# Revaluation of historical buildings with timber-concrete composite in compliance with fire resistance demands

Klaus Holschemacher and Ulrike Quapp



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**Klaus Holschemacher[1] and Ulrike Quapp[2]**

**Abstract.** The requirements concerning the guarantee of sufficient fire resistance of structures have significantly changed with time. Hence, when revaluating or reconstructing existing older or even historical buildings a decision about necessary measures for ensuring the demanded fire resistance is needed. Timber-concrete composite is a proven technology for reconstruction and strengthening of existing timber beam ceilings. Timber-concrete composite floors have a high load-bearing capacity and very advantageous building-physical properties like fire resistance and sound insulation. A further essential benefit is the circumstance that the bottom side of timber beam floors may be unchanged in the reconstruction process. This fact very often is a basic demand for reconstruction of historical buildings. The paper analyses Germany's recent fire protection regulations for reconstruction of historical buildings. It is verified that timber-concrete composite is a profitable solution for improvement of fire protection of existing buildings.

**Keywords:** fire protection, historical buildings, timber-concrete composite, revaluation, heritage protection.

## 1 Requirements of fire protection

### 1.1 Objectives of fire protection

Fire protection contributes essentially to the prevention of death, injury, property loss and environmental damage [1]. In case of fire, smoke, heat and fire gas as well as fire spreading may cause serious injuries and destruction of buildings [2]. Costs caused by direct and indirect fire damages amount around 0.2% of the gross domestic product, which means around 2.5 to 3 billion Euro per year in Germany. Additionally, each year hundreds of people die because of fire. But, due to the high standards and the continuous legal and technical development in fire protection, Germany was able to reduce the death by fire significantly. That's why the level of damages caused by fire is relatively low related to other western industrial nations [3].

Nevertheless, there will be fire disasters, which cause irrevocable damages especially in historical buildings, such as in the Anna-Amalia Library in Weimar in 2004 and in the Museum for Bavarian History in Regensburg in 2017. Therefore, in older or state protected historical structures fire protection is extremely important due to former times construction methods and the frequent use of easily flammable construction materials, e.g.

[1] Full Professor, Structural Concrete Institute, Faculty of Civil Engineering, Leipzig University of Applied Sciences - HTWK, Leipzig, Germany, klaus.holschemacher@htwk-leipzig.de

[2] Faculty Manager, Faculty of Civil Engineering, Leipzig University of Applied Sciences - HTWK, Leipzig, Germany, ulrike.quapp@htwk-leipzig.de

timber or straw. Furthermore, especially monuments are particularly worth to be protected to preserve them for posterity. Thus, preventive fire protection can also be seen as heritage protection [4].

**1.2 Historical development and current requirements in Germany**

In Germany fire safety has a long tradition. Due to historical fire tragedies such as the great fire in the cities of Luebeck in 1276 and Munich in 1327 where a large number of buildings was destroyed, strict fire protection regulations have been developed over hundreds of years to prevent these kinds of disaster in Germany. Especially the regulations for fire resistance of building elements and flammability of building materials have been changed significantly over the years leading to comprehensive fire safety concepts for structures nowadays.

Current fire protection requirements for Germany can be found in the local building regulations of the German Federal States (e.g. in Saxon Building Regulations 2017 [6]) and in nationwide applicable technical standards such as Eurocodes or German DIN Codes (e.g. DIN 4102 [7], DIN EN 13501 [8] or Eurocode 2 [9]). Normally, fire protection regulations are made for new constructed buildings. But, additionally they contain schemes to deal with the specialties of existing structures.

Regarding fire safety requirements a distinction has to be made between preventive fire protection and defensive fire protection [10]. Furthermore, specific regulations exist for special buildings such as hospitals, skyscrapers, schools and stadiums, e.g. (Section 51 [6] in conjunction with the [11]). Due to the paper topic, only preventive fire protection will be of interest. Preventive fire protection includes structural, technological and organizational fire protection. The following information relates to structural fire protection.

