Fire resistance of timber-concrete composite slabs

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Mario FONTANA
Professor
ETH Zürich
Zurich, Switzerland

Andrea FRANGI
Civil Engineer
ETH Zürich
Zurich, Switzerland

Summary

The use of timber in multi-storey buildings is limited due to fire regulations. Timber-concrete composite elements show promise to overcome this handicap thus cutting down on the use of the sustainable building material timber. A research project at ETH on the fire behaviour of timber-concrete composite slabs is described.

1. Design and application of timber-concrete composite slabs

A rigid connection between concrete slabs and timber beams improves the serviceability and resistance of such floors. In Europe the refurbishment of old buildings with timber floors has drawn attention to this new and efficient floor system in recent years. Fig. 1 shows a traditional timber floor with slag filling between the beams and the new type of timber-concrete composite slabs after refurbishment. Beams and planks are reused and the slag is replaced by (preferably lightweight) concrete. If the planks have deteriorated over the years they can be replaced by profiled steel sheets, timber boards or wood-based panels.

As timber-concrete composite floors show excellent behaviour with regard to serviceability, resistance, noise insulation and fire resistance, they are not only used for refurbishment but also for new slabs in dwellings and public buildings in Europe. Besides the beam type floors, slab type floors using laminated wood decks of sawn timber planks nailed together with the longer side of their cross-section vertical or glued laminated beams with the longer side of their cross-section horizontal are common (fig. 2). They create a pleasant looking ceiling for the room below.

The behaviour of timber-concrete composite slabs is governed by the shear connection between timber and concrete. Because timber exhibits brittle behaviour (no yield plateau as for steel) only elastic design methods can be applied. Fig. 3 shows the influence of the shear connector stiffness on the stress distribution. Table 1 gives an example of timber-concrete composite beam of 6 m span, a permanent load of 2 kN/m^2 and a live load of 2 kN/m^2. The connectors have a stiffness of 13 kN/mm and are spaced 90 mm. Propping of the beam during the concrete setting is crucial for the efficiency of timber-concrete composite floors.

The Annex B of Eurocode 5 [1] gives a simplified design method applicable to simply supported beams with uniform loads. For more general boundary conditions nonlinear finite element analysis needs to be performed because the differential equation has no general solution for such cases. A finite element program taking into account even thermal action in the case of fire is currently being developed at our institute by Prof. Dr. E Anderheggen and his team.

As the shear connectors markedly influence the efficiency of timber-concrete composite slabs many forms of connectors have been developed and tested during the last years. From the variety of connectors two types (figs. 4 and 5) are being tested in an ongoing research project at our institute sponsored by the industrial partners SFS, Hilti and Lignum and the Swiss Commission for Technology Transfer and Innovation. The Hilti connector (fig. 4) was developed together with the Institute of Timber Construction (IBOIS) at the ETH in Lausanne. It consists of a glued threaded bar M12 which is post-tensioned after the setting of the concrete to improve the stiffness. The shear is transferred by grooves perpendicular to the span [7].

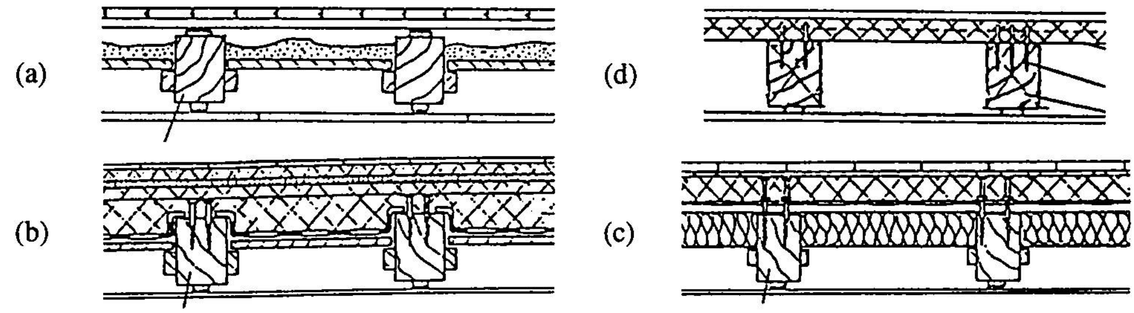


Fig. 1 Typical traditional timber floor (a) and three types of refurbishment as timber-concrete composite slabs using the existing planks (b) or a new timber board (c) or steel deck (d)

