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Research Article

Numerical modelling of heat transfer through protected composite structural members

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ABSTRACT

Among many various types of passive fire protection materials (i.e. plaster boards, sprayed materials and intumescent coatings) thin film intumescent coatings have become the preferable option owing to their good advantages such as flexibility, good appearance (aesthetics), light weight to the structure and fast application. Despite their popularity, there is also a lack of good understanding of fire behaviour. In general, experimental methods are used to push this knowledge with labour and high-energy consumption and extremely expensive processes. With the development of computer technology, numerical models to predict the heat transfer phenomena of intumescent coatings have been developed with time. In this work, the numerical model has been established to predict the heat transfer performance including material properties such as thermal conductivity and dry film thickness of intumescent coating. The developed numerical model has been divided into different layers to understand the sensitivity of steel temperature to the number of layers of intumescent coating and mesh sizes. The temperature-dependent thermal conductivity of intumescent coatings can be calculated based on inverse solution of the equation for calculating temperatures in protected steel according to the Eurocodes (EN 1993-1-2 and EN 1994-1-2). However, as the temperature distribution in the intumescent coatings is highly non-uniform, that Eurocode equation does not give accurate coating thermal conductivity-temperature relationship for use in numerical heat transfer modelling when the coating is divided into a number of layers, each having its characteristic thermal conductivity values. The comparison study of steel temperature under Standard (ISO 834) and Fast fire conditions against Eurocode analytical solution has also been made by assuming both constant thermal conductivity and variable thermal conductivity. The obtained results show close agreement with the Eurocode solution choosing a minimum certain mesh, number of layer and best-fitted thermal conductivity of the intumescent coating.

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1. Introduction

Using steel with composite structural members such as slab is a major building construction type in commercial, residential and other buildings in worldwide. However, one big issue with steel as a building structural material is its poor behavior in fire due to rapid increase in temperature leading to sudden drop in strength. Moreover, high temperatures cause elongation and deformation in terms of decrease of the mechanical properties (Wang, 2002). Thus, fire protection is generally necessary to enable structural steel to survive under fire attack. Fire performance of various slim floors in fire with loading conditions has been studied by Alam et al. (2018). Besides, fire behavior of composite slab-beam systems has been investigated by Nguyen et al. (2015) by experimentally and numerically claiming that the experimental results provide only basic information on the membrane behavior in fire for the numerical models.

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The parameters such as emissivity and the moisture content of the concrete effecting thermal performance of composite slabs have been given in the paper of Jiang et al. (2018) declaring that the moisture content with an increment of 1% leading to an increase on fire performance of the composite floor system. Among various types of fire protection materials, intumescent coatings are commonly used passive fire protection material owing to their ease and flexibility in application, good durability, aesthetic view and light weight. Intumescent coatings are specially formulated reactive paints designed to expand by a factor of between 5 to 100 times by releasing gases and forming a final char which acts as a thermal barrier (Horacek and Pieh, 2000; Mariappan, 2016; Zhang et al., 2012a, 2012b; Cirpici et al., 2016a, 2016b; Bourbigot et al., 2004; Di Blasi, 2004). Despite these advantages of intumescent coatings, the fire behavior of it has not been thoroughly understood because of the complexity of the expansion process, rate of temperature increase and the composition of the coatings.

Fire testing of intumescent coatings used in structural steel members is seen as necessary to cover different applications, but also an expensive process to the people like intumescent coating manufacturers and academicians. Therefore, the validation study in terms of steel temperature based on intumescent coating protected I-steel section has been performed with mesh sensitivity study firstly. Then, numerical heat transfer has been used to compute the temperatures in composite structural members in terms of steel beam, steel decking protected with intumescent coating and concrete under standard fire condition (ISO 834) specified by the International Standard Organization ((ISO) 2014) herein this study. The numerical simulations are accomplished by the Transient Thermal analysis module of ANSYS Workbench 18.1.

Nomenclature	
λ_{st}	Thermal conductivity of steel
T_{st}	Steel temperature
C_{st}	Specific heat of steel
ρ_{st}	Density of steel
λ_p	Thermal conductivity of fire protection material
A_p/V	Section factor of the protected steel section
d_p	Fire protection material' thickness
c_p	Specific heat of fire protection material
ρ_p	Density of fire protection material
ΔT_f	Fire temperature differences respect to time

2. Validation Study based on I-Steel Section against Eurocode Solution

The validation study has been done based on comparing against Eurocode – EN 1993-1-2 (CEN, 2005a). Fig. 1 shows the 2-D intumescent coating protected steel system obtained from 3-D. Green line shows the intumescent coating applied to 4-side of the steel beam.

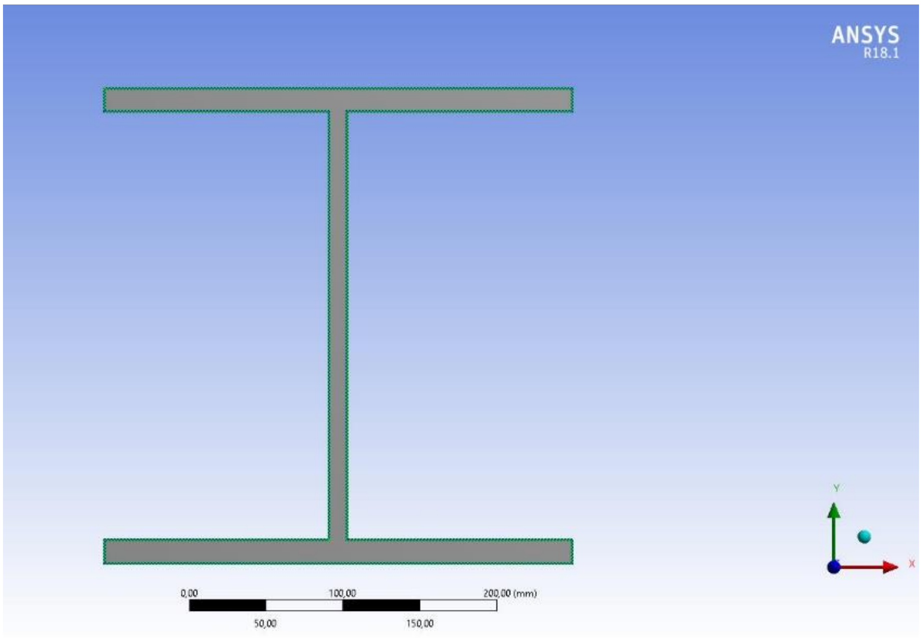

Fig. 1. ANSYS simulation 2-D view.

The intumescent coating used in this model has been assumed to be non-reactive fire protection material with no change in thickness. Therefore, the expansion process has not been considered in this validation. Although, this does not reflect the actual behavior of intumescent coatings, this is considered acceptable for the validation purpose.

