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A detailed methodology for the finite element analysis of asymmetric slim floor beams in fire

The aim of this paper is to present a detailed methodology for the three-dimensional finite element analysis of asymmetric slim floor beams under fire conditions. A fully controlled solution process is suggested through a detailed step-by-step presentation of the simulation parameters incorporated into the model. Work has been carried out so that any asymmetric slim floor beam can be assessed using the same consistent method, which is validated against two reported fire tests. Time–temperature and time–vertical displacement curves are calculated for the appropriate comparisons with experimental results, which show that the proposed methodology can accurately predict the thermal and structural behaviour of such beams.

1 Introduction

The composite slim floor structural system is a fast, economical and reduced-weight construction system. A typical asymmetric slim floor (Fig. 1) consists of a steel beam that is almost encased within the depth of the concrete floor slab, with its lower flange wider than its upper, and a composite concrete slab with profiled steel decks. There are usually additional reinforcing bars in the composite floor. The behaviour of this structure under fire conditions has been investigated experimentally and numerically by many researchers worldwide. The Steel Construction Institute (SCI) [1], [2] and the Warrington Fire Research Centre (WFRC) [3] have carried out fire tests on slim floor systems.

Unprotected simply supported composite beams with different geometries and load ratios have been examined in particular. The test specimens are initially loaded and then heated using the ISO standard fire curve under static loads. Time–temperature and time–vertical displacement relationships in combination with failure modes have been observed in the tests and reported [1]. The realization of fire tests is a demanding procedure that needs advanced technological equipment in order to give reliable results. Therefore, numerical modelling can compensate for the lack of test data and provide a good insight into the behaviour of composite structures under fire conditions. Many researchers have developed and proposed numerical models for the simulation of slim floor beams in fire. The best-known models available in the literature are those of *Newman* [4], *Bailey* [5], *Ma* and *Mäkeläinen* [6]–[10], *Both* et al. [11] and *Ellobody* [12]. However, there is a lack of data available for the detailed finite element simulation of slim floor beams with three-dimensional elements as performed in this study. The objective of this paper is to present a detailed methodology for the analysis of asymmetric slim floor beams under fire conditions using ABAQUS software [13]. A fully controlled solution process is suggested through a detailed step-by-step presentation of the simulation parameters incorporated in the model.

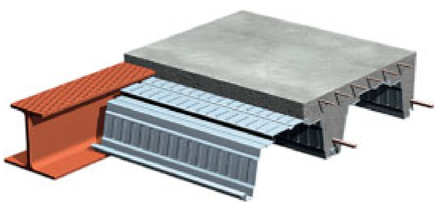

Fig. 1. Typical layout of an asymmetric slim floor beam

2 Experimental data

The reported fire tests [1], [3] on unprotected composite slim floor structures are used for the verification of the suggested simulation. The nominal and measured material and geometric properties of the steel sections are summarized in Table 1, and the

Table 1. Geometric and material properties of steel sections [1], [3]

		WFRC 66162		WFRC 67756	
Section dimensions [mm]		Nominal	Actual	Nominal	Actual
Top flange	Width	180	183	190	198
	Thickness	18	16.6	20	21.7
Bottom flange	Width	280	280	300	306
	Thickness	18	18.4	20	20.6
Web thickness		18	19.5	18	17.2
Section depth		280	279	304	305.8
Material properties		Nominal	Actual	Nominal	Actual
Yield strength [MPa]		355	402	355	392

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corresponding section dimensions are shown in Figs. 2 and 3. The beams are simply supported, span 4.5 m and have a total length of 5.0 m, and the distance between the furnace walls is 4.0 m (Fig. 4). The concrete used is normal weight grade 30 and A142 mesh reinforcement (∅6/200) is incorporated in the upper part of the composite slab. The profiled steel decks used are PMF 210 and 225. Four point loads of 84.6 kN are applied to the first specimen, reference number WFRC 66162, by hydraulic rams positioned along the centre line of the web of the steel section at points corresponding to 1/8, 3/8, 5/8 and 7/8 of the simply supported span. The loads are applied directly to the upper flange of the steel section and not to the concrete slab above it. The applied loads together with the self-weight of the test specimen result in a load ratio of 0.423, ignoring composite action between steel and concrete. The second slim floor tested, reference number WFRC 67756, is loaded by four hydraulic rams, each applying a point load of 85.0 kN to the concrete surface of the slab above the web of the steel section. The rams are positioned symmetrically about mid-span of the beam and spaced at 520 mm. The applied load combined with the self-weight of the specimen results in a load ratio of 0.390.