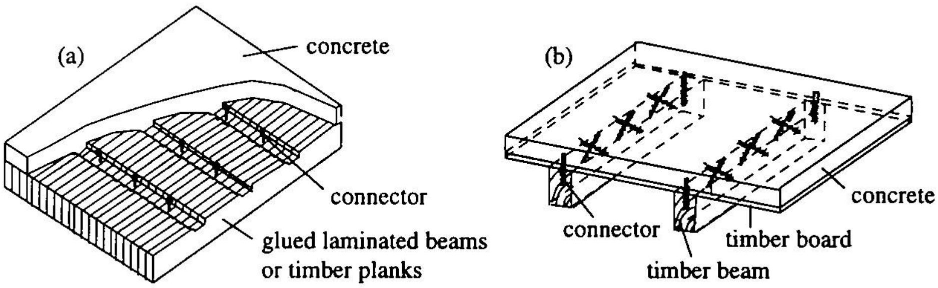


Fig. 2 Design of timber-concrete composite floors: slab type floor (a) made of glued laminated beams with the longer side of their cross-section horizontal or nailed laminated wood of sawn timber planks and beam type floor (b) with glued laminated or sawn sections

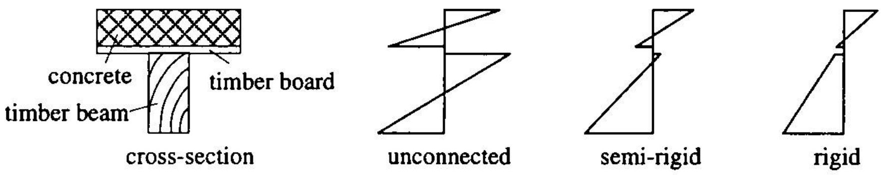
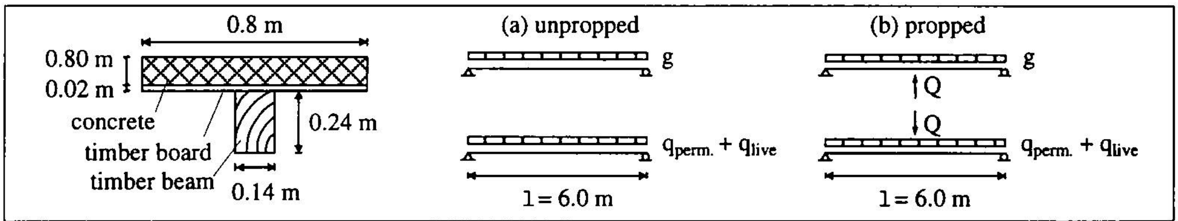


Fig. 3 The stiffness of the shear connection has a marked influence on the stress distribution and the efficiency of timber-concrete composite slabs



	unpropped			propped	
	unconnected	semi-rigid	rigid	semi-rigid	rigid
mid-span-deflection (longterm inside building)	70 mm	27 mm	25 mm	13 mm	11 mm
maximum longterm tensile stress in timber	16.6 N/mm²	9.7 N/mm²	9.4 N/mm²	4.9 N/mm²	4.4 N/mm²

Table 1 Example of deflection and stress in a timber-concrete composite beam. The construction process (propped/unpropped) and the rigidity of the connectors are important parameters

The SFS connector VB-48-7.5x100 (fig. 5) is a self-drilling screw with a collar to limit the screwing depth and a head for connection with the concrete. The net section in the threaded part has a diameter of 4 mm, the upper part of the connector a diameter of 6 mm. By arranging the connectors at 45° inclination a virtual truss is formed with the timber and the concrete as girders and the connectors as diagonals. Such an arrangement improves the stiffness by a factor of 3 compared to a vertical arrangement where the connector acts in bending and bearing [6].

