delayed if intumescent paint protection thicker than that required for the load bearing steel member is used. The result also showed that CLT temperatures exceed 100°C already in the early stages of the fire which decrease the strength and stiffness properties of CLT much before the start of charring. Therefore, the fire design of the CLT slab support should not only consider the char depth and residual cross-section analysis but also the reduction in strength.

Keywords: Steel-timber, Composite beam, Hybrid beam, Slim floor, CLT, Fire resistance, Charring

1. Introduction

Steel-timber hybrid beam systems have recently been studied and developed in many configurations as they enable light and shallow floor construction with longer spans compared to traditional timber construction. Other benefits include high speed in installation, dry construction, recyclable components and, in the case of slim-floor-type of construction, a flat soffit. In the slim floor construction, the steel sections are encased partially within the timber floor and the good fire

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resisting qualities of timber can be used to reduce the heat transfer into the hybrid section. However, very limited research and design guidance is available on the fire performance and resistance of these beam solutions.

The structural fire design of CLT panels is normally based on standardised fire tests as well as approved calculation methods and charring rates presented, for example, in EN 1995-1-2 [1]. At present, there is very limited information available about the fire performance of CLT panels at the beam support of a steel-timber hybrid floor system. The steel beam protects the panels from direct fire exposure but also transfers heat deeper into the floor, thereby increasing the temperature of the wood adjacent to or in direct contact with the steel section. Charring of the CLT floor slab and the loss of strength of timber through heating affects the floor slab's shear and bearing resistance and can also reduce the efficiency of possible shear connectors used to attain composite action between the slab and beam. It is therefore important for the slab and beam design that there is reliable information available on thermal profiles and the heat impacted timber that occurs locally at steel-to-CLT interface during a fire.

Barber et al. [2] have studied numerically the thermal profiles of a steel-timber hybrid beam system where the structural steel section protected by intumescent coating was located beneath the timber floor slab. In this construction heat was transferred into the CLT slab via the top flange of the steel beam and screws connecting the top flange to the CLT slab. The numerical results indicated that it is difficult to prevent the charring of CLT above the beam top flange even if the beam is fire-protected through intumescent coating. Based on the results, the support reaction forces from the CLT floor slab are to be transferred to the steel beam through a charred wood layer. West et al. [3] report the results of a loaded fire test on a slim-floor-type of construction, with the steel beam (DELTABEAM) contained within the depth of the CLT floor slab. In this system the welded steel beam section and the gaps between the vertical ends of CLT panels and steel beam webs were filled with concrete. The bottom flange of the steel section and the CLT panels were not fire-protected from underside. Based on the observations made after the test, the vertical charring of CLT panels at the beam support at 90 min was around 50 mm. In this beam solution, the design assumption is that the support reaction forces are transferred to the beam section through a compression arch locating above the char layer.

Heinisuo et al. [4] have introduced a hybrid slim floor system consisting of CLT panels installed on the top of a steel plate welded to a rectangular hollow steel section, as shown in Fig. 1. No design guidance is available to help determine the amount of heat transferred through the steel hollow section into CLT slabs or to assess the char depths that occur locally at the slab support area. In the recommended practice by American Wood Council [5] it is required that all components of a connection are to be protected so that no part of the connection is exposed to an individual temperature rise of 181°C. The method limits the temperatures well below the charring temperature of timber and significant fire protection is required to meet this condition. Intumescent paint protection may only provide a limited solution as the paints are not fully active to limit the steel temperatures

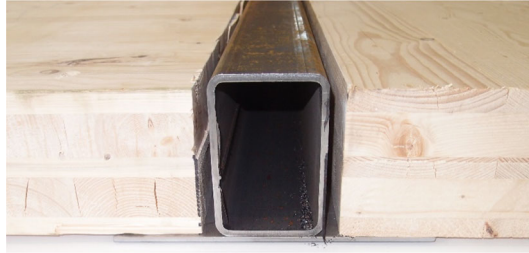


Figure 1. Slim-floor type of a steel-timber hybrid beam consisting of a CLT slab and a steel beam consisting of an RHS section and steel bottom plate.

until 300–350°C and at these temperatures the timber in contact with the steel has already lost strength and charred [6, 7].

This paper presents the experimental and numerical studies carried out to obtain more realistic and reliable information on the temperature development, thermal profiles and charring of the hybrid beam section when it is exposed to standard fire conditions. Fire safety design of buildings is conventionally based on prescriptive fire-resistance ratings of individual building elements and the rating is determined using standard fire resistance tests, where the time–temperature curve corresponds to the ISO 834 standard [8]. The standard fire conditions do not reflect a real fire, especially in a fire compartment where a part of the wooden surfaces remain visible and are therefore exposed to fire, but it provides a relative measure of fire resistance. In this study a reference is made to a 60-min fire rating which is a typical requirement for office and multi-story residential buildings. In further research, it is important to investigate other fire scenarios as well. Broadening the research topic to natural fire models will require a much larger experimental and numerical approach.

The aim of the study was to determine how the charring of the CLT slab should be considered in the structural fire design of the slabs and hybrid beams. The effects of intumescent paint protection on temperatures and charring performance were also investigated. Based on the experimental results, a numerical model including the performance of intumescent fire paint and applicable to everyday structural fire design applications was developed. The model was used to assess if intumescent paint protection thicker than required for the fire resistance of the steel beam member is able to prevent the start of charring at CLT panel support for the duration of the required fire resistance time. In these experimental investigations the main intention was to clarify temperature and charring development and the number of parameters affecting the results was minimized. Therefore, the effects of external loading have not been studied and the tests were conducted unloaded. To complement the results with loaded tests, the experimental set-up and instrumentation must be developed for further research.