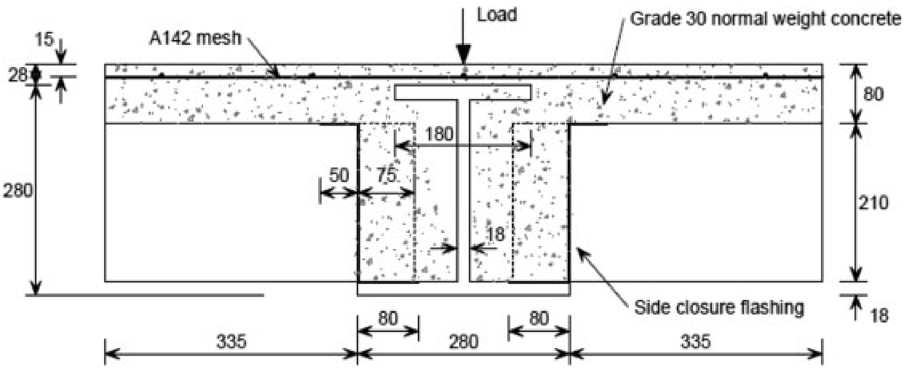

Fig. 2. WFRC 66162, composite section [1]

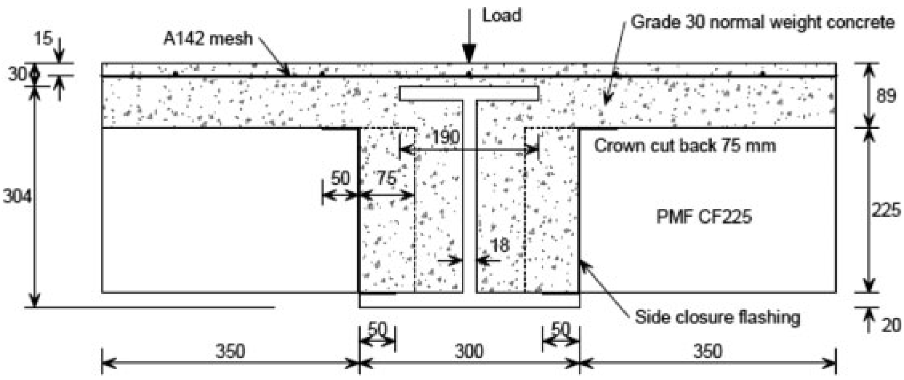

Fig. 3. WFRC 67756, composite section [1]

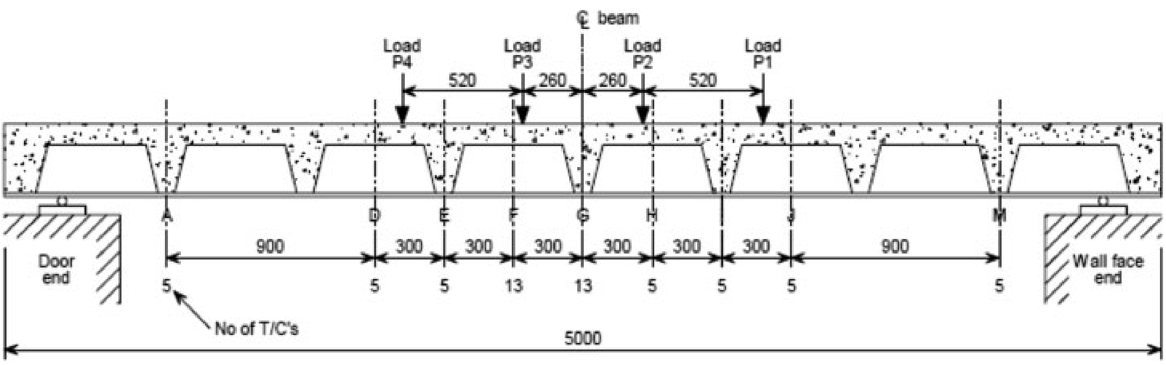

Fig. 4. WFRC 67756, slim floor beam [1]

3 Finite element modelling

Finite element modelling of the slim floors is performed with eight-node hexahedral solid elements (Fig. 5) taking into consideration the interface between the steel section and surrounding concrete through appropriate thermal and mechanical contact properties, with the reinforcing bars modelled as well for estimating the structural response. The non-linear thermal and mechanical properties of steel and concrete at elevated temperatures are calculated according to Eurocode recommendations as described below. Due to symmetry, only one quarter of the composite beam is modelled using appropriate boundary and load conditions in order to be compatible with the experimental procedures. The thermal response of the model is calculated via transient uncoupled heat transfer analysis and the structural response via non-linear static analysis performed in two steps. In the first step, the composite beam is subjected to static loads at ambient temperature. In the second step, the composite beam is heated using the temperatures predicted by the heat transfer analysis with the previous static loads remaining. The temperatures are applied using the *TEMPERATURE option available in ABAQUS software [13].