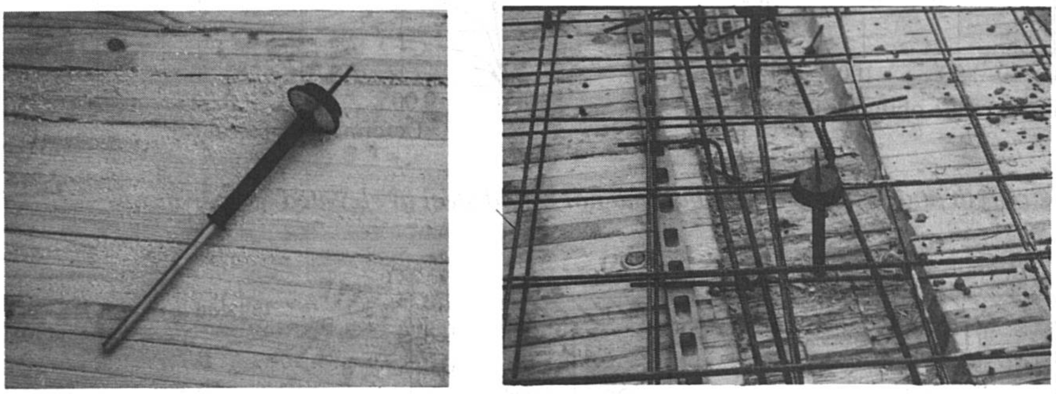


Fig. 4 Hilti connector. It consists of a glued threaded bar M12 which is post-tensioned after the setting of the concrete. The shear is transferred by grooves perpendicular to the span

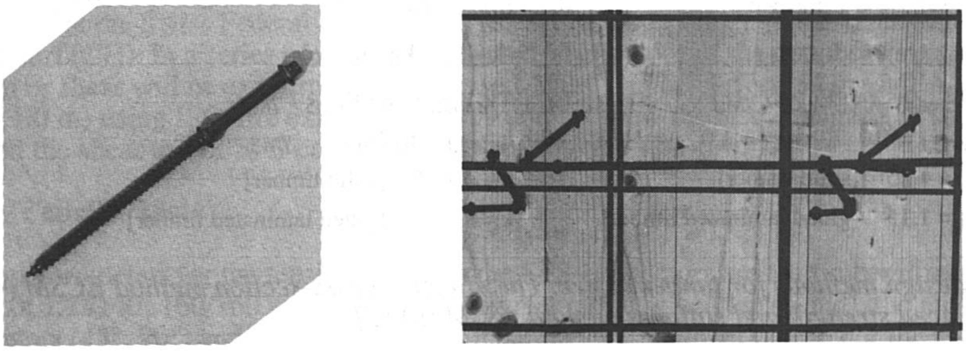


Fig. 5 SFS connector. It consists of a self-drilling screw with a collar to limit the screwing depth and a head for connection with the concrete.

2. Fire resistance of timber-concrete composite slabs

The fire resistance of timber-concrete composite elements is mainly influenced by the behaviour of the timber and the connectors. Timber is a combustible material and if heated the decay of cellulose and lignin produces combustible gases and charcoal. The burning rate is mainly influenced by the specific density, the moisture content, the thermal conductivity and specific heat capacity. In a room fire the heat flux will influence the burning rate so that the fire behaviour is a rather complex phenomenon. For design purposes a simplified method based on a constant burning rate is commonly used. The fire reduces the cross-section and the stiffness and strength of the timber close to the burning surface. Fig. 6 shows the reduction of stiffness and strength for timber [3] and of the yield stress of steel [4].