2. Experimental Research

Two fire tests were carried out to investigate temperatures in CLT and steel components as well as the charring of CLT adjacent to the steel-beam section. The beam sections, unprotected in the first test and fire-protected in the second test, were exposed to standard fire test conditions in accordance with EN 1363-1 [9]. The tests were conducted unloaded.

The test specimens were installed on the top of a full-scale fire test furnace chamber with internal dimensions of 3000 mm × 3000 mm × 1200 mm (height × width × depth), and they formed part of the furnace roof structure. The char development in CLT members was estimated based on visual observations made after tests and on temperatures measured inside the specimens during the test. The position of the char line in the test specimen was assumed as the position of the 300 °C isotherm [1].

2.1. Test Specimen and Setup

In a fire test, the steel beam was installed across the 1, 2 m wide opening of the furnace chamber. The beam section was made of a 150 × 100 × 6 mm (RHS) rectangular steel hollow section welded to a 300 mm wide and 6 mm thick steel bottom plate. A schematic vertical cross-section of the test set-up and specimen are shown in Fig. 2. In the first test, the steel beam was unprotected. In the second test, the underside and sides of the steel bottom plate were fire-protected with intumescent paint (Tikkurila Fontefire ST60-1 with TERMACOAT GPL-S primer). The coating thickness was chosen in such a way that it would limit the temperature of the steel bottom plate to less than 600 °C at 60 min. The paint was applied using a brush in the testing laboratory.

CLT panels (600 mm × 1200 mm) were installed on both sides of the steel beam and supported on the bottom plate of the beam. 10 mm vertical air gaps were left between the steel beam web and the vertical face of the panels. This was considered to be an adequate adjustment tolerance for CLT element installation on construction site. Typically, this space is filled with, for example, concrete. However, in this study it was left unfilled, which was assumed to lead to conservative results. The 10 mm gaps were closed from above with cement-bonded fibre-board strips mounted on the top of the gap, as Fig. 3 shows. The other ends of the panels were supported from aerated concrete slab elements. The panels were unsupported along the furnace walls. The panel thickness was 140 mm, consisting of five layers (20–40–20–40–20 mm). The 20 mm thick lamellae ran perpendicular to the beam span. The CLT panels were made of spruce timber with a density of 425 kg/m³ and strength class of C24. The specimens had one-component polyurethane (PUR) adhesive. Before testing, test specimens were conditioned in climate conditions with temperature of 22°C and relative humidity of 50%. The moisture content of the CLT specimens on the day of testing was 10.7–11.0%.

After the termination of the test, the CLT elements were extinguished by immersing them in a pool of water. A crane located above the furnace chamber was used to lift and move the CLT panels. The first of the two CLT panels in a test was moved to the pool in less than 30 s. The second panel was moved to the pool immediately thereafter. The visual observations presented below were made from the first panel.