3.1 Thermal response

Three-dimensional heat transfer elements (DC3D8, 8-node linear bricks) are used for estimating the thermal response of the slim floors. The temperature distribution in the composite beam is predicted based on the standard fire curve (ISO 834). A con-

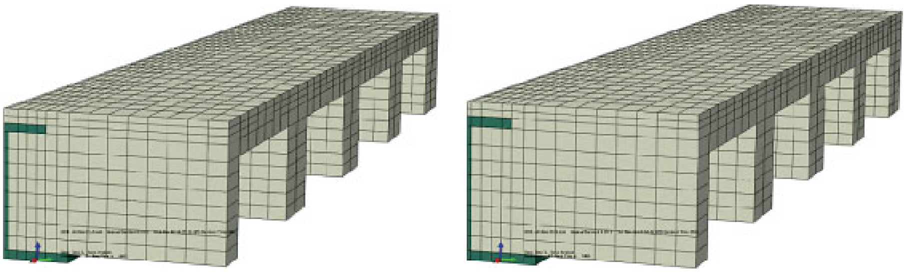

Fig. 5. Finite element models for WFRC 66162 (left) and 67756 (right)

vection coefficient of 25 W/m^{2}K is assumed for the exposed surface and 9 W/m^{2}K for the unexposed one. The radiation emissivity for the bottom steel flange is taken to be 0.5, that for the composite floor 0.25. The heat flow due to radiation is neglected for the upper side. The interface conductivity between concrete and steel is considered as infinite (perfect thermal contact). No heat is transferred normal to the symmetry axes. Heat is applied to the bottom surface of the composite beam. Moreover, the specific heat and thermal conductivity of structural steel and concrete are calculated according to EC 4-1.2 [14] (Figs. 6 and 7) and their densities are taken as 7850 kg/m^3 and 2300 kg/m^3 respectively.

3.2 Structural response

Three-dimensional solid elements are used for estimating the structural response of slim floor structures. The concrete slab is modelled with 8-node linear brick elements (C3D8) because of numerical instabilities regarding the inelastic behaviour of concrete. On the other hand, the steel beam is modelled with three different element types in order to examine their influence; apart from C3D8 elements, bricks enhanced with incompatible modes (C3D8I) and reduced integration bricks (C3D8R) are used. The boundary and loading conditions are identical to those used in the tests. All the nodes on the symmetry surfaces are prevented from displacing in the perpendicular direction. Steel nonlinear behaviour is modelled by the *von Mises* plasticity model (*PLASTIC option), whereas concrete nonlinear behaviour is modelled using the damaged plasticity model (*CONCRETE DAMAGED PLASTICITY option in combination with hardening and stiffening options) with a dilation angle equal to 55° for numerical