2.1. Material thermal properties

The main required thermal properties for heat transfer analysis are specific heat, thermal conductivity, emissivity and density.

2.1.1. Steel properties

The thermal conductivity, specific heat and density of steel structural steel has been obtained from Eurocode 3 Part 1.2 (CEN, 2005a).

- The thermal conductivity of steel is:

If steel temperature T_{st} (K) is lower than 800°C;

$$\lambda_{st} = 54 - 3.33 \times 10^{-2}\, T_{st} \tag{1}$$

If steel temperature is higher than 800°C;

$$\lambda_{st} = 27.3 \tag{2}$$

where λ_{st} is the steel thermal conductivity (W/mK). Fig. 2 presents the thermal conductivity of steel-temperature relationship based on EN 1993-1-2.

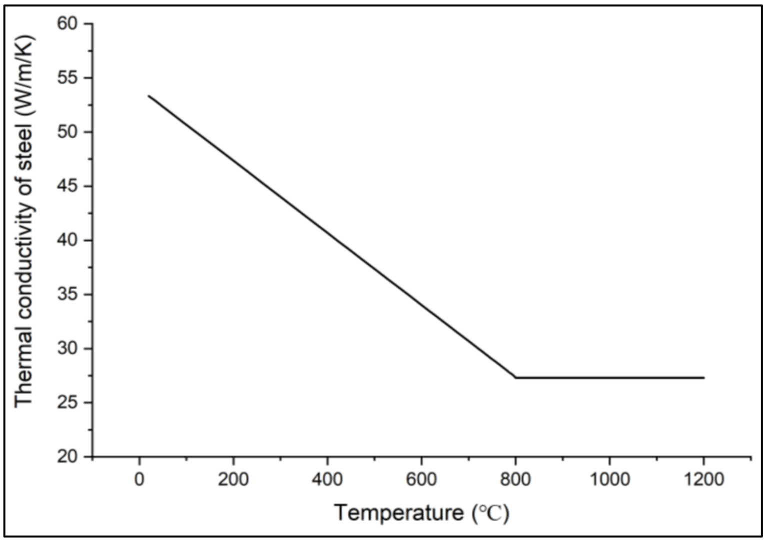

Fig. 2. Variation of thermal conductivity of steel with temperature (CEN, 2005a).

- The specific heat-temperature relation is:

If $20°\text{C} \leq T_{st} < 600°\text{C}$;

$$C_{st} = 425 + 7.73 \times 10^{-1} T_{st} - 1.69 \times 10^{-3} {T_{st}}^2 + 2.22 \times 10^{-6} {T_{st}}^3 \tag{3}$$

If $600°\text{C} \leq T_{st} < 735°\text{C}$;

$$C_{st} = 666 + \frac{13002}{738 - T_{st}} \tag{4}$$

If $735°\text{C} \leq T_{st} < 900°\text{C}$;

$$C_{st} = 545 + \frac{17820}{T_{st} - 731} \tag{5}$$

If $900°\text{C} \leq T_{st} < 1200°\text{C}$;

$$C_{st} = 650 \tag{6}$$

where C_{st} is the specific heat $\left(\frac{J}{kg} \cdot K\right)$ (Fig. 3).

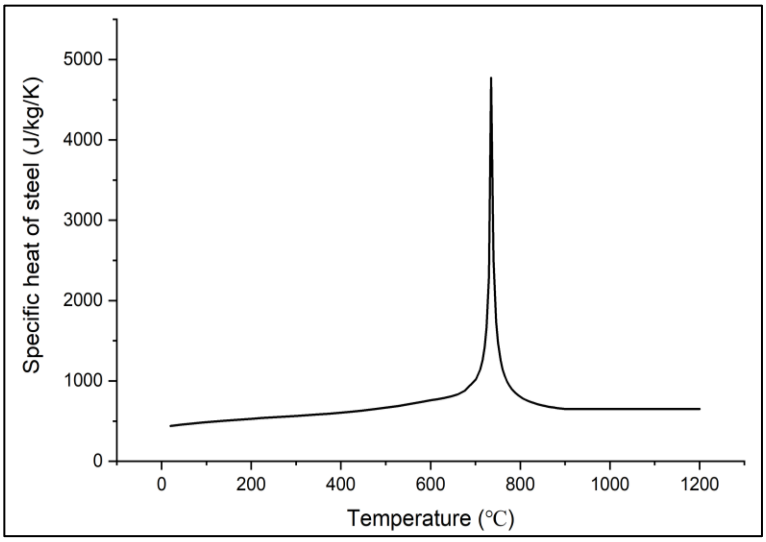

Fig. 3. Variation of specific heat of steel with temperature (CEN, 2005a).

Fig. 3 shows the specific heat of steel-temperature relationship based on EN 1993-1-2. The high values are around 735°C as a result of change of microstructure of the steel. The density of structural steel used in the model is 7850 kg/m^3.

2.1.2. Intumescent coating thermal properties

As the thickness in the validation study is very small, the effect of its density and specific heat on the protected steel temperature is very little. Hence, the constant values according to Annex E of EN 13381-8:2013 (CEN, 2013) has been used. Those values are 1000 J/kg · K for the specific heat, and 100 kg/m^3 for the density respectively. However, the effective thermal conductivity has been obtained by Wang et al. (2013) based on their fire tests. This effective thermal conductivity-temperature relationship is shown in Fig. 4. In their model, fire has been exposed to the protected surfaces as it is also applicable herein author's study though. The considered convective heat transfer coefficient in the model is 25 W/m^{2}K (CEN, 2005a) and the resultant emissivity of the coating for the radiation has been taken as 0.92 (CEN, 2005a).

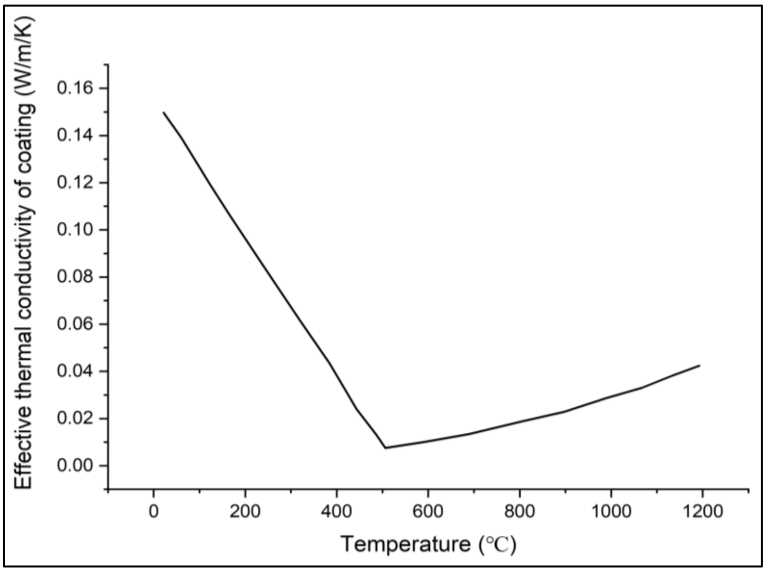

Fig. 4. Effective thermal conductivity-temperature curve (Wang et al., 2013).