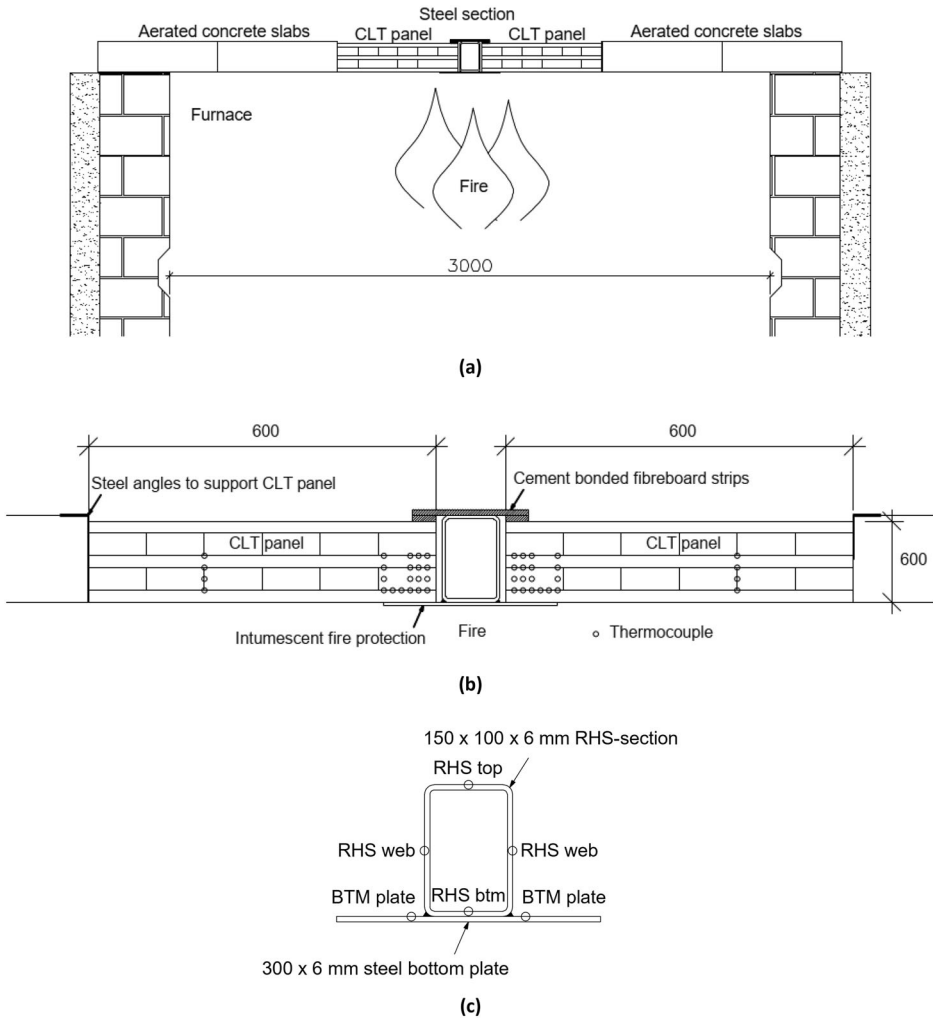


Figure 2. Schematic views of the vertical cross-sections through the (a) test furnace, (b) hybrid beam specimen and (c) positioning of thermocouples on a steel beam section.

2.2. Instrumentation

Steel temperatures were recorded using fibreglass-wrapped Type K24-2-305 thermocouples. Five thermocouples with a welded junction were installed into pre-drilled holes in an RHS section, and eight thermocouples were weld-fixed to the steel bottom plate and the bottom flange of the RHS section. The positioning of these thermocouples are shown in Fig. 2c.

A total of 44 thermocouples were used to measure temperatures inside the CLT panels, as Fig. 2b shows. The distance between the vertical edge of CLT panels

and the first set of measurement points and the horizontal distance between measurement points was 15 mm. In the unprotected beam test, sheathed K-type thermocouples installed in holes drilled horizontally and parallel to the exposed surface were used. The thermocouples were run through the air gap between steel web and CLT panels. The test results showed that this installation was not satisfactory because the heat transferred from the air gap and along the metal sheath affected the measurements, so they were considered unreliable. Therefore, for the unprotected case, the charring of the CLT panels is estimated based on visual inspection only. In the second test, with the fire-protected steel beam, temperatures inside the CLT panels were measured with fibreglass-wrapped Type K24-2-305 thermocouples installed in vertical holes drilled in the panels' unexposed face. To ensure the correct installation depth, the thermocouple wire installation was assisted with thin wooden sticks. After installation, the holes were sealed with fire-resistant mastic sealant.

2.3. Test Results

During the tests, furnace temperature, specimen temperatures, oxygen content within the furnace and the pressure differences between the furnace and test hall were monitored. Four plate thermometers were used to monitor the furnace temperature. The oxygen concentration was monitored in the middle of the furnace chamber using a Dräger EM200-E multi gas detector and the oxygen levels varied between 4 and 8%. Furnace temperatures and the oxygen concentrations measured during the test are reported in Fig. 4. The furnace pressure at the furnace ceiling level was set to 20 Pa.

Figure 5 shows the cross-section of the charred CLT panel supported by the unprotected steel bottom plate. This first test was terminated at 70 min, and the specimen was immediately extinguished. Based on visual inspection, the vertical charring had progressed through the first two lamella layers (20 mm + 40 mm). The charring depth is almost constant across the panel's width, and the steel bottom plate did not reduce charring behind the plate. Visual observations through the furnace camera showed that the first lamellae layer had fallen off at 36 min, but the part on top of the steel bottom plate remained in place until the end of the test. Horizontal charring depth measured from the vertical face of the top lamella adjacent to the steel web at 71 min was around 11 mm.

Figure 6 presents steel temperatures measured during the test. At 70 min, the temperatures of the steel bottom plate and the web were around 850°C and 700°C, respectively. At this stage, radiation from the steel web and the entry of hot gases through cracks formed in the charred layer above the steel bottom plate increased temperatures in the air gap and on the vertical surface of the CLT panel.

Figure 7 shows the cross-section of the charred CLT panel supported by a fire-protected steel bottom plate. Based on the visual observations through the furnace camera, the underside of the CLT panels started to char at 70 s after the commencement of the test and the reaction of the intumescent coating started at 120 s. The test was terminated at 60 min, and the specimen was immediately



Figure 3. Test set-up seen from above.

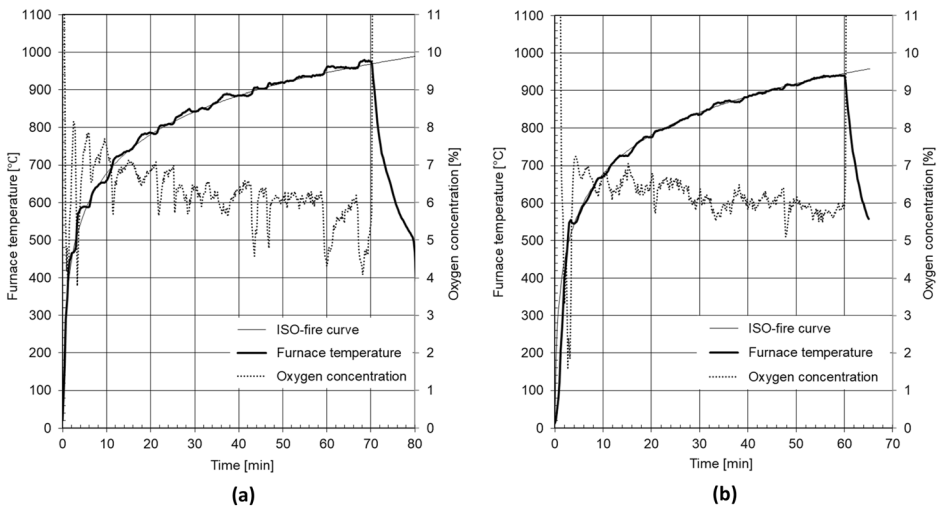


Figure 4. Furnace temperatures and oxygen concentrations measured during the fire tests for specimens (a) unprotected and (b) fire-protected floor beams.