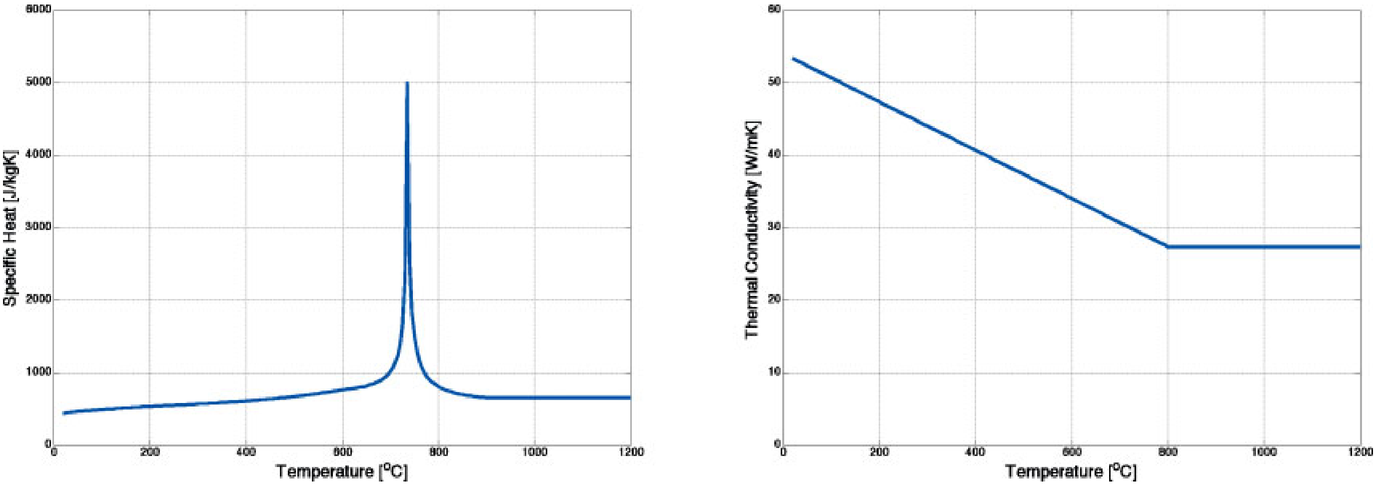

Fig. 6. Specific heat and thermal conductivity of steel

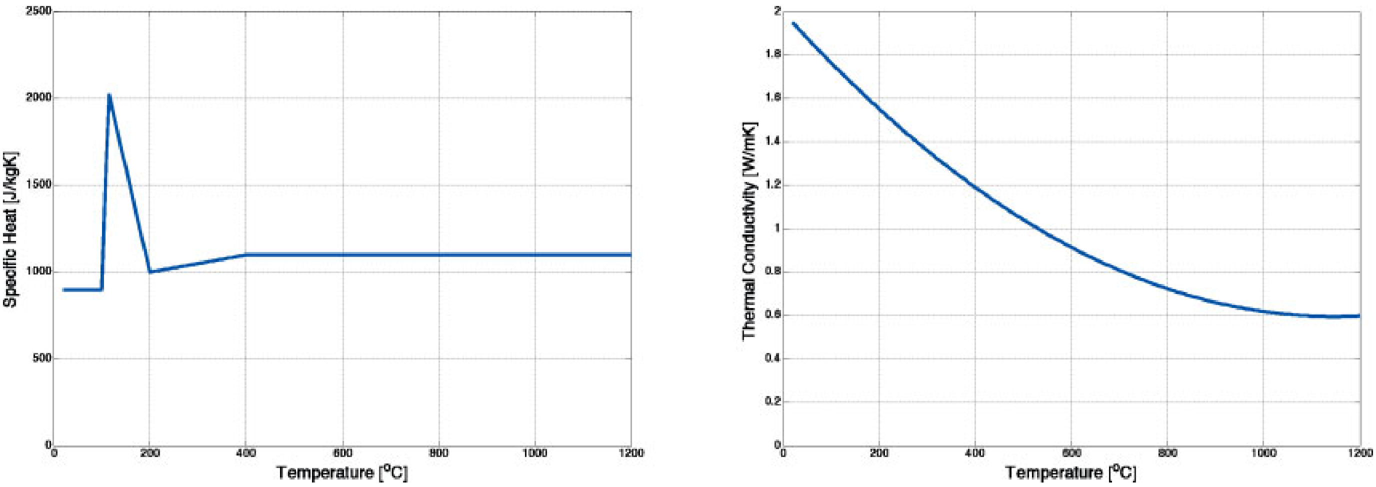

Fig. 7. Specific heat and thermal conductivity of concrete

reasons. The measured yield strength of steel is used (not 355 MPa as in Fig. 8, left). The stress–strain–temperature curves are based on the EC 4-1.2 [14] reduction factors (Figs. 8 and 9). For temperatures below 400 °C, the stress–strain relationships of structural steel are extended by the strain hardening option. The thermal expansion coefficients are based on EC 4-1.2 [14] relationships as well (Fig. 10). Reinforcing bars are modelled via the *REBAR option, but they do not participate in the heat transfer analysis. The interaction between concrete and steel is modelled with the *CONTACT PAIR option. A friction coefficient μ = 0.50 is considered for the tangential

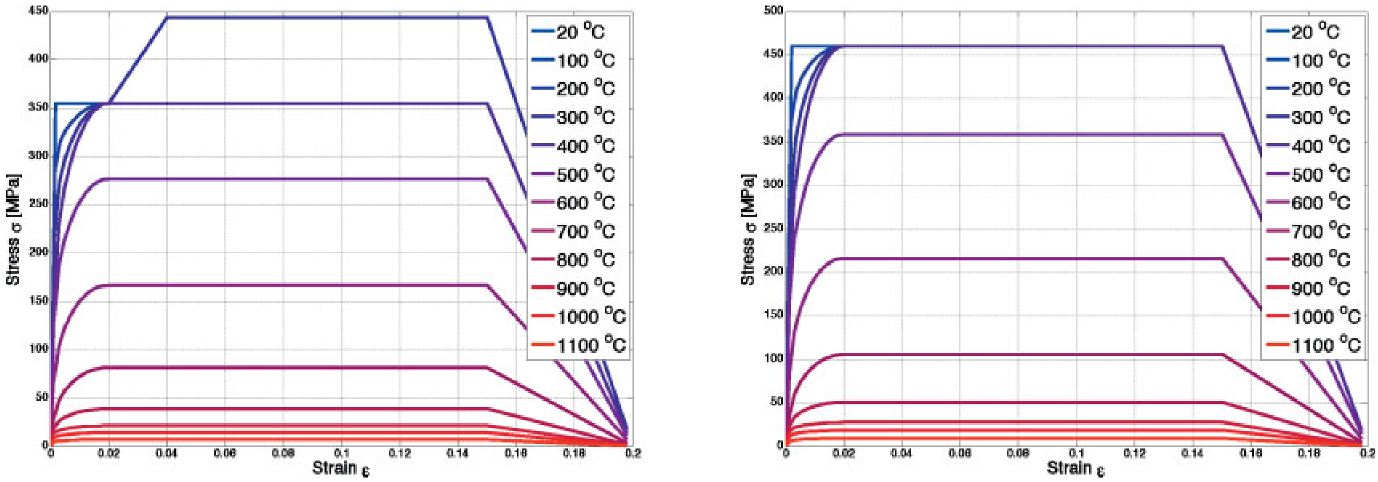

Fig. 8. Stress–strain–temperature curves for structural steel (left) and reinforcing bars (right)

