Numerical simulation on behaviour of timber-concrete composite beams in fire

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Abstract: This paper established sequentially coupled thermal-mechanical models of timber-concrete composite (TCC) beams by finite element software ANSYS to investigate the fire resistance of TCC beam. Existing experimental results were used to verify the coupled thermal-mechanical model. The influencing parameters consisted of the width of timber beam, the thickness of the concrete slab and the timber board. Based on the numerical results, the effects of these parameters on fire resistance of TCC beams were investigated in detail. The results showed that modeling results agreed well with test results, and verified the reliability of the finite element model. The width of the timber beam had a significant influence on the fire resistance of TCC beams. The fire resistance of TCC beams would be enhanced by increasing the width of timber beam, the thickness of concrete slab and the timber board.

1. Introduction

The timer-concrete composite (TCC) beam represents a new composite structural form, which consists of a timber beam and a concrete slab connected by reliable shear connectors. The timber beam is normally in tension, while the concrete slab is under compression. Consequently, the TCC beam can take full advantages of the properties of both materials. Compared with the traditional timber beams, various aspects of TCC beams can be enhanced, including the load-carrying capacity, the bending stiffness, the acoustic insulation as well as the fire resistance [1, 2]. In order to ensure the safe application of TCC beams in real projects, it is of importance to study the fire resistance of TCC beams.

The research on the fire performance of the timber member is an important basis for analyzing the fire resistance of TCC beams. Existing research of timber structural members under fire are briefly reviewed. Buchanan [3] conducted fire tests on timber members, and the section of timber members after fire could be divided into three parts: char layer, pyrolysis zone and normal timber. Njankouo [4], König [5] and Lau [6] et al performed tests to research the charring rate of different kinds of timber under standard fire curve. The experimental results showed that the density of timber had a great effect on the charring rate of timber. EN1995-1-2 [7] proposes two methods to predict the mechanical resistance of timber members subjected to fire, including the reduced cross-section method and the reduced properties method. Furnace tests were conducted to assess the fire resistance of TCC beams [8-10]. Eva Caldová et al [11] conducted furnace tests on timber steel fiber–reinforced concrete floor slabs, and established a finite element model of the composite slab by using finite element software. In recent years, most Chinese researches focused on the mechanical properties of timer-concrete composite beams at ambient temperature, but little research on the behavior of TCC beams under elevated temperature.

This paper established sequentially coupled thermal-mechanical model of TCC beams by finite
element software ANSYS to study the fire resistance of TCC beams. Experiments conducted by Frangi A et al [10] were used to compare the FEA simulation results. Furthermore, the finite element models with different parameters were established to investigate the influences of critical factors, including the width of the timber beam, the thickness of the concrete slab and the timber board.

2. Material Model

2.1 Thermal Properties of Timber and Concrete

The thermal parameters of materials have an important influence on the temperature field distribution of the building components in fire. The thermal parameters mainly include the thermal conductivity, the density and the specific heat. During the heating process, the thermal parameters of the timber change with the increase of timber temperature. EN1995-1-2 [7] presents the thermal conductivity, the density and the specific heat of timber at different temperature. The parameter values from EN1995-1-2 were used in the finite element modeling of TCC beam. The thermal conductivity of the concrete is mainly influenced by the type of aggregates, the concrete mix properties and water-cement ratio. The data for the thermal properties of concrete were adopted from EN1994-1-2 [12].

2.2 Mechanical Properties of Timber and Concrete

The mechanical properties of materials under high temperature have a great effect on the fire behavior of the structural parts. Therefore, in order to obtain the numerical simulations accurately, it is of importance to define reasonable mechanical properties of timber and concrete at high temperature. The pyrolysis and charring process of timber could cause the loss of mechanical properties of timber. In the finite element model, the effect of timber charring was considered by setting different elastic modulus and strength under different temperature. The values were determined by a temperature dependent reduction factor according to EN1995-1-2. So far, some researchers have proposed the linear models to calculate the elastic modulus of concrete at high temperature. The results suggested that the elastic modulus of concrete decreased with the increase of temperature. The material model of concrete at elevated temperatures was adopted from EN1994-1-2 [12].

3. Verification of Finite Element Model

In order to verify the accuracy of the finite element mode, this paper simulated the test of TCC beam under fire which was tested by Frangi A et al [10], and the FEA results were compared with the experimental results. A 340 mm deep TCC beam was designed with a span of 5370mm. The details of the TCC beam were shown in Fig. 1. The TCC beam was designed for a fire resistance of 60 min. With the increasing time of fire exposure, the effective cross-section of timber beam was reduced, and the mechanical property of shear connectors was weakened. The fire test of TCC beam finally stopped after 67 min of ISO 834 fire exposure.