Structures in Germany are to design, to construct, to maintain and to alter in a way that the incipient fire as well as spread of fire and smoke will be prevented. Furthermore, in case of fire the rescue of humans and animals as well as an effective fire-fighting must be possible (e.g. Section 14 [6]). Dependent on the building class, local building regulations contain, amongst others, requirements regarding building elements, building materials and construction methods. Thus, the fire resistance of building elements using fire resistance classes and the flammability of building materials using building material classes are defined. Additionally, there are rules regarding the structure's division in fire compartments and provision of access routes for the fire service. The responsible building authority controls the compliance with the local building requirements.

Fire resistance of building elements, which is an important part of any design for fire safety [1], defines the duration while the building element keeps its functionality when exposed to fire. That means at least to guaranty load bearing function and/or to prevent fire spread (flame, hot gases, excessive heat) beyond designated areas (separating function). Dependent on the building elements' function in the structure, local building regulations and respective national technical standards contain different requirements regarding their fire resistance and the flammability of the building materials they consist of. Thus, for example a load bearing wall in a building lower than or equal to 22m, which correspond to the highest building class number 5, must be fire resistant and not only fire retardant. Furthermore, it has to consist from non-flammable materials in its essential parts and, in the case of a space-enclosing building element, there must be a continuous layer of non-flammable material in the element.

For classification of construction products and building elements regarding their fire resistance the reaction-to-fire performance of the element must be verified according to DIN EN 13501 [8], DIN EN 1363 [12] or DIN 4102 [7]. Fire resistance classification according to DIN EN 13501 contains letters, which mark the respective performance criteria, and the information of the minimum duration of fire resistance in minutes (e.g. REI 90). The most important performance criteria of DIN EN 13501-2 can be found in Table 1.

German building law contains requirements regarding the fire resistance of construction products and building elements depending from their function in the structure (see Table 2). These requirements must be met in structural design of buildings. As higher and more complicated the structure as higher the demands on the building elements used. In addition to the mentioned regulations the flammability of the building materials must be considered.

In Germany, usability of building materials and construction methods normally is proofed by compliance with national technical regulations. If building materials and construction methods are not regulated in one of the acknowledged technical regulations or are not in compliance with them, usability must be proofed on the basis of official certificates of usability. Then, a general German or European technical approval, a general construction supervision test report or an approval in the individual case given by the highest building authority is required.

**Table 1.** Examples of performance criteria according to DIN EN 13501 (DIBt 2015 [13]).

| Abbreviation | Performance criteria | Application |
|---|---|---|
| R | Load-bearing capacity<br>(ability of a structural element to carry the design load in a standard fire) | Description of the equivalent time of fire exposure |
| E | Integrity separating function<br>(capacity of a building element to retain its integrity against flames or hot gases) | |
| I | Thermal insolation separating function<br>(capacity to maintain a defined temperature on the unexposed side of the building element, usually 140°C) | |
| M | Mechanical effects<br>(ability of the structural element to cope with the mechanical impact) | |
| i→o<br>i←o<br>i↔o | Direction of the classified fire resistance duration | Non-load-bearing exterior walls<br>Installation shafts/channels<br>Ventilation systems/flaps |

**Table 2.** Examples of fire resistance classes of building elements in DIN EN 13501-2 and their allocation to building authority requirements (DIBt 2015 [13]).

| Building authority requirements | Load-bearing elements | | Non-load bearing interior walls | Non-load bearing exterior walls |
|---|---|---|---|---|
| | Without separating function | With separating function | | |
| Fire-resistant | R 30 | REI 30 | EI 30 | E 30 (i→o) and EI 30-ef (i←o) |
| Highly fire-resistant | R 60 | REI 60 | EI 60 | E 60 (i→o) and EI 60-ef (i←o) |
| Fireproof | R 90 | REI 90 | EI 90 | E 60 (i→o) and EI 60-ef (i←o) |
| Highly fireproof (120 minutes) | R 120 | REI 120 | | |
| Fire wall | | REI 90-M | EI 90-M | |

Most of the construction methods for preventive fire protection are regulated in national technical codes (such as reinforced concrete, steel, masonry). Only for a few construction methods, e.g. timber-concrete composite (TCC) there are no sufficient regulations in the national technical codes. That's why these methods normally need a certificate of usability before they can be used in the construction.