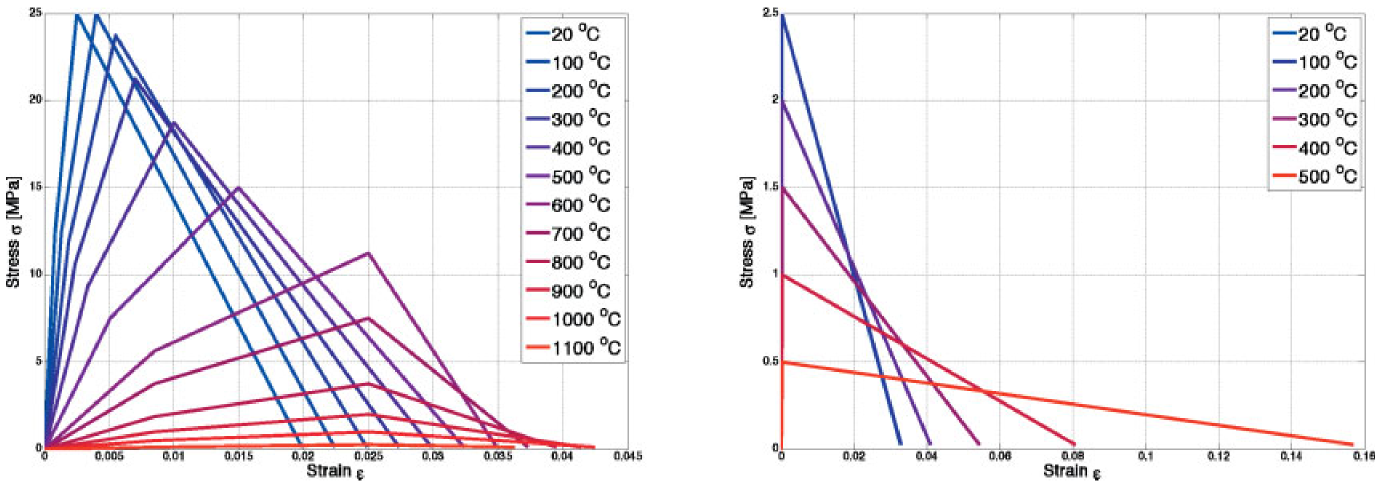

Fig. 9. Stress–strain–temperature curves for concrete in compression (left) and tension (right)

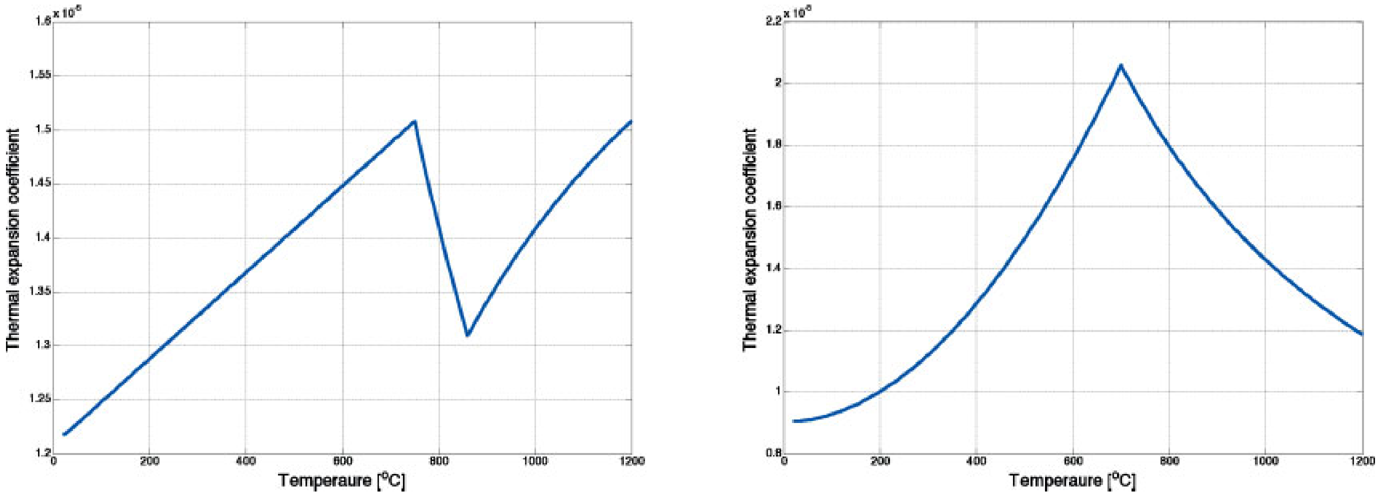

Fig. 10. Thermal expansion coefficient of steel (left) and concrete (right)