extinguished. Based on visual inspection, the vertical charring of CLT panels far from the steel section was progressing in the second lamella layer. The position of the char line passed the first lamella layer and the mid-depth of the second layer at 30 min and 52 min after the commencement of the test, respectively. The temperature measured at the interface between the second and third layers at 60 min was 100°C. The charring depth was significantly reduced at the beam support, where the fire paint limits the heating of the steel. The charring affected the first lamella layer, and horizontal charring adjacent to the steel web was insignificant.



Figure 5. Residual cross-section of a CLT panel supported by an unprotected steel beam at 71 min of fire exposure. The CAD drawing corresponds to original dimensions.

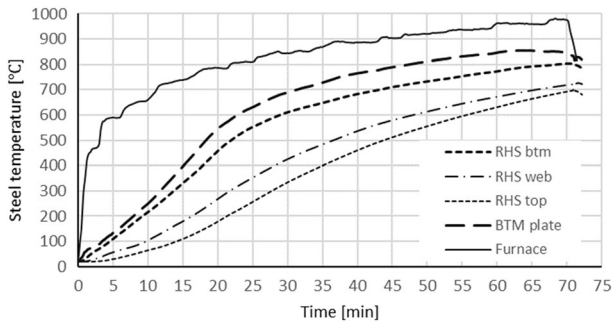


Figure 6. Temperatures of unprotected steel profile.

Figure 8 presents temperatures of the fire-protected steel-beam members. The results show that the temperature of the beam bottom plate and the web were around 580°C and 400°C at 60 min, respectively. After the test, the thickness of the activated intumescent fire paint was measured using a vernier calliper. The average thickness of the ash layer was 10.0 mm, see Fig. 9.

3. Numerical Simulations

3.1. Numerical Model

Numerical 2D thermal simulations for unprotected and protected cases were conducted using SAFIR (version 2022.a.3) [10]. The results from the numerical model are compared to those from the tests. The main objective is to investigate how well the thermal behaviour (including charring of CLT, radiation in cavities, behaviour of intumescent paint) of the considered section can be predicted using relatively simple numerical models that could be applicable to everyday structural fire design applications.

Figure 10 presents the numerical model for the fire-protected case. The model for the unprotected case is similar but naturally does not include the fire protection material. ISO 834 [8] fire was applied to the model's lower edge, and 20°C

ambient temperature was applied to the model's upper edge. Symmetry-boundary conditions were applied on the model's left and right edges.

Rectangular elements approximately $2 \text{ mm} \times 2 \text{ mm}$ were applied in the model (total of approx. 32 000 elements). The element size was chosen as small as it was practically possible so that the calculation times were reasonable for the purpose of this study (typically between 1 and 2 h). Potentially the element size could have been larger without compromising the accuracy, especially in CLT slab further from the connection. However, the benefits from this mesh optimization were considered relatively small and the same element size was applied for the whole model. The three cavities shown in Fig. 10 were modelled by using the VOID command in SAFIR, which required the use of a relatively small time step in the calculations (1 s in this case). The VOID command in SAFIR takes the convection and radiation in the cavity into account.

The following coefficients of heat transfer by convection were applied in the model: $25 \text{ W/m}^2\text{K}$ for fire-exposed side and $4 \text{ W/m}^2\text{K}$ for the non-exposed side [11]. Surface emissivities were as follows: 0.7 for steel [12], 0.9 for intumescent paint [7] and 0.8 for other materials [1]. For the paint thermal conductivity, a formulation proposed by Lucherini [7] was chosen to take the swelling of intumescent paint into account in some (relatively simple) way. Figure 11 shows the effective thermal conductivity curve used in the simulations. Table 1 summarizes the material properties and models applied.

Based on the visual observations made during the tests, the char layer against the steel bottom plate remains in place throughout the test even if the char fall-off is clearly visible further away from the steel section. The char fall-off was not taken into account in the simulations of this study. However, the possible effects will be briefly discussed later in this paper and studied numerically in the next phase of the research.

3.2. Results from Numerical Analysis

Figures 12 and 13 present the temperatures of the steel profiles from numerical analysis and a comparison to test results. Based on the figures, it can be concluded that on average, the steel temperatures from numerical analysis are slightly higher (conservative) than those from the tests.

The curves in Fig. 12 show that the numerical model produces temperature values higher than the temperatures measured in the tests in the first 20 min, with steel temperatures ranging from 100° to 600° . One clear reason for this difference could not be identified. The surface emissivity used for the steel bottom plate was 0.7 as per EN 1991-1-2. This value corresponds to the oxidized steel surface. However, the material used in the test specimen was new and clean, so the actual value is likely to be less than the value used. A lower value would result in lower steel temperatures. Other possible factors include the coefficients of heat transfer by convection and the airflows that may occur in the cavities of the structure. Since the aim of the study was to produce a simple design model, there was no desire to use non-standard values for the solution.



Figure 7. Charring of a CLT panel supported by a fire-protected steel beam at 61 min of fire exposure.