2.2. Boundary conditions and relevant data for the validation

The relevant data for the simulation of intumescent coating protected I-section (305mm × 305mm × 97kg/m) has been tabulated in Table 1. This section has been exposed to the standard fire condition all around (4-side). The boundary conditions are shown in Fig. 5.

Table 1. Specimen details for comparison with Eurocode calculation.

Section	Dimensions (mm)			
305 × 305 × 97	B 303	D 308	T_f 14.3	T_w 10.5
Protection thickness	1.0 mm			
Fire exposure	4-sided			
Steel properties ($\lambda_{st}, C_{st}, \rho_{st}$)	EN 1993-1-2			
Protection properties (C_p, ρ_p)	EN 13381-8			
Protection thermal conductivity	Wang et al. (2013)'s study			

According to EN 1993-1-2, the temperature of a protected steel section is calculated using Eq. (7).

$$\Delta T_{st} = \frac{\lambda_p A_p/V}{d_p c_{st} \rho_{st}} \frac{T_f - T_{st}}{\left(1+\frac{\phi}{3}\right)} \Delta t - \left(e^{\phi/10} - 1\right) \Delta T_f$$

$$\text{with } \phi = \frac{c_p \rho_p}{c_{st} \rho_{st}} d_p \frac{A_p}{V} \qquad (7)$$

where λ_p (W/mK) is the thermal conductivity of the fire protection material (intumescent coating shown in Fig. 4), A_p/V (m^{-1}) is the section factor of the protected steel section based on the diameter presented in Table 1, d_p (m) is the fire protection thickness, c_p (J/kg · K) and ρ_p (kg/m^3) are specific heat and density of the protection material given in Section 2.1.2, T_f (°C) and T_{st} (°C) is the exposed fire temperature (ISO) and steel temperature respectively, Δt (s) is the time interval in seconds.

The considered fire conditions (i.e. fire curves such as Standard (ISO) and Fast) as inputs for the developed models are shown in Fig. 6.

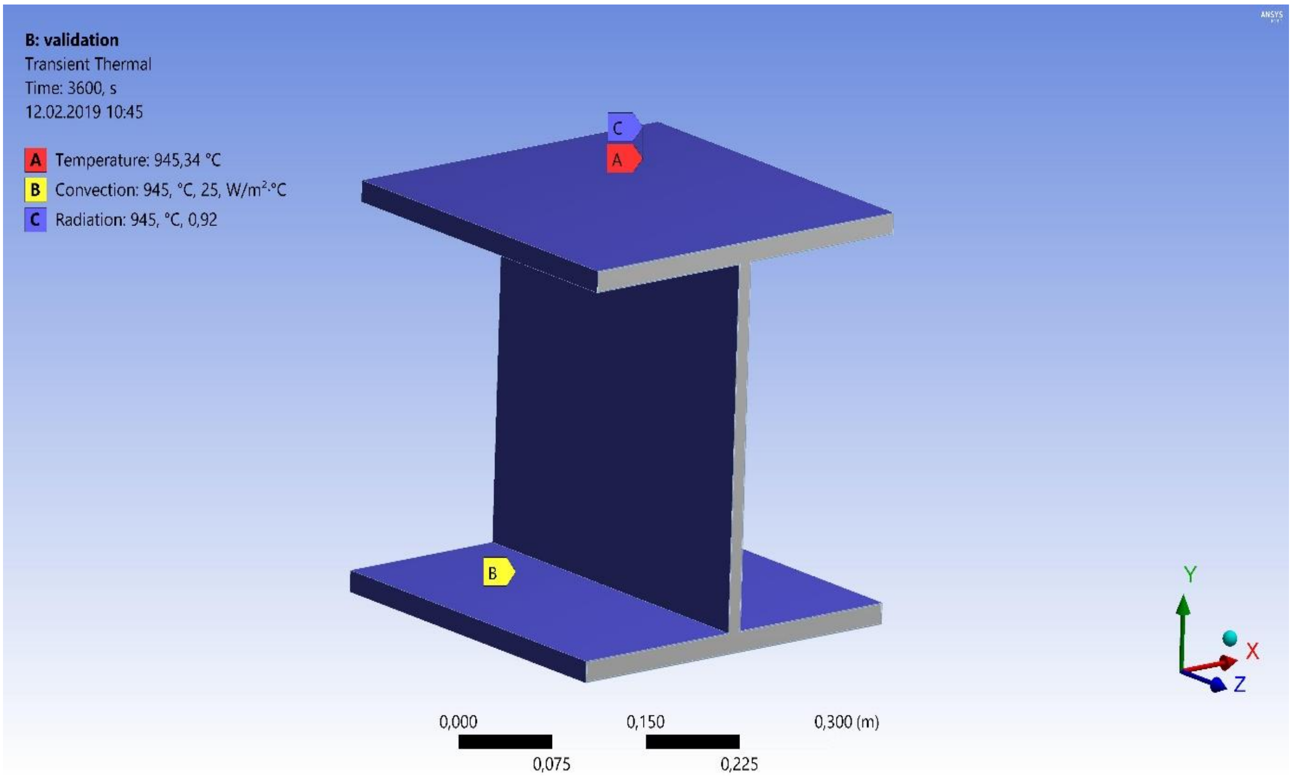

Fig. 5. Boundary conditions of the validation study.

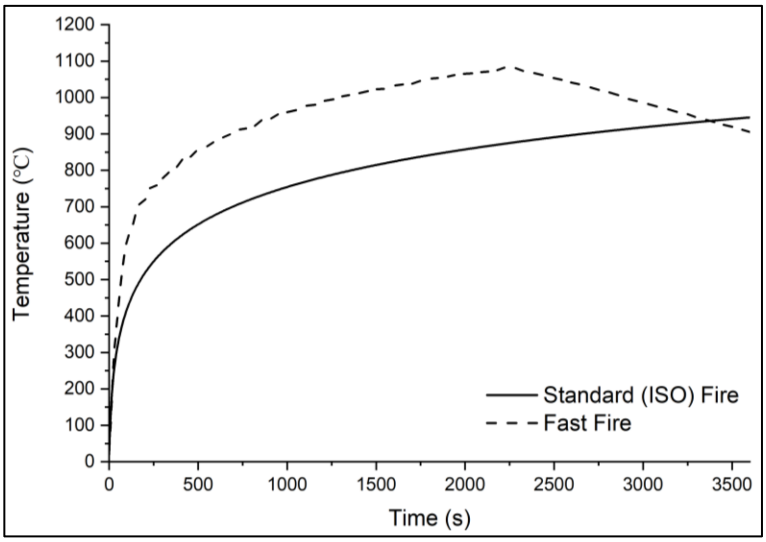

Fig. 6. Exposed fire conditions for the numerical models.