## 1.3 Differences between new, existing and protected historical structures

### *1.3.1 General remarks*

The design and construction of new buildings must be in compliance with all currently applicable fire protection standards. This will be checked by the responsible building authority. If non-compliance with legal requirements has been found, the authority may stop the construction works, prohibit the usage of the building or may issue a removal or adjustment order.

To establish law conforming fire protection in an existing building is much more demanding than in a new structure. Often, because of their age, existing buildings are in conflict with modern and currently applicable fire protection requirements [2]. If the existing structures are protected historical buildings, furthermore, the preservation order often collides with legal fire protection requirements (e.g. in the case of wooden staircases) while both are of equal importance [5]. It is to discuss, if and under which circumstances the owner of an existing building can be forced to upgrade the fire protection facilities in the structure to ensure compliance with the currently applicable regulations.

A difference must be made between two situations: local building authorities require to establish a fire protection law-conforming state (see under 1.3.2) or the owner intends construction works in the existing structure which may require the application of the current applicable fire safety law (see under 1.3.3).

### *1.3.2 Building authority's order*

If local building authorities responsible for checking fire safety get informed about non-compliance with current fire protection requirements, they have to act. But, in existing buildings the ownership and the resulting "prior rights" of the owner, guaranteed in Article 14 of the German Constitution [14] and in the Federal States Constitutions (e.g. Article 31 of the Constitution of the Free State of Saxony [15]) must be respected, if at any time of the existence of the building, its fire safety had been in compliance with the former legal requirements. Authorities therefore only can enforce the establishment of a sufficient fire protection in an existing structure if there will be a real danger for life or health of human or animals, for example if there is no escape and rescue route. If it is a state protected historical building, the building authority furthermore must find a balance between fire safety and heritage protection interests.

### *1.3.3 Alteration intensions of the owner*

If the owner intends to start construction works in an older or protected historical structure, normally he or she must plan and construct in compliance with the current fire safety regulations. That would mean, that the fire safety concept of the existing structure must be adjusted to the current legal situation, which causes financial or other problems for the owner. And, when appropriate, heritage protection must be respected. But, under certain circumstances the owner of the historic structure may also relay on his or her owner's "prior rights". If the alteration, reconstruction or modernization is only of marginal character the owner cannot be forced to adjust the structure to the new legal status. But, if there will be comprehensive construction works which change the character of the building or the usage (e.g. from a residential building in a hotel), current fire safety regulations must be observed.

Nevertheless, there is no need to meet every single current fire safety requirement. Only the fire protection objective must be reached [5]. The building authority has the right to decide about the extent of fire safety measurements as well as the reduction of legal and technical requirements for fire safety (Section 3 (3) and 67 [6]). Regarding historical protected structures, additionally the authority for the protection of historic buildings and monuments may decide about the extent of preservation of historical structures based on the respective heritage protection law of the Federal German States as well as the reduction of requirements in the interest of the protection of life and health. Because of the owners' "prior rights" and heritage protection interests, existing structures should be not more affected than necessary by fire protection requirements. Generally, it is allowed to plan and build not in compliance with technical code requirements if standards will be met in an equivalent manner with a deviating technical solution (Section 3 (3) [6]). The structural engineer must proof the equivalence of his/her planning with the code requirements – ideally within a fire safety concept. If the engineer is able to proof the equivalence of the deviating technical solution the fire safety authority has to allow the deviating solution.

# 2 Revaluation with timber-concrete composite (TCC)

## 2.1 General remarks

Timber-concrete composite (TCC) is a well-established technique for strengthening of existing timber beam ceilings as well as for construction of floors in new buildings. Basically, TCC consists of timber beams that are connected with a reinforced concrete slab by shear connectors, Fig. 1. There is a big variety of connections between the timber and the concrete. The shear connectors are responsible for the interaction of timber beams and concrete slab in the composite member. Ultimate load and stiffness of shear connectors influence essentially the load-bearing behavior of the complete TCC system. Besides, shear connectors should be easy to assemble and must not be too expensive to give them a chance in construction practice from the point of economy. Therefore, many investigations have addressed the development of suitable shear connectors in past. Usually, sheer connectors cause a flexible, but not a rigid bond between the timber and the concrete part of the composite section, see Fig. 2 [16].