behaviour of the interfaces using the isotropic *Coulomb* friction model (*FRICTION option). Finally, geometric non-linearities are considered during the analysis.

4 Numerical results

4.1 Thermal response

Thermocouples were used to record the temperature of the steel section, decking, concrete infill and furnace atmosphere during the fire test. The time–temperature curves are calculated and compared with the experimental ones at the middle cross-section of the beam (position G), where there are thermocouples attached to the steel section and others embedded in the concrete casing around it, as shown in Fig. 11. The heat transfer analysis results are presented in Figs. 12 and 13 for each tested beam. The accuracy of the thermal modelling is satisfactory and can be used to predict the temperature distribution throughout a composite slim floor beam heated with the standard fire curve. The small differences in concrete temperatures can be attributed to the water evaporation at 100 °C.

4.2 Structural response

The deformed shapes and temperature contours of the finite element models are presented in Fig. 14, and time–vertical displacement curves obtained from the fire tests and the numerical analyses are shown in Fig. 15. Beam deflection was measured during the test with a displacement transducer located at the top point of the mid-span of each specimen. Three different hexahedral finite element types were used for modelling the steel beam (C3D8, C3D8R and C3D8I). The added internal degrees of freedom due to the incompatible modes mean that C3D8I elements are computationally more expensive than the regular elements, but they seem to produce better results in this case. Hence, the sensitivity analyses that follow are carried out using C3D8I finite elements for the asymmetric steel beam modelling.

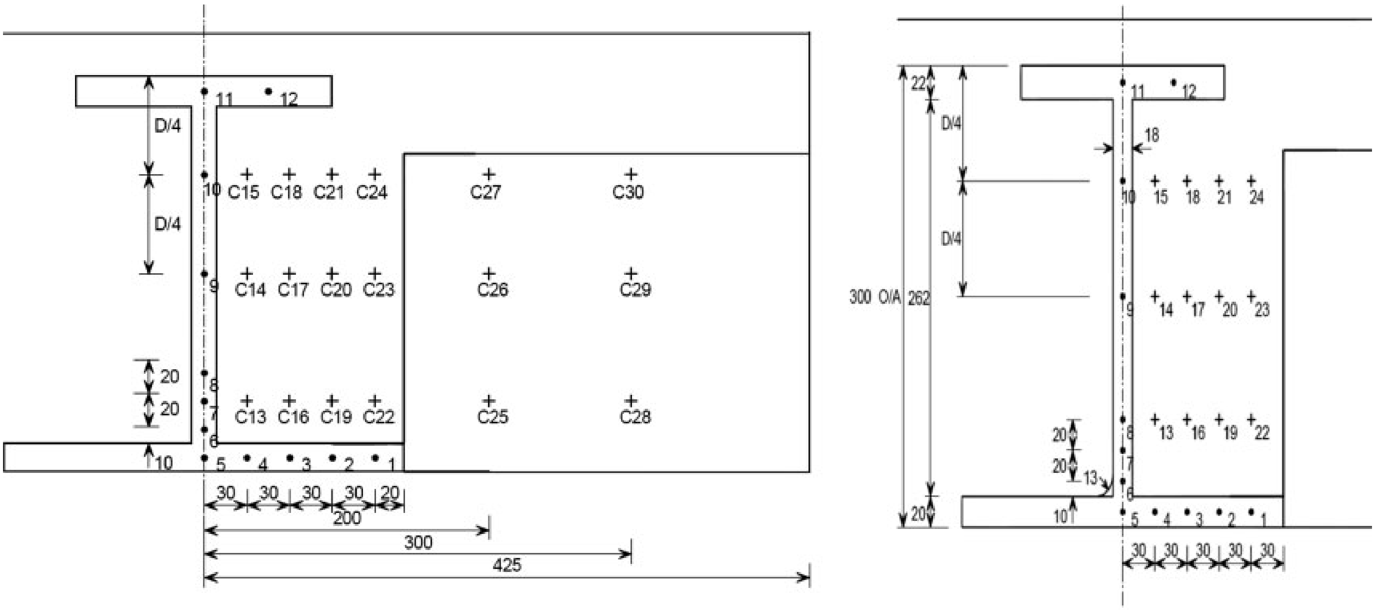

Fig. 11. Thermocouple arrangement at position G for WFRC 66162 (left) and 67756 (right) [1]