The simplified design methods consider the strength and stiffness reduction either by a) an effective cross section (ECSM) e.g. adding an additional depth to the charred depth or b) by a general reduction of stiffness and strength for the residual section depending on the ratio between the exposed boundary p and the residual section A_r (RSSM). More sophisticated methods also consider the higher charring in the corners which leads to a „rounding“ of the corners in fire [2].

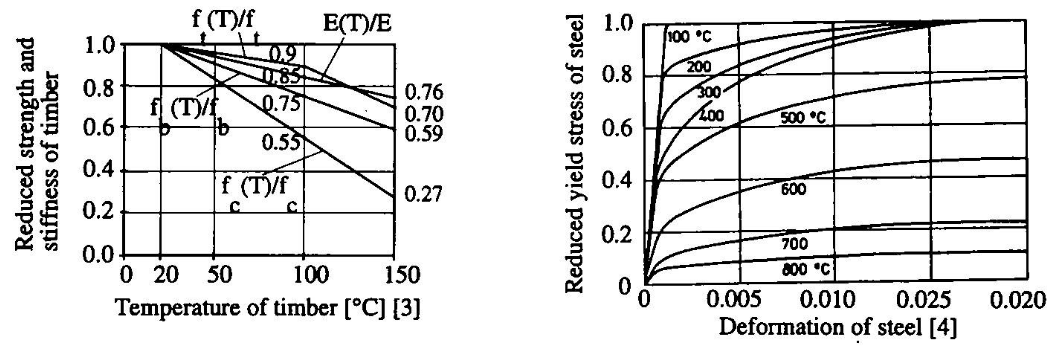
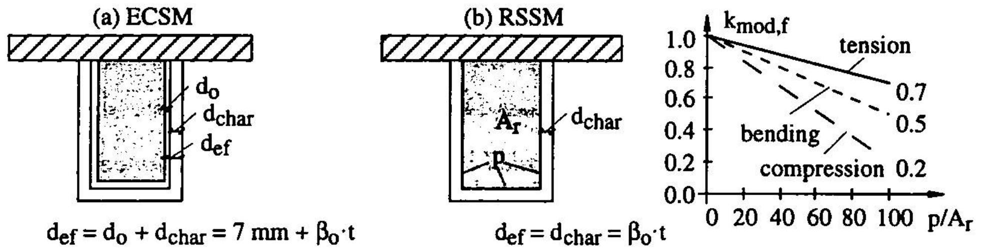


Fig. 6 Reduced strength and stiffness for timber and hot rolled steel at elevated temperatures



$d_{ef} = d_0 + d_{char} = 7\ \text{mm} + \beta_0 \cdot t$

$f_{fi,d} = k_{mod,f} \cdot k_{fi} \cdot f_k / \gamma_{M,f}$

$E_{fi,d} = k_{mod,f} \cdot k_{fi} \cdot E_{k,05} / \gamma_{M,f}$

With $k_{mod,f} = 1.0$; $\gamma_{M,f} = 1.0$

$k_{fi} = 1.25$ [solid timber]

$k_{fi} = 1.15$ [glued laminated timber]

$d_{ef} = d_{char} = \beta_0 \cdot t$

$f_{fi,d} = k_{mod,f} \cdot k_{fi} \cdot f_k / \gamma_{M,f}$

$E_{fi,d} = k_{mod,f} \cdot k_{fi} \cdot E_{k,05} / \gamma_{M,f}$

With $k_{mod,f} = f(p/A_r)$; $\gamma_{M,f} = 1.0$

$k_{fi} = 1.25$ [solid timber]

$k_{fi} = 1.15$ [glued laminated timber]

Fig. 7 Simplified design methods for timber in fire. The effective cross-section method ECSM (a) and the reduced strength and stiffness method RSSM (b) [2]

For timber-concrete composite floors the strength and stiffness reduction of the connectors and the thermal stresses between timber and concrete have to be considered. It is the aim of the ongoing research project to investigate these parameters. The temperature distribution in the timber and concrete section is an important parameter. The temperature field analysis is based on the differential equation of the transient heating process.