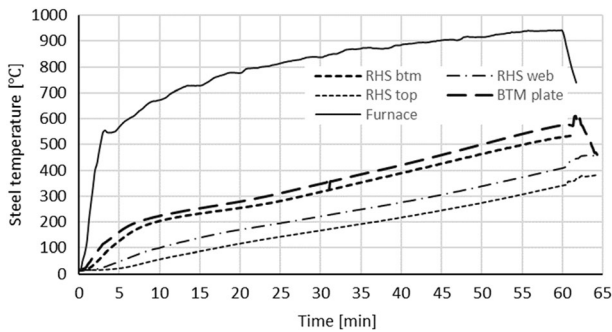


Figure 8. Temperatures of fire-protected steel profile.



(a)



(b)

Figure 9. Intumescent fire protection (a) during and (b) after the test.

Figure 13 shows that the numerical model underestimates the protected plate's temperatures in the early phases of the fire (approx. 2–13 min), then overestimates the temperatures until approximately 55 min, and finally leads to approximately the same temperature with the tests at 60 min. This behaviour was expected

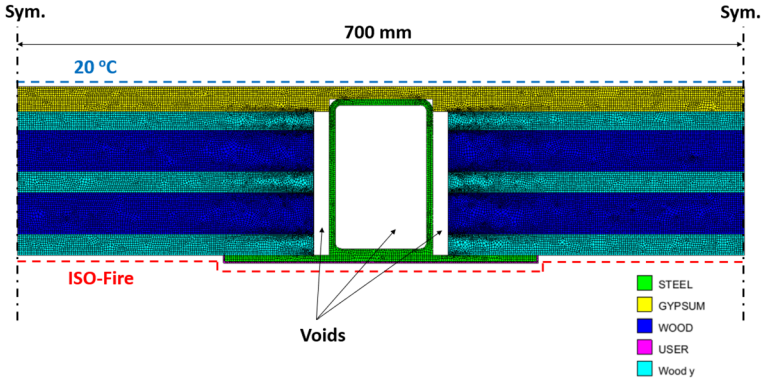


Figure 10. Numerical model of the fire-protected case.

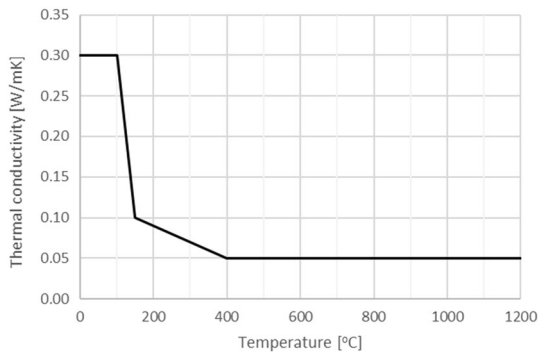


Figure 11. The applied model of the intumescent paint's thermal conductivity, based on [7].

because in the test, the bottom plate heats up quickly during the first minutes of the fire because the intumescent paint has not swelled up yet. The thickness of the intumescent paint in the model (1.7 mm) was calibrated so that the temperature of the lower flange at 60 min was essentially the same as in the test. The swelling of the intumescent paint is not modelled i.e. the thickness remains the same the full duration of the analysis. In reality, the intumescent paint expands approximately to 10 mm thickness. As the swelling is taken into account indirectly (using temperature-dependent thermal conductivity), the model doesn't capture completely the actual behavior of the fire protection. Consequently, the results can't be perfectly accurate.

However, it is considered that the accuracy in the analysis is adequate for typical structural fire design applications, where 'consistent level of crudeness' should be followed in the analysis. In order to obtain even more accurate results, the expansion of the intumescent paint should be modelled which is considerably more demanding and laborious task with limited benefits in the accuracy.

Table 1
Assumptions Related to Material Properties and Models

Material	Material model
Steel	Density: 7850 kg/m ³ [12] Temperature-dependent values for specific heat and thermal conductivity per EN 1993-1-2 [12]
Timber	Density: 425 kg/m ³ , based on the average value of the tested specimens Moisture content: 11%, based on the average value of the tested specimens Temperature-dependent values for specific heat and density per EN 1995-1-2 [1] Temperature-dependent values for thermal conductivity per EN 1995-1-2 [1]. Note that for the layers where the heat transfer occurs also in the direction of the grains (indicated as material “Wood y” in Fig. 8), thermal conductivity in horizontal direction increased by a factor of 2.0 based on [13–16]. It is understood that thermal conductivity in horizontal direction may have more effect on the charring if delamination occurs close to the support. This will be studied numerically in the next phase of this study
Gypsum board	The custom values of SAFIR type X gypsum board were applied. These values are based on studies by Cooper [17]. It is assumed that these values do not significantly affect the objective of this study because the gypsum boards are located on the non-exposed side of the structures, where the temperatures are relatively low
Intumescent paint	Density: 100 kg/m ³ [18] Specific heat: 1200 J/kg K [19] Thermal conductivity: Varies from 0.30 to 0.10 W/mK in the temperature range 20–100°C, from 0.10 to 0.05 W/mK in the range 100–400°C, after which it is assumed that full swelling has occurred and that the value remains constant, as proposed by Lucherini [7] based on multiple effective thermal conductivity curves The thickness of the protection was determined iteratively so that the temperature of the protected plate at 60 min was the same as in the test. The thickness was determined to be 1.7 mm. The procedure is described in the following: <ol style="list-style-type: none"> 1. Use sophisticated guess for the intumescent paint thickness, e.g. between 1 and 5 mm 2. Compare the temperature from the test (T_{test}) and from the model (T_{mod}) at 60 min of standard fire in the same point If $T_{\text{mod}} - T_{\text{test}}$ is between -5 °C and 5 °C, the thickness is considered appropriate. If $T_{\text{mod}} - T_{\text{test}} > 5$ °C, increase the thickness of the intumescent paint in the model and go back to item 1, and if $T_{\text{mod}} - T_{\text{test}} < -5$ °C, decrease the thickness of the intumescent paint in the model and go back to item 1