3. Results of Validation and Mesh Sensitivity Study

Fig. 7 compares the ANSYS simulation results and EN 1993-1-2 analytical solution results. As seen, very close results confirm the validity of the numerical model based on applied Standard (ISO) fire condition. Moreover, 3-D heat transfer simulations has been carried out using different mesh types and sizes. The steel temperature differences between author's results and Eurocode solution is significantly small up to 200°C since the intumescent coating is almost inert at around that temperature. However, the coating begins to be active afterwards with the increase in temperature. The differences are quite small with the range of 2-3% based on the mesh size of 2 mm and 5 mm. This also provides additional confidence in the authors' simulation model. It is concluded that the mesh sizes have a little effect on the predicted steel temperature. Tetrahedral elements have been used for meshing of coating as its section thickness is relatively thin. For the steel profile meshing, hexahedral elements have been preferred. Mesh structure has been presented in Fig. 8. From the mesh sensitivity study, mesh size of 5 mm are chosen for the intumescent coating as acceptable and will be used in the heat transfer simulations of composite slab with steel decking and steel beam.

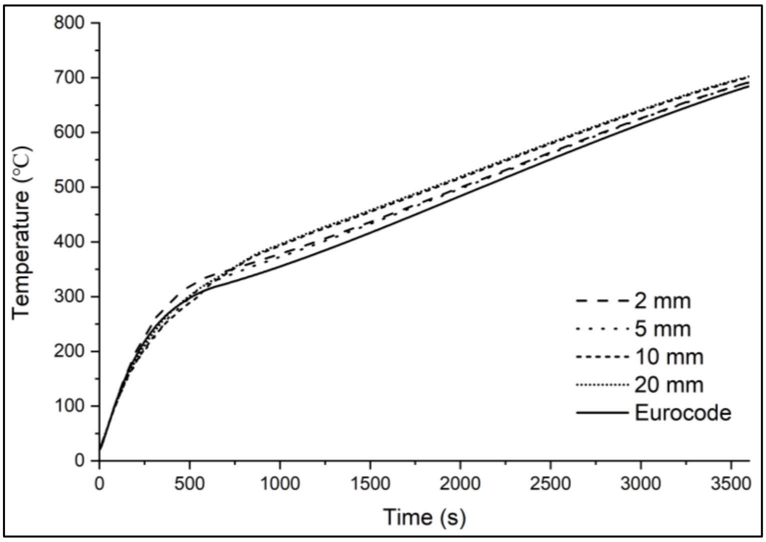

Fig. 7. Comparison of insulated steel temperatures predicted from ANSYS 3-D model and calculated according to EN 1993-1-2.

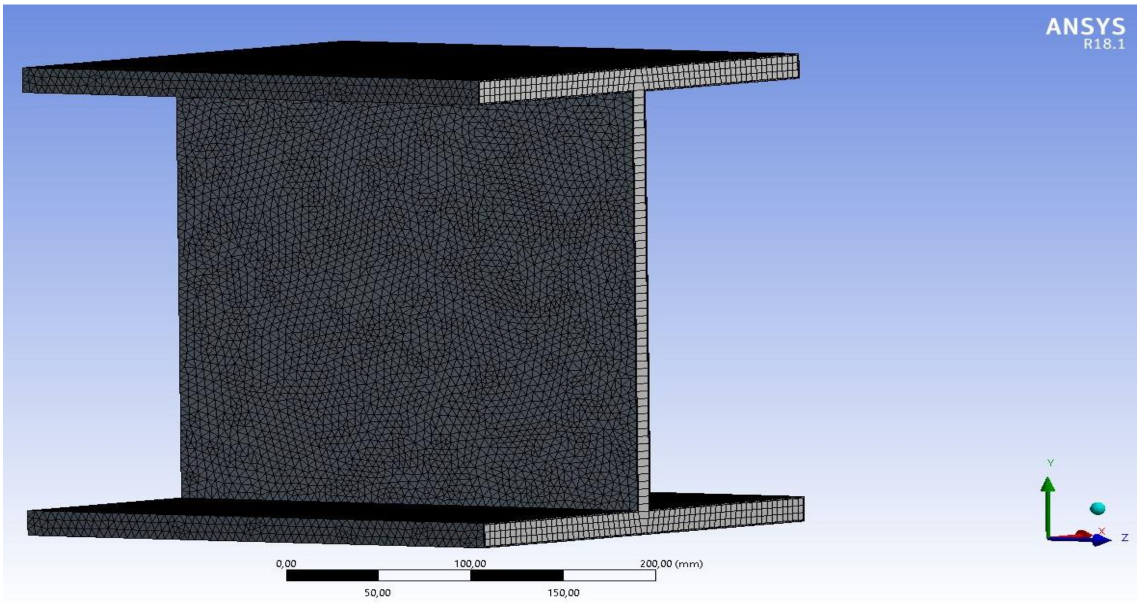

Fig. 8. Structure of the mesh for the validation study.

4. Temperature Distribution in Protected Composite Structural Member

After validating the developed 3-D model, a steel beam with a steel decking, both protected by intumescent coating supported a concrete slab on top in 3-D model has been developed to predict the steel temperatures for both decking and beam and concrete temperature after Standard fire (ISO 834) and Fast fire exposures to steel parts of the model.

For this purpose, two models has been proposed and developed. One of them is to apply intumescent coating to the steel parts with the same protection thickness (1 mm) with the validation model in one-layer. The other one is to apply the same coating by 4-layers. This study aims to understand how the layers have an influence on temperature distributions on proposed composite structural member. Moreover, it is also proposed to see the effect of fire exposure side (only to steel parts of the model) on the temperature distribution on both steel beam and decking and also concrete.

4.1. Model properties and setup

4.1.1. Steel beam and decking properties

In this study, in a typical composite steel-concrete flooring system whose geometric properties are shown in Fig. 9, two different model of which the same intumescent coating is applied in two different ways, were used. In the models; as floor structural beam, the section properties of the standard UC 305×305×97 steel profile and as composite decking, the section properties of a typical trapezoidal steel sheet produced for this purpose in Turkey (Ataçelik, 2019), have been considered here in this study. Two different composite floor system have been modelled in two different ways considering that the intumescent coating as the fire protection material was applied to surfaces of the steel beam profile outside the cross-section and to only bottom surface of the trapezoidal steel sheet as a single layer with 1 mm thickness and successive four layers with 0.25 mm thickness. Since the intumescent coating is applied after the composite floor assembles, coating has not been applied to the parts of the trapezoidal steel deck where it is seated on the steel beam. In both composite floor models, as the same way, it was thought that the structural concrete parts of whom the deep section with 120 mm thickness, to be made of normal weight concrete. The length of composite floor models are 1 meter in transverse and longitudinal direction having one square meter unit surface area.