First applications of TCC have been caused by the lack of resources in the early 20$^{th}$ century. It has been recognized that concrete is a valuable construction material for bearing compressive forces. Other advantages of concrete in comparison to other often-applied construction materials are the good fire resistance and durability. However, in flexural concrete members the tensile zone of the cross section has to be strengthened by materials with high tensile strength. Besides steel – leading to reinforced concrete – timber is an excellent material for this purpose. So, application of TCC leads to structural systems with advantageous load-bearing capacity and low dead load at reasonable costs. An example for the increase of the stiffness of a TCC section by variation of concrete slab height and concrete strength is given in Fig. 3.

Beside the mentioned advantages, TCC owns also some disadvantages. One of those is the fact that there are no normative rules for the design of TCC. Of course, TCC members can be designed according to codes for timber structures, e.g. Eurocode 5 [17]. But there is no information about characteristic or design values of stiffness and ultimate load of shear connectors available in the codes. These parameters must be defined in the technical approvals of the shear connectors. This circumstance is the main obstacle for application of TCC in practice. Hence, in Germany TCC is mainly limited to strengthening of existing timber beam ceilings. For this purpose it is a very economic technology because the boarding can stay in place whereas for other strengthening techniques the boarding has to be removed [18]-[20]. A particular advantage is the fact that the bottom side of the existing timber beam ceiling may be unchanged. In contrast, the application of TCC in new constructions is limited to few special new buildings.

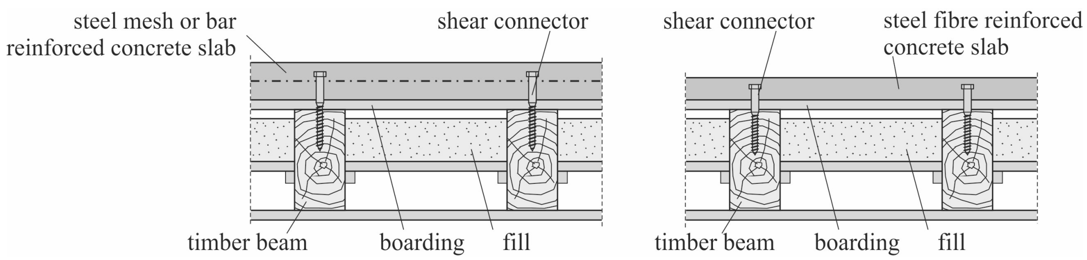


**Figure 1.** Strengthening of existing timber beam ceilings with TCC; left: application of a steel bar or mesh reinforced concrete slab, right: application of steel fibre reinforced concrete.