Figure 14 shows a comparison of the experimental and numerical results at the end of the tests. The brown line indicates the 300°C isotherm from the numerical analysis and can be considered the charring line of the CLT panel. Figure 15a represents the unprotected and Fig. 15b fire protected steel section. Figure 15 presents the charred part of the CLT panel (300°C isotherm) from the numerical analysis at 60 min. Figure 15a shows the charring depth of the unprotected steel section and Fig. 15b of the fire protected section. The red portion indicates members and areas where temperatures are above 300°C. The figures show that numerical analysis predicts the charring depths relatively well at the support. For the unprotected steel beam, the horizontal charring depth is slightly underestimated

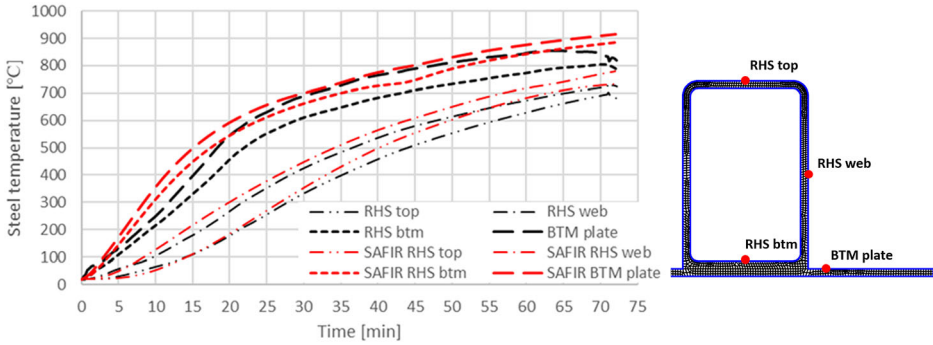


Figure 12. Temperatures of the unprotected steel profile from the numerical analysis as well as a comparison to test results.

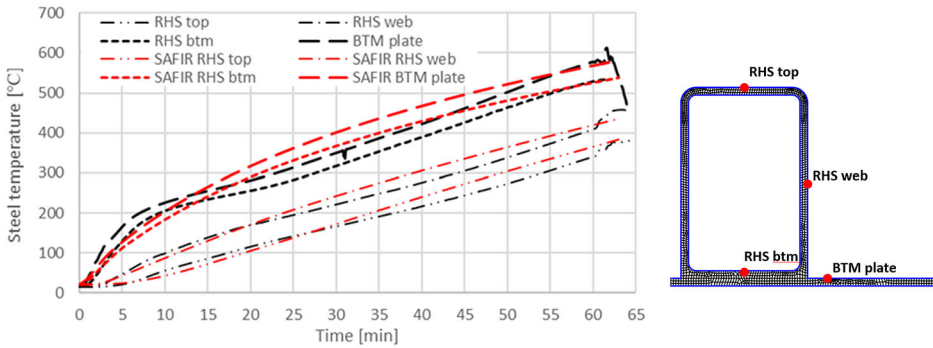


Figure 13. Temperatures of the fire-protected steel profile from the numerical analysis as well as a comparison to test results.

and on the unsafe side. For the protected beam, the horizontal charring depth is overestimated, leading to conservative results. In both cases, the vertical charring depth above the bottom plate is slightly higher than from the test, leading to a conservative estimate. However, when moving further from the support or the bottom plate, the numerical model underestimates the charring depth of CLT due to the delamination, for which the model does not account. This suggests that delamination should be included in the model if it is a relevant factor in the connection design. In this case, it is assumed that delamination does not affect the connection’s behaviour but naturally needs to be accounted for in the fire design of the CLT panel.

Figure 16 presents charring depths calculated by numerical simulations in different locations and directions. C1 and C2 refer to vertical charring depth over time far from the beam support (symmetry edge of the model) and at mid-width of the steel bottom plate, respectively. C3 refer to the horizontal charring depth at mid-depth of the CLT panel.

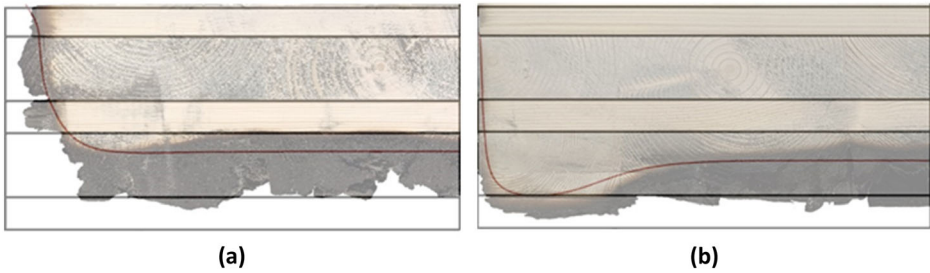


Figure 14. Comparison of test results with simulation results at the end of the tests. Charring depth of the CLT panel above: (a) the unprotected steel beam bottom plate at 71 min and (b) the fire-protected steel beam bottom plate at 61 min of fire exposure. The brown line indicates the 300°C isotherm from the numerical analysis.