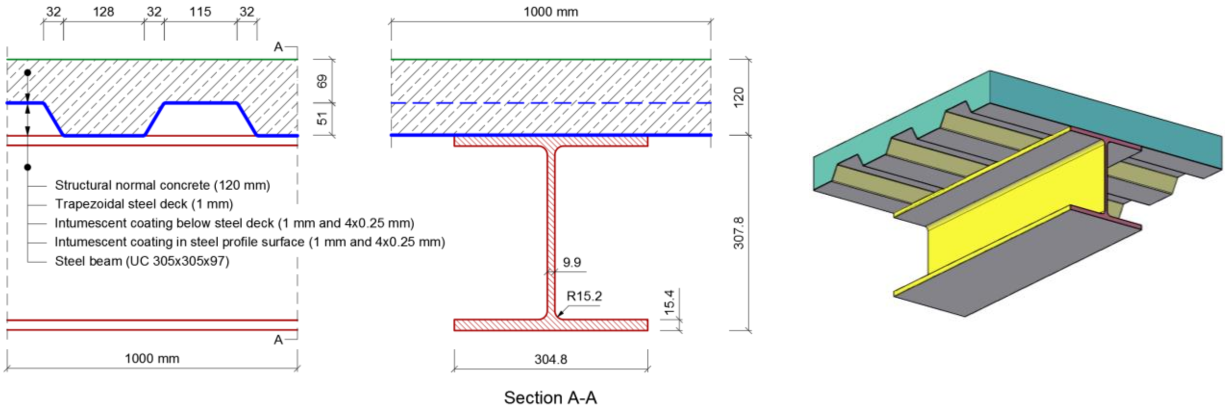

Fig. 9. Composite structural member properties.

4.1.2. Thermal properties of concrete

The variation of thermal conductivity of concrete with temperature depending on concrete weight (i.e. lightweight – LC, normal weight – NC) is illustrated in Fig. 10 (CEN, 2005b). Normal weight with lower limit values for the thermal conductivity of concrete has been considered in the developed ANSYS model.

Specific heat of normal weight concrete (NC) and lightweight concrete (LC) as a function of temperatures is given in Fig. 11 according to EN 1994-1-2 (CEN, 2005b). The change of specific heat of normal weight concrete respect to temperature input into the developed model as the considered concrete slab part of the composite structural member is normal weight concrete. The concrete density has been taken into account as 2400 kg/m^3. The unheated side (i.e. on the top of the slab) interacts with the environment through a coefficient of heat transfer by convection of 4 W/m^{2}K and a convection coefficient of 5 W/m^{2}K applied to the fire exposed face of the slab model (i.e. on the bottom of the slab) (Both et al., 2016).

4.1.3. Finite element model properties

Having the confidence of the validation model, composite structural member has been developed in the same way with the previous study adding the steel decking and concrete slab. The boundary conditions and the general mesh structure of the developed model has been shown in Figs. 12 and 13, respectively. Moreover, all contacts between the materials are modelled as bounded.

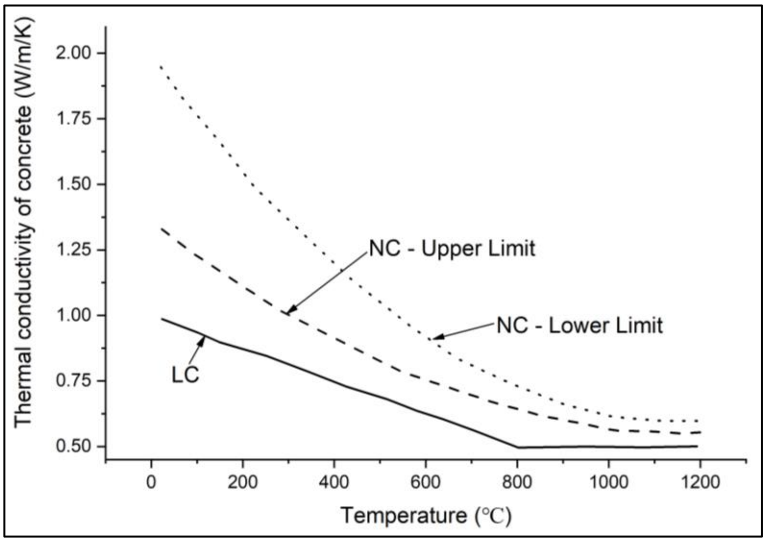

Fig. 10. The change of thermal conductivity of concrete respect to temperature.

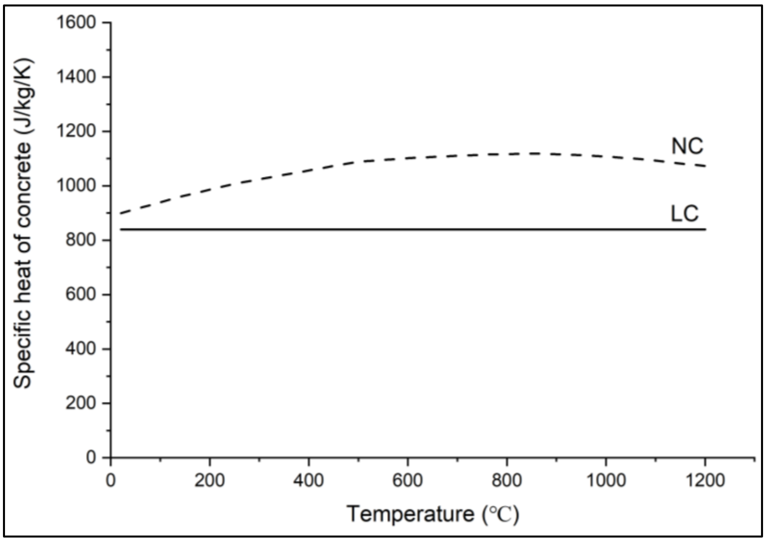

Fig. 11. Change of specific heat of normal weigh concrete (NC) and lightweight concrete (LC) with temperature.