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda}{c \cdot \rho} \cdot \left[\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} \right]$$

With ϑ = temperature; λ = thermal conductivity; c = specific heat capacity; x,y = coordinates; ρ = specific density

For the analysis of standard fire tests the surrounding temperature is given by the standard fire curve according to ISO 834. The heat transfer is mostly considered by constant values for the resultant emissivity ε_{res} and the coefficient of heat transfer by convection α_c. Thermal conductivity and specific heat capacity of wood are a function of the temperature (fig. 8). The peak in the specific heat at 100°C results from the dissipation of energy due to the vaporisation of water (moisture content of 10%). Temperature field calculations in timber sections are usually based on a finite element analysis [8]. With increasing temperature the timber transforms into charcoal and later disappears. This phenomenon is simplified in the programs by gradually changing the thermal properties of wood into those of charcoal and finally into those of air with increasing temperature.

Temperatures of more than 50 to 80°C (depending on the type of glue) may affect the strength of the glue and the shear strength of the timber close to the connection [9]. A sufficient cover of the connectors is therefore important. In the fire situation the reinforcement of the concrete used for crack control in the cold situation can make an important contribution to the fire resistance as it is insulated by the timber especially in wood laminated slabs. The benefical effects of such global behaviour will also be investigated within the research project.

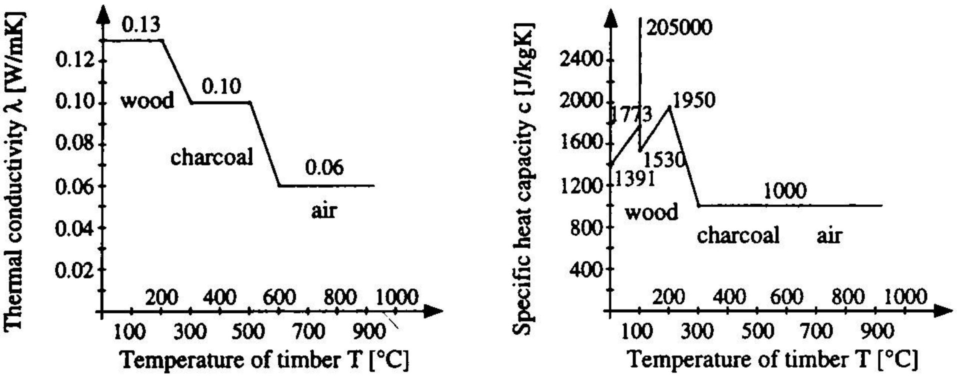


Fig. 8 Thermal conductivity and specific heat capacity of wood as a function of the temperature

3. Fire tests

An extensive testing program is planned to enlarge the experimental background of the design models for the fire resistance of timber-concrete composite floors. All fire tests are being performed at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Dübendorf (CH). In a series of small scale tests the behaviour of the connectors subjected to tension or shear will be experimentally analysed. They will be performed in EMPA's small furnace (1.2 x 1.0 m) using ISO-fire exposure. Figs. 9 and 10 show the test arrangement for the tensile test and the shear test of SFS-connectors subjected to the ISO-fire.

3.1 Tensile tests

The test parameters for the tensile tests with the SFS-connectors are the timber dimensions (80/120; 120/140; 160/160 mm), the type of timber (solid, glued laminated), the inclination of connectors (45°; 90°) and the gap between timber beam and timber board. For the Hilti-connectors with slab type floors the influence of the timber cover of the connector at the bottom (20, 40, 60 mm) and the type of planks (sawn, planed, glued laminated) are varied, whereas for the beam type floors with Hilti-connectors the timber dimensions (80/90; 80/100; 80/120; 120/140; 160/160 mm) and the type of timber (timber, glued laminated) are changing parameters. In the tests the temperature in selected locations, the deformation of the connectors and the tensile force are measured.