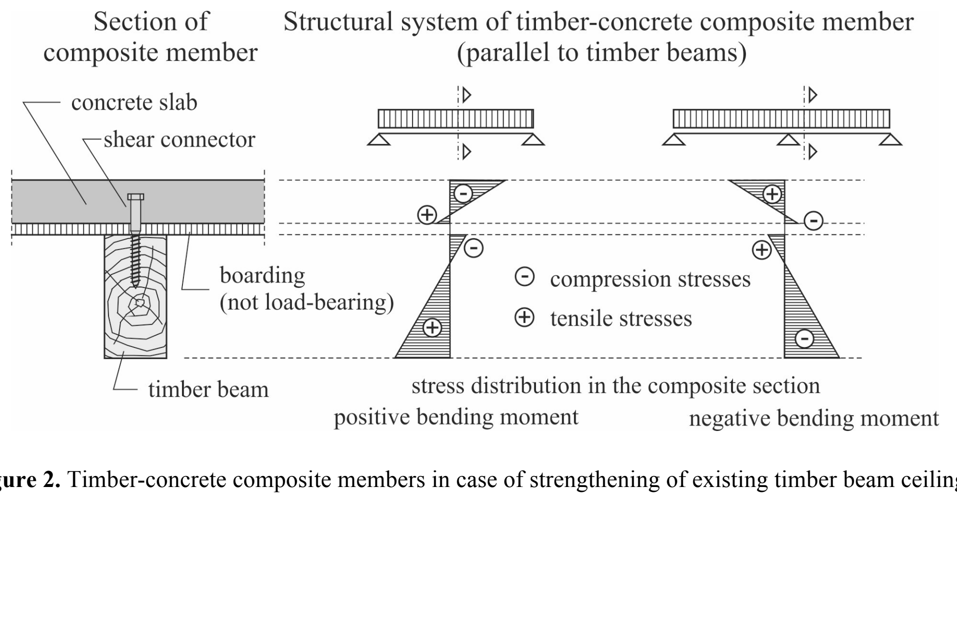


**Figure 2.** Timber-concrete composite members in case of strengthening of existing timber beam ceilings.

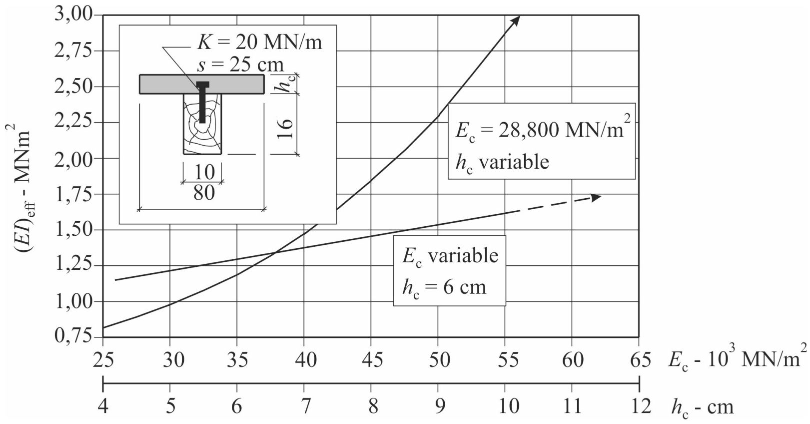


**Figure 3.** Influence of concrete slab depth and modulus of elasticity on stiffness of TCC systems, calculation according to Eurocode 5.

### 2.2 Fire resistance of TCC

The behaviour of TCC floors in fire has been investigated by many researchers, e.g. [21]-[26]. A review of the literature indicates in broad consensus that the fire resistance of TCC is essentially improved in comparison to pure timber floors. The combination of beneficial building-physical properties (especially fire resistance and sound insulation), increased load-bearing capacity and the possible integration of heating elements inside of the concrete slab has led to numerous applications of TCC in Germany when revaluating older timber floors.
By the concrete slab the request for the integrity separating function and the thermal insulation separating functions can bet met relative easily. Caused by the constructional design of the concrete slab smoke and fire gas are shielded in both directions. However, own practical experience shows that the joint between the TCC floor and adjacent masonry walls should be paid particular attention. A gap between the concrete slab and the walls must be avoided. Otherwise, the integrity separating function is risked. Furthermore, installation parts and through-ceiling ducts should be checked for appropriate assembly. Regarding the load-bearing capacity in fire case it is advantageously that two components of different materials bear together the load in the composite section. After charring of timber and the following reduction of the cross-section of the beams the load shares can be redistributed from the timber beam to the concrete slab. Furthermore, it is to state that the shear connectors are located in the inner part of the section enclosed by timber and concrete. So, the connectors are secured against rapid temperature increase and loss of their stiffness and load-bearing capacity.

For calculation of the fire resistance of TCC floors the charring of the timber beams has to be considered together with the temperature dependent decrease of the connection strength and stiffness [1]. Carried-out experiments and revaluations of timber floors using TCC showed that a fire resistance class REI 60 is easy achievable without any cover of the bottom side of the timber beams.

## 3 Summary/Conclusions

TCC is an attractive and proved construction method for strengthening of existing timber beam ceilings even in case of protected historical structure because the bottom side of the floor mostly can be unchanged. This shows that while the revaluation of historical buildings, meeting legal fire resistance requirements, economic considerations and heritage protection do not have to be contradictions. TCC floors give an outstanding possibility to solve various requests like building-physical and structural performance and the demands for preservation of historical buildings.

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