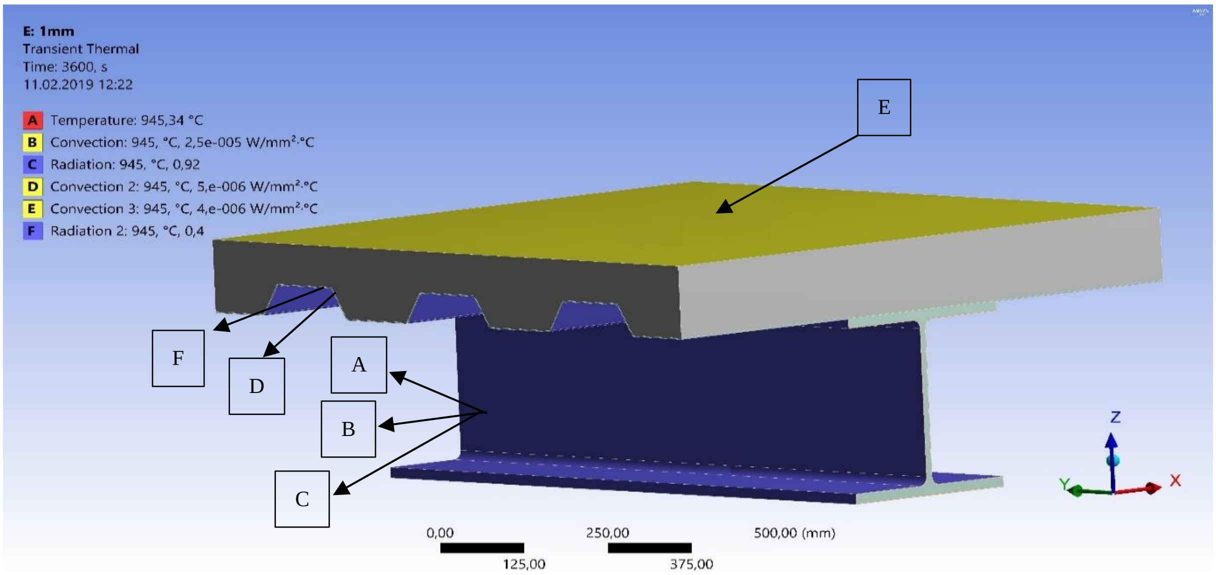

Fig. 12. Thermal boundary conditions of the composite structural member.

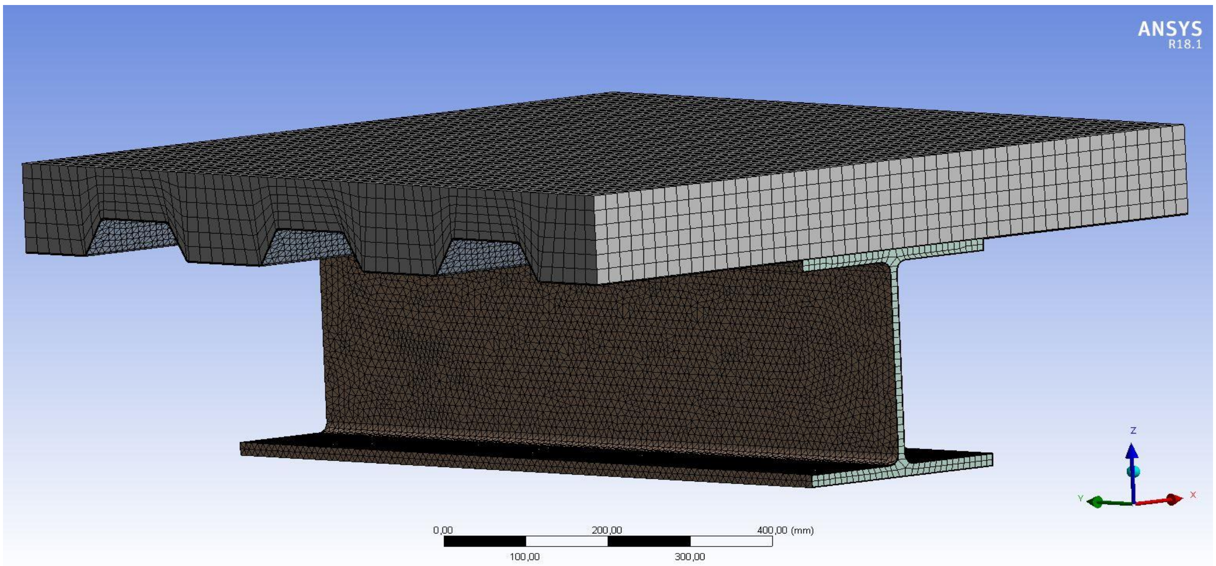

Fig. 13. Meshed models of composite structural member.

5. Results and Discussion

Fig. 14 shows the steel beam (UC 305×305×97) temperature-time relationship under the standard fire (ISO-834) exposure for an hour. The fire has been exposed to the surface where the coating has been applied on. As explained in Section 4.1.1, two different scenarios had been proposed, one layer of coating with 1 mm thickness and 4-layers of coating with 0.25 mm thickness individually. It is found that assigning number of layers to intumescent coating produced a bit less temperature results especially the coating has moved to be active around after 150°C. However, the differences between results of 1-layer and 4-layers has been decreasing when the intumescent coating turns into char after approximately 450°C. This was also obtained by Podolski (2017) where the author demonstrates the sensitivity of steel temperature to the different number of layers using 1, 2, 4, 6 and 12 layers. He concludes that using 4-layers is sufficient. The simulation results and this study also provides more information about which part of the composite structural floor system has been effected more under possible fire attack such as web of the beam, edges of the flanges of the beam, steel decking itself due to being thinness and also the parts of the floor system where the openings are (the openings between steel decking and steel beam). Fig. 15 shows this overall fire performance and behavior of the proposed composite structural member.

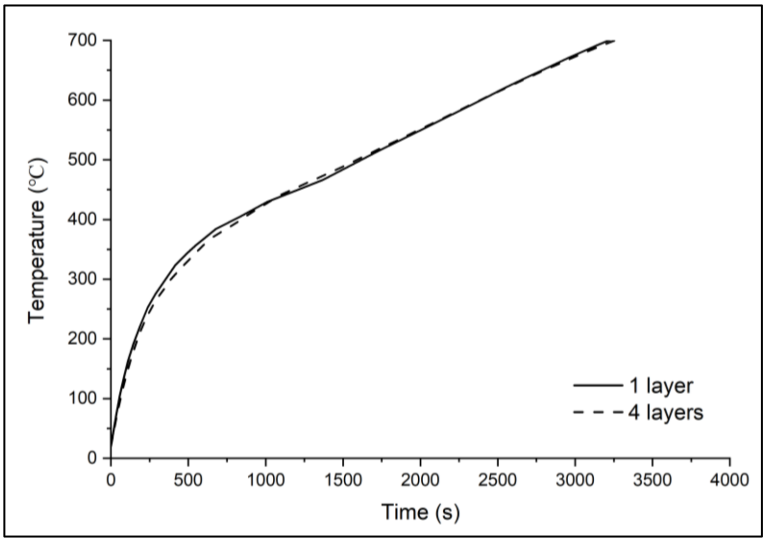

Fig. 14. Steel beam temperatures protected by intumescent coating with one-layer and 4-layers exposed to ISO 834 Standard fire.