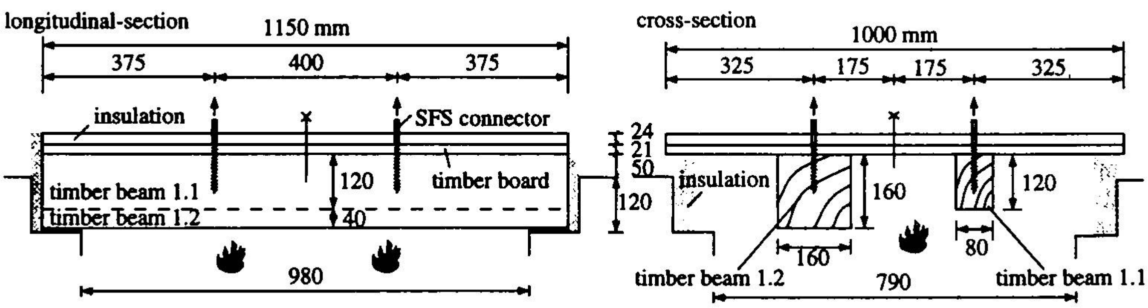


Fig. 9 Test arrangement for the tensile test of SFS-connectors subjected to the ISO-fire

The tests will be performed using two different procedures:
a) The specimens are exposed to 30 minutes of the ISO-fire with the permissible load applied to the connectors. If no failure has occurred after 30 minutes the load is increased until failure occurs.
b) The specimens are loaded with the permissible load and then exposed to ISO-fire until failure.

3.2 Shear tests

The test parameters for the shear tests with the SFS-connectors are the timber dimensions (80/120; 120/140; 160/160 mm) and the type of timber (timber, glued laminated). For the Hilti-connectors with slab type floors the influence of the timber cover of the connector at the bottom (20, 40, 60 mm) and the type of planks (sawn, planed, glued laminated) are analysed. For the beam type floors with Hilti-connectors the timber dimensions (80/110; 80/120; 80/140; 120/160; 160/180 mm) and the type of timber (solid, glued laminated) are varied.

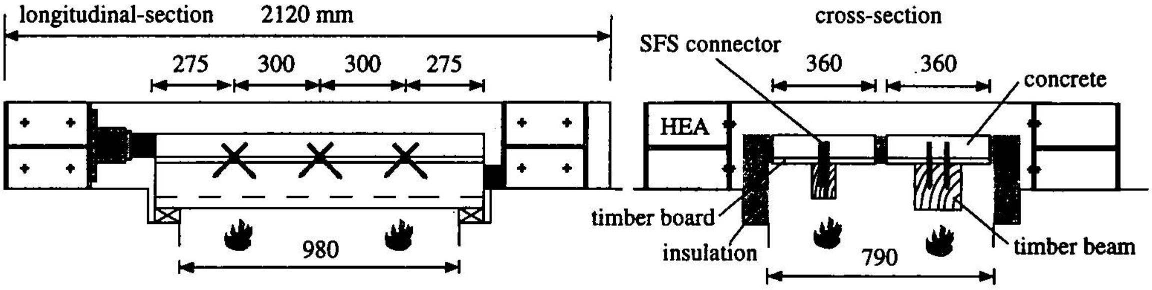


Fig.10 Test arrangement for shear test of SFS-connectors subjected to the ISO-fire

The test procedures follow the same principles as for the tensile tests. The relative deformation and the temperatures in selected locations are measured. Results of the tensile and shear tests are expected to be available in summer 1997.

A series of fire tests on slabs (3.0 x 5.0 m) is planned for the end of 1997, which will look at the global behaviour of timber-concrete composite slabs. The research project should lead to construction details improving the fire resistance of timber-concrete composite elements and form a background for a new consideration of the application of timber in multy-storey buildings by the fire authorities and for a liberalisation of the present fire regulations for timber-concrete composite construction. This should then lead to new markets for timber in multi-storey buildings.

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