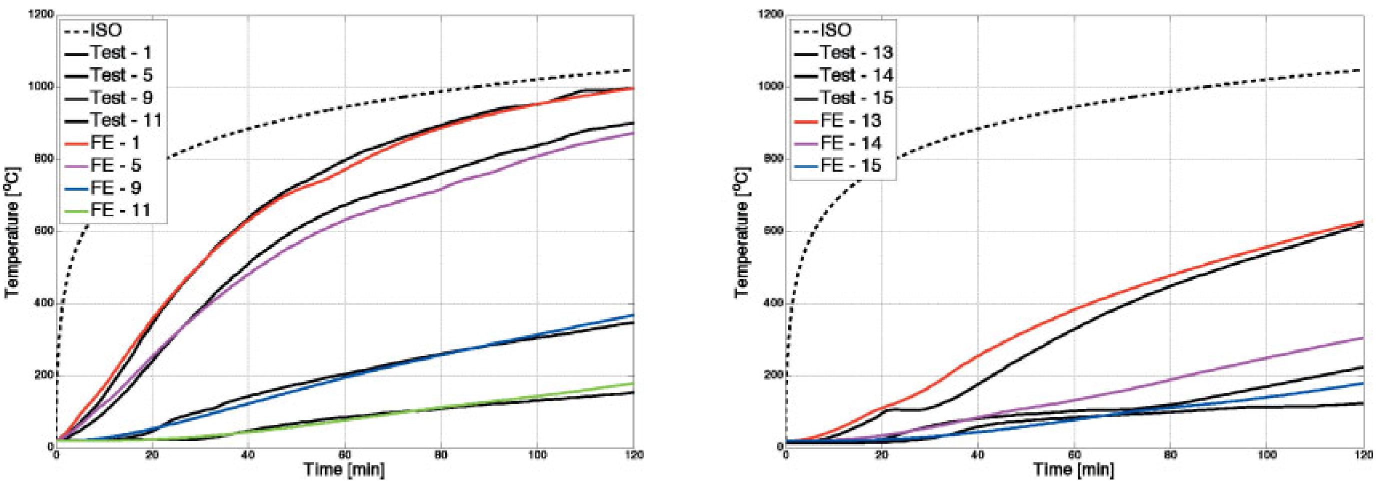

Fig. 12. Time–temperature curves at position G for WFRC 66162

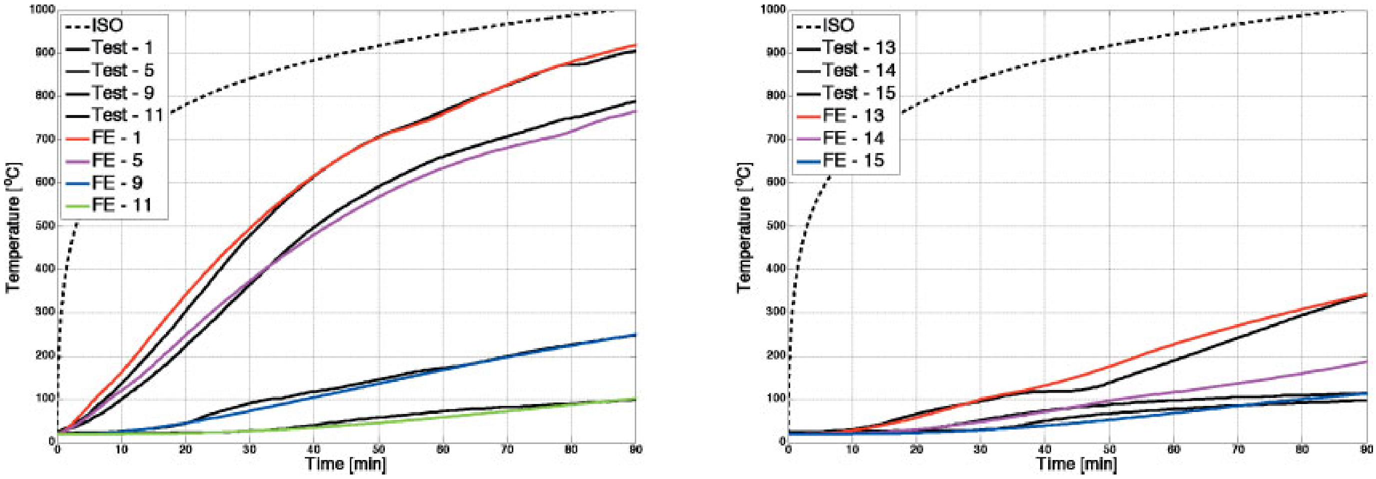

Fig. 13. Time–temperature curves at position G for WFRC 67756

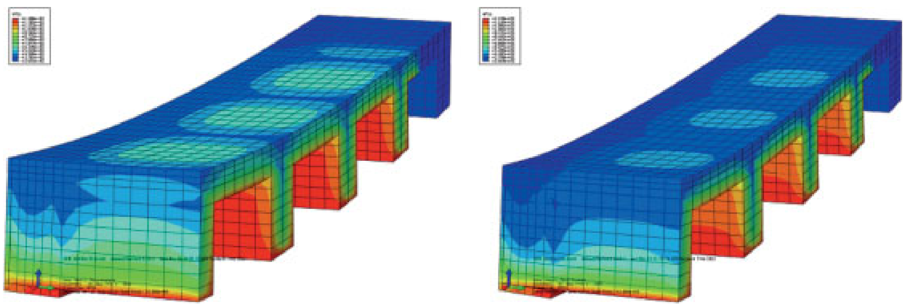

Fig. 14. Deformed shape and temperature contours after fire exposure for WFRC 66162 (left) and 67756 (right) (C3D8I elements for steel)

5 Sensitivity analyses

5.1 Thermal expansion coefficient of steel

One factor that plays an important role in the structural response of this type of structure is the thermal expansion coefficient of steel. Therefore, a sensitivity analysis of this factor is carried out using the constant value a = 14E-06 that EC 3-1.2 [15] recommends and the temperature-dependent curve of ASCE [16]. There are also numerical analyses ignoring the thermal expansion of steel in order to show its importance. The results are presented in Fig. 16 and remain almost the same for the different curves recommended by the codes.

5.2 Friction coefficient