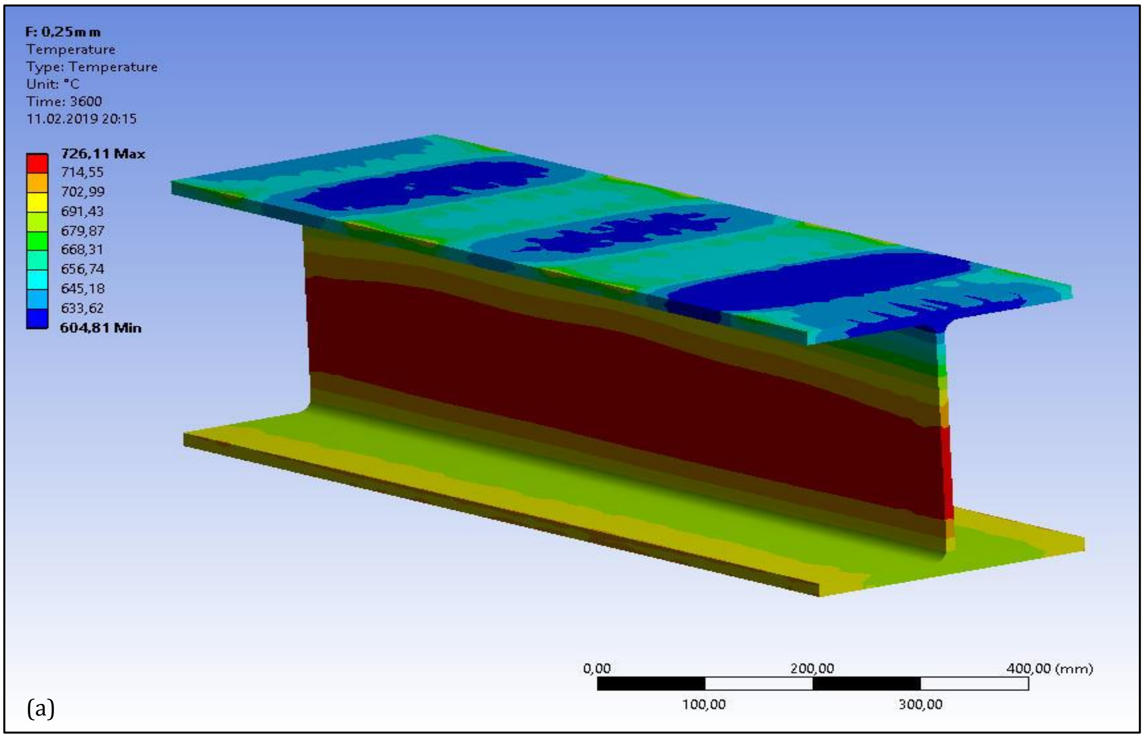

Fig. 15. (continued).

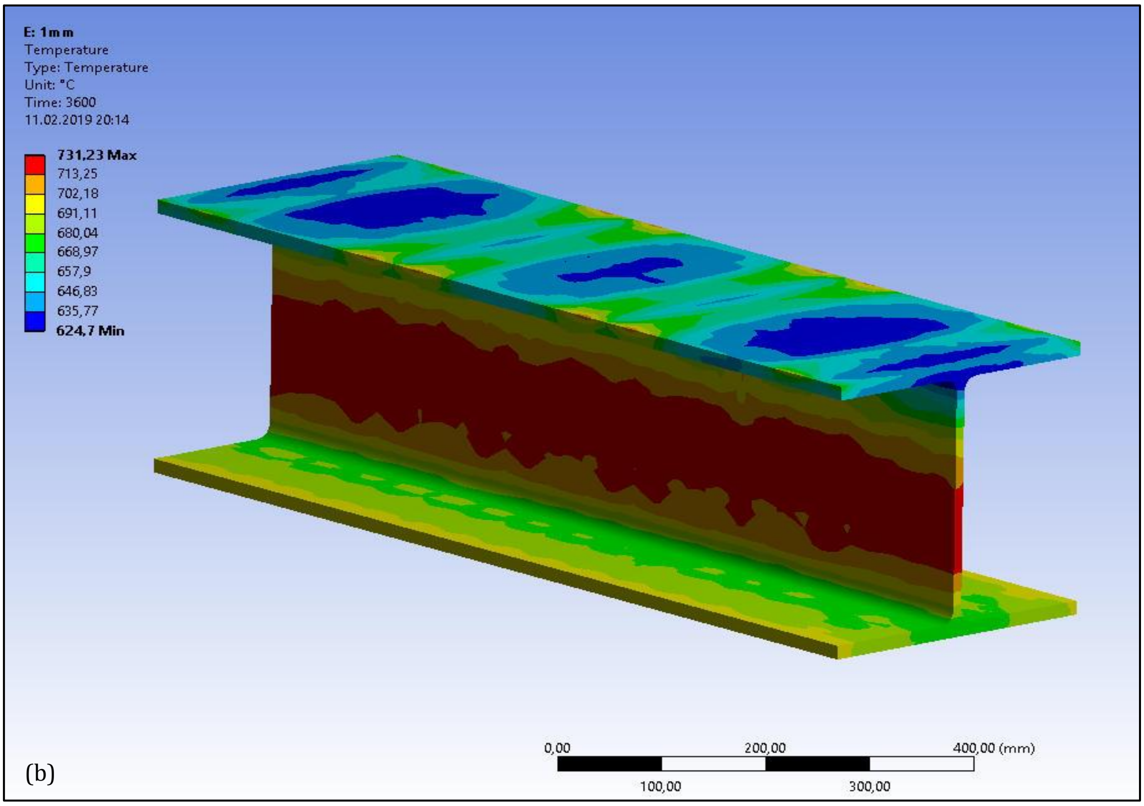

Fig. 15. The fire behaviour of the composite structural member under the exposure of Standard (ISO 834) fire: (a) applied 4-layers of coating each having 0.25 mm dry film thickness; (b) applied single layer having 1 mm dry film thickness.

Fig. 16 presents the steel beam temperature results of 1-layer and 4-layers of intumescent coating applied when it is exposed to Fast fire. Comparing to Standard (ISO) fire exposure, the difference between 1-layer and 4-layer results is a little bit more after approximately half one hour. At the end of the simulation, the temperature difference is just 25°C which can be acceptable when the heat transfer phenomena applies to layers. Beyond that, the identical behaviour and temperature results have been obtained for both 1-layer and 4-layers. Due to the nature of the Fast fire, the temperature increases rapidly contrast to Standard fire resulting in higher temperatures in the steel section almost 150°C differences. The overall fire performance and behaviour of steel beam after Fast fire exposure is shown in Fig. 17.