![Fig.1 Details of TCC beam tested by Frangi [11] (mm): (a) Cross section of TCC beam; (b) Longitudinal section of TCC beam](Image)

The finite element model was built to conduct 3D sequentially coupled thermal-mechanical analysis by the finite element software ANSYS. Firstly, this paper performed thermal analysis to determine the temperature field distribution of the TCC beam under fire. The element type used in the thermal analysis was Solid 70. Boundary conditions on the surfaces subjected to fire were set by radiation and
convection according to the ISO 834 standard fire curve. Then, the mechanical analysis of TCC beam was made by importing the results of thermal analysis into the structural model. During the mechanical analysis, the thermal element for timber and concrete was replaced by Solid 185 and Solid 65, respectively. The shear connectors were set by the element Combination 39. Fig.2 shows the results of finite element analysis. As shown in Fig.2 (a), the cross section of timber beam showed obvious temperature gradient. With the increasing time of fire exposure, the effective cross section of timber beam was reduced due to the charring of the timber. The rounding of corners occurred in the timber beam owning to two surfaces of the corners exposed to fire. Fig.2 (b) compared the time-deflection curve from fire test with that obtained by the finite element analysis. It was found that the FEA results were in good agreement with experimental results. Generally, the results showed that the finite element model could accurately simulate the behavior of TCC beam in fire.

![Finite Element Analysis](image)

**Fig.2** FEA results: (a) Temperature field in the cross-section of TCC beam after 60 minutes fire exposure; (b) Comparison between experimental results and FEA results of the mid-span deflection

### 4. Analysis of Influencing Factors

The fire resistance of TCC beams has been investigated using experimental results conducted by Frangi [10]. However, the mechanical behavior of TCC beam in fire could be influenced by various parameters. Therefore, the influence of various parameters, such as the width of timber beam, the thickness of concrete slab and the timber board on the mechanical performance of TCC beams in fire are investigated by finite element modeling. The model of TCC beam established in the previous part was used as the basic model for parametric analysis.

#### 4.1 Width of Timber Beam

In order to analyze the influence of the width of timber beam on the mechanical behavior of TCC beams under ISO 834 fire, three TCC beams with the different widths of timber beam were investigated by software ANSYS. Fig.3 showed the relationship between the time and the mid-span deflection in 60 minutes obtained from the numerical simulations on three TCC beams. It was found that the mid-span deflection of TCC beams was increased with the increasing time of fire exposure, since mechanical properties of timber and concrete were weakened at elevated temperature. Furthermore, the mid-span deflection of TCC beams was reduced with increasing the width of timber beam. This is because the char layer of timber has positive effects in heat insulation, and it could isolate oxygen to protect the remaining timber against heat. Increasing the width of timber beam enlarges the residual cross section of timber beam. Therefore, the load-carrying capacity and stiffness of TCC beam could be enhanced.

#### 4.2 Thickness of Concrete Slab

Three TCC beams with 60mm, 80mm and 100mm thickness of concrete slabs were investigated to study the effect of thickness of concrete slab on the fire resistance of TCC beam. Fig.4 showed the time-deflection curves of TCC beams in 60min of ISO 834 fire exposure. When the thickness of concrete slab was 60mm, the calculation of FEM did not converge after 57min. It indicated that the composite beam
failed. Besides, the mid-span deflection of TCC beam was reduced with the increase of the thickness of concrete slab. The temperature of thinner concrete slab increased at a much greater rate than that of the thicker concrete slab. It can be concluded that the concrete slab had a significant effect on the fire resistance of TCC beam, since concrete slab could absorb a large amount of heat and have a protective effect on the top of the timber beam.

4.3 Thickness of Timber Board
Timber board could be set as the permanent formwork for casting the concrete slab. It could be used as a construction platform to provide convenience for construction, and keep the integral beauty of the timber buildings. In order to investigate the effect of thickness of timber board on the mechanical performance of TCC beam in fire, three finite element models of TCC beams with 0mm, 10mm and 20mm timber board were investigated. Based on the FEA results, the time-deflection curves of TCC beams in 60 min were shown in Fig.5. When the timber board was not set in TCC beam, the composite beam failed after 53 min. By comparing the time-deflection curves of TCC beams with 10mm and 20mm timber board, it was found that in the early stage, there was no significant difference in the deflections between the two. With the increasing time of fire exposure, the deflection of TCC beam with 20mm timber board was significantly smaller than that of TCC beam with 10mm timber board. The timber board had a protective effect on concrete slab against fire. However, the protective effect was gradually weakened with the increase of time owning to the charring of timber board. Therefore, the fire resistance of TCC beam was improved with the increase of thickness of timber board.

5 Conclusions
According to the calculated results and analysis made in the previous contents, the following conclusions were achieved in this paper:

(1) The established finite element model could be used to study the performance of timber-concrete composite beam in fire, and the FEA results agreed well with experimental results.

(2) The width of timber beam was a significant factor for the fire resistance of TCC beam. The fire
resistance of the TCC beam was improved with the increase of the width of timber beam, due to the increase of the residual cross section of timber beam in fire.

(3) The concrete slab had important influence on the fire resistance of TCC beam, since concrete slab could absorb a large amount of heat and have a protective effect on the top of the timber beam.

(4) The deflection of TCC beam with timber board was smaller than that of TCC beam with no timber board. Timber board could be used as a construction platform to provide convenience for construction, and it had a protective effect on concrete slab against fire. The fire resistance of TCC beam was improved with the increase of the thickness of timber board.

Acknowledgements
The research conducted in this paper was supported by National Natural Science Foundation of China (51478220), (51678295). The test results were obtained from the paper published by Frangi A et al [10]. The writers are grateful for their research work on the fire resistance of TCC beams.

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