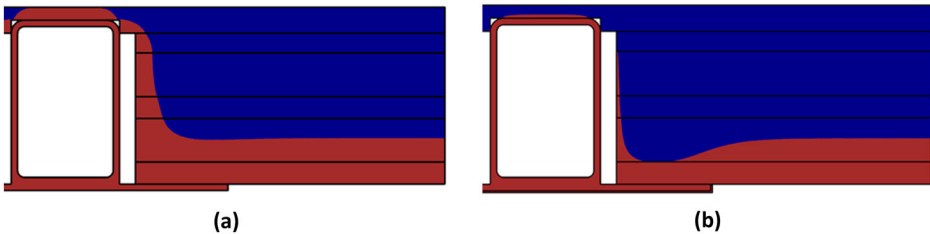


Figure 15. Charring depth of the CLT panel (300°C isotherm) from the numerical analysis at 60 min: (a) the unprotected beam section and (b) the fire-protected steel beam bottom plate. Red area representing areas where temperatures exceeded 300°C at 60 min.

The comparison between curves C1 and C2 (Unprotected) shows that the unprotected bottom plate causes a slight delay (approximately 5 min) in the vertical charring. However, after this initial delay, the charring rate is basically the same as in the CLT far from the beam support. Actually, in this case the rate increases to even higher values after approximately at 40 min because of the heat transfer and charring in horizontal direction (C3). In the protected case, the vertical charring rate at the support (C2, Protected) is clearly smaller than in the unprotected case. However, even this lower rate can be significant for the mechanical behaviour of the hybrid beam. If the design criteria do not allow charring of CLT panels at beam support, it may be challenging to meet the criteria by using intumescent coating as fire protection material.

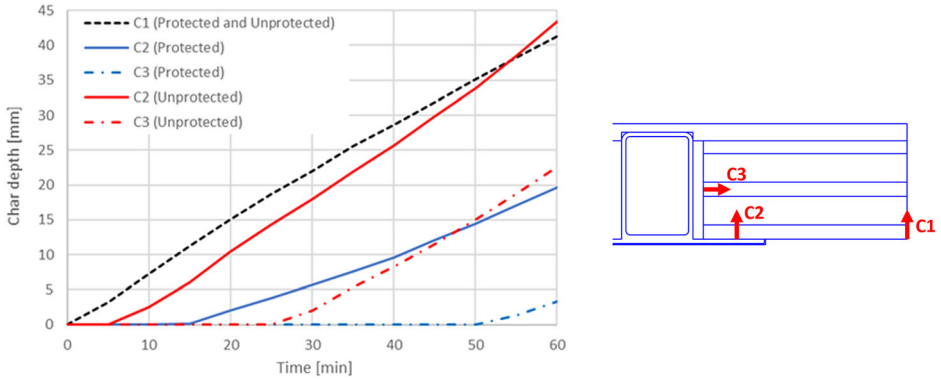


Figure 16. Numerically simulated charring depths of the CLT panel as a function of time in different locations.

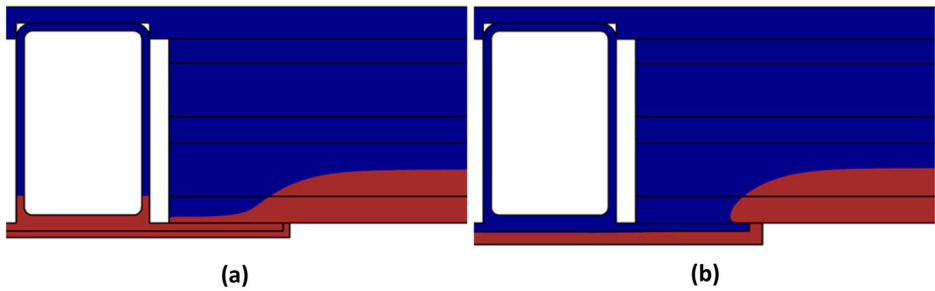


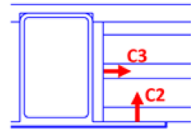
Figure 17. Charring depth of the CLT panel above the protected steel beam bottom plate at 60 min: (a) when bottom flange protected to 2-h (b) when bottom flange protected to 3-h.

4. Further Analysis and Discussion

The observations presented in Chapter 3 raised a question if a thicker intumescent paint thickness could completely prevent the charring of the CLT panel at the support area by keeping the steel temperature below the charring temperature for the 60 min period. Therefore, similar numerical analysis as presented in Chapter 3 were conducted also for the following two cases:

- Fire protection thickness of the steel bottom plate was increased from 1.7 to 5 mm in the model. This effective protection thickness corresponds approximately 2-h protection to limiting steel temperature of 570°C;
- Fire protection thickness of the steel bottom plate was increased to 10 mm. This effective protection thickness corresponds approximately 3-h protection to limiting steel temperature of 540°C.