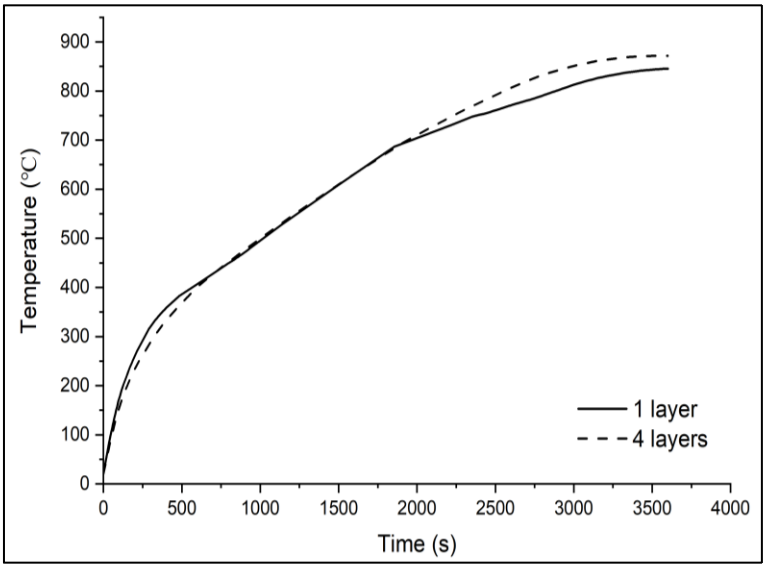

Fig. 16. Steel beam temperatures protected by intumescent coating with one-layer and 4-layers exposed to Fast fire.

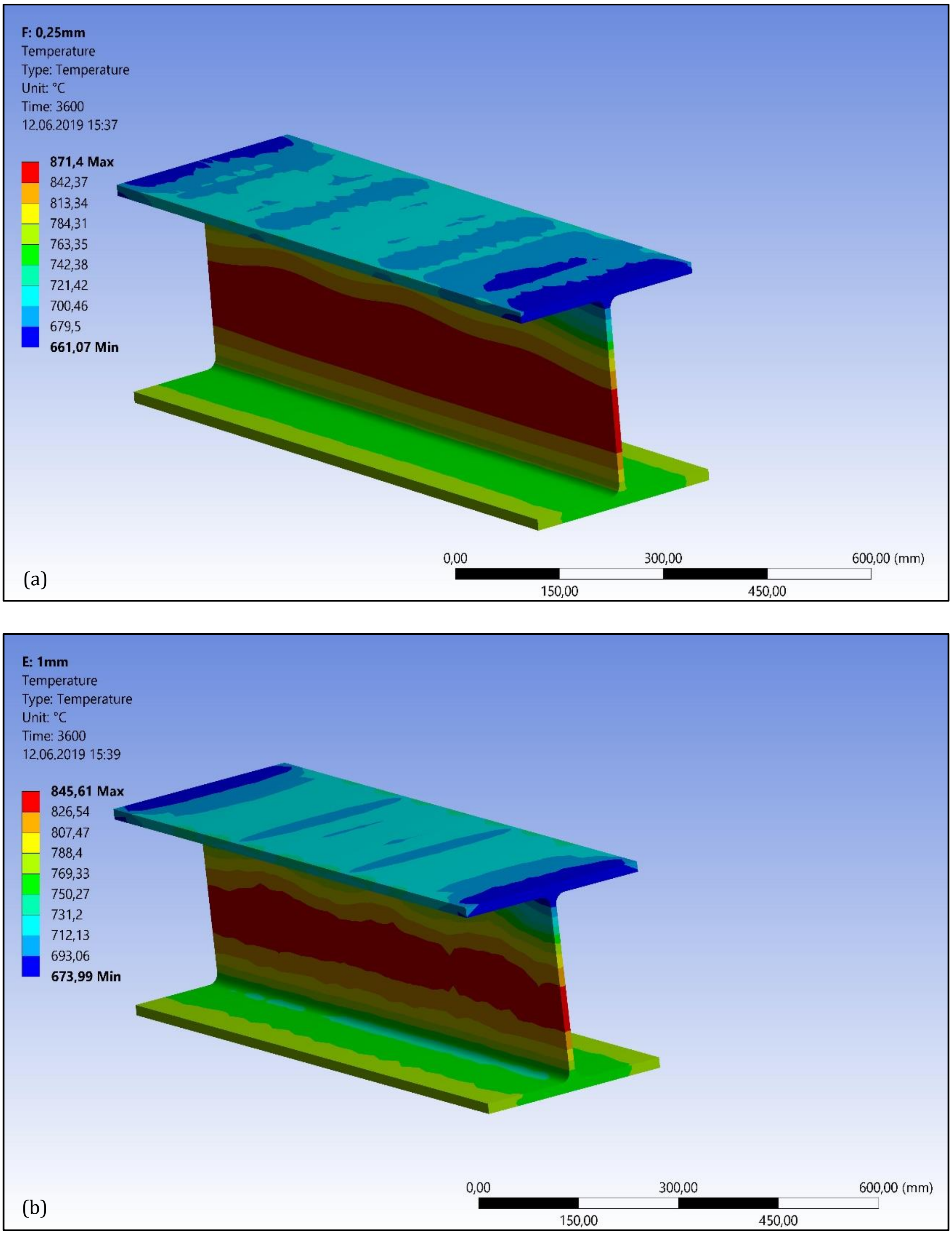

Fig. 17. The fire behaviour of the composite structural member under the exposure of Fast fire:
(a) applied 4-layers of coating each having 0.25 mm dry film thickness;
(b) applied single layer having 1 mm dry film thickness.

6. Conclusions

This study has presented the main features of a heat transfer simulation model using ANSYS and evidences to demonstrate that the simulation model is able to provide accurate results of intumescent coating protected steel temperature. Based on the results of the sensitivity and validation studies, the following numerical modelling parameters have been determined:

- A mesh size of 5 mm can be used with tetrahedral elements for the thinner parts and hexahedral elements for the thicker parts.
- The radiant and convective thermal boundary conditions obtained from Eurocode EN 1993-1-2 can safely be used to predict the protected steel temperature.
- The comparison of validation study is adequate.

For the study of composite structural member with steel beam, steel decking and concrete floor under the exposure of both Standard and Fast fire, dividing the intumescent coating into layers gives more accurate results than considering single layer as it reflects the heat transfer behavior in a very good way. Moreover, the fire exposure side from steel parts to concrete results in fewer temperatures in concrete as it is expected because of good fire behavior and performance of concrete. In addition to this, this study also helps to understand which parts of the composite structural floor system influences more from a fire attack. Applying intumescent coating to steel parts including steel beam and decking provides a good fire protection performance to the whole structural system.

Publication Note

This research has previously been presented at International Civil Engineering and Architecture Conference (ICEARC'19) held in Trabzon, Turkey, April 17-20, 2019. Extended version of the research has been submitted to Challenge Journal of Structural Mechanics and has been peer-reviewed prior to the publication.

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