Table 2
Start Time of Charring and the Char Depths at 60 min in Vertical (C2)
and Horizontal (C3) Directions for Different Fire Protection
Thicknesses

Case	Start time of charring [min]		Char depth at 60 minutes [mm]		
	Vertical	Horizontal	Vertical (C2)	Horizontal (C3)	
1-hour protection	15	53	20	3.5	
2-hour protection	37	94	6	0	
3-hour protection	70	143	0	0	

The aim of the analysis was to study the effect of thicker intumescent paint thicknesses on the charring at the CLT panel support and to estimate the paint thickness that would be required to completely prevent the start of charring. Figure 17 presents the positions of the char lines at 60 min for (a) 2-h fire protection and (b) 3-h fire protection. As earlier, the red portion indicates members and areas where temperatures are above 300°C which can be considered the charred area of the CLT panel. The results suggests that charring at panel supports at 60 min can be reduced or even avoided if using heavier protection. In the case of the 2-h protection, the vertical charring behind the steel bottom plate started at 37 min and at 60 min the charring front had progressed 6 mm into the CLT. In the case of the 3-h protection, vertical charring behind the steel bottom plate had not started at 60 min and the material properties of intact timber can be assumed for almost the entire width of the steel bottom plate. In both cases analyzed, horizontal charring started significantly later. Start time of charring and the char depths at 60 min are shown for vertical (C2) and horizontal (C3) directions in Table 2.

The results of Table 2 indicate that a thicker intumescent paint layer than required for the steel member may delay the start of charring and reduce the char depth in the CLT-slab at the support. In the design and selection of the fire protection system for a steel-timber hybrid structure, the design temperature must consider both the critical temperature determined for the steel structure and the charring temperature of the timber. Intumescent paints have usually potential for up to 120 min fire protection, but also systems up to 240 min are available. The 3-h protection, which in this study led to an acceptable solution, would therefore be possible. Heat transfer from steel section to CLT panels can be further reduced by filling the gaps between the steel beam webs and vertical end of CLT panels.

It should be noted that the strength and stiffness properties of CLT are reduced much earlier than the charring starts. The properties are significantly reduced already at a temperature of 100°C [1]. In the simulations made, the temperatures

in CLT above the steel bottom plate exceeded this limit at very early stage. In the cases of 2- and 3-h fire protection, the limit was exceeded at 6 and 11 min, respectively. The reduction will, therefore, affect the design compressive strength of CLT at slab support significantly earlier than the charring starts. The fire design of the CLT slab support should not only take into account the char depth and residual cross-section analysis but also the reduction in strength. Further research is needed on this issue.

If the fire protection used cannot prevent the charring front to progress into the CLT behind the steel bottom plate and the support reaction forces cannot be transferred through this char layer, one option could be to hang the reaction forces from above using reinforcing bars installed over the RHS steel profile and anchored into the intact CLT slab above the char layer. The method has been applied in the fire design of top-hat beams supporting hollow core slabs [20]. The feasibility of this solution in the CLT slab has not been analysed in this study.

Delamination of CLT was not in the scope of this study. However, it may have effect on the charring at the support. If CLT delaminates close to the support, more exposed timber surface may be available. This may increase especially the horizontal charring at the support. Delamination will make numerical modelling slightly more complicated, but it can be done with stepwise approach. This will be included to the scope of the next phase of the study.

The tests were conducted unloaded. In a real fire, the floor would be supporting loads and, depending on the compressive strength of the char layer, the layer is crushed against the steel bottom plate. This may affect the transfer of heat and hot gasses in the direction of the grains. In the fire-protected case, charring was limited to the first lamella layer, so the possible compression of the char layer would be relatively small. The steel beam bends due to the vertical loading and as a result, a gap can appear between the steel bottom plate and CLT slab, through which the hot gasses can directly affect the RHS profile inside the CLT floor. A detailed investigation of these effects requires further research and tests.

5. Conclusions

Two fire tests on steel-timber hybrid floor beams were conducted to investigate the thermal profiles of the steel member and CLT slabs and to obtain more realistic and reliable information on the heat transfer from the steel member into CLT floor and on the charring of the beam section when it is exposed to standard fire conditions. Also, a relatively simple numerical model applicable to everyday structural fire design applications was developed to analyse the temperatures in the hybrid beam section. Numerical 2D thermal simulations for the unprotected and protected cases were conducted using SAFIR software, and the agreement between experiments and numerical analysis predictions were in general very good.

The experimental and numerical results reported above show that charring of CLT panels supported on the bottom flange plate of a slim floor beam is significant unless the heat transfer to CLT floor through the steel beam is restricted.

Intumescent protection applied to the steel section exposed to fire was an effective way to reduce the temperatures of the steel and CLT components as well as the charring depth. The numerical results indicated that an intumescent paint layer thicker than required for the steel member to meet 60 min fire resistance may prevent the start of charring during the stated fire resistance period of 60 min. The results also showed that CLT temperatures exceed 100°C already in the early stages of the fire which decrease the strength and stiffness properties of CLT much before the start of charring. Therefore, the fire design of the CLT slab support should not only take into account the char depth and residual cross-section analysis but also the reduction in strength.

Further research is needed to ensure the load transfer mechanism of the support reaction forces from timber slab into the steel beam during the fire and to determine a fire protection solution that meets all the structural fire resistance requirements of composite beams and CLT floor slabs. The numerical further analysis and results reported in Chapter 4 are based on relatively simple model, and they also need to be verified in fire tests. Further research is also needed to investigate the charring performance in natural fires.

Author Contributions

All authors contributed to the study conception and design. Funding acquisition and supervision by MM. Experimental research was designed, performed and documented by MM and MA. Numerical studies were carried out by MS, TJ and RR. The first draft of the manuscript was written by MM and MS. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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