Another factor that affects the structural response of slim floor structures is the friction coefficient between steel and concrete. A sensitivity analysis is carried out considering zero (μ = 0.0) and higher (μ = 2.0) composite action for the beams examined, apart from the μ = 0.5 value already used. The results are presented in Fig. 17. There is a significant effect on the numerical results because the friction coefficient affects the stiffness and strength of the slim floor beams.

6 Conclusions

The behaviour of unprotected asymmetric slim floor beams exposed to standard fire has been investigated and a detailed methodology for the analysis of these structures using three-dimensional finite elements proposed. The main conclusions are:

1. Their fire resistance is not given by the Eurocodes and as a result arithmetical models are necessary for predicting their behaviour under fire conditions. The suggested method-

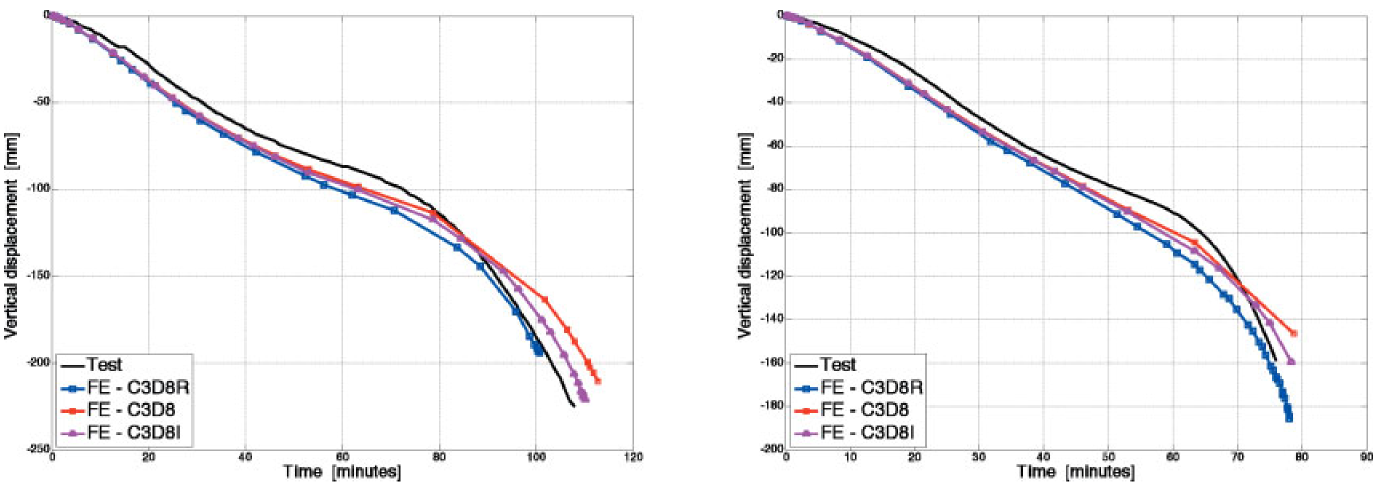

Fig. 15. Time–vertical displacement curves for WFRC 66162 (left) and 67756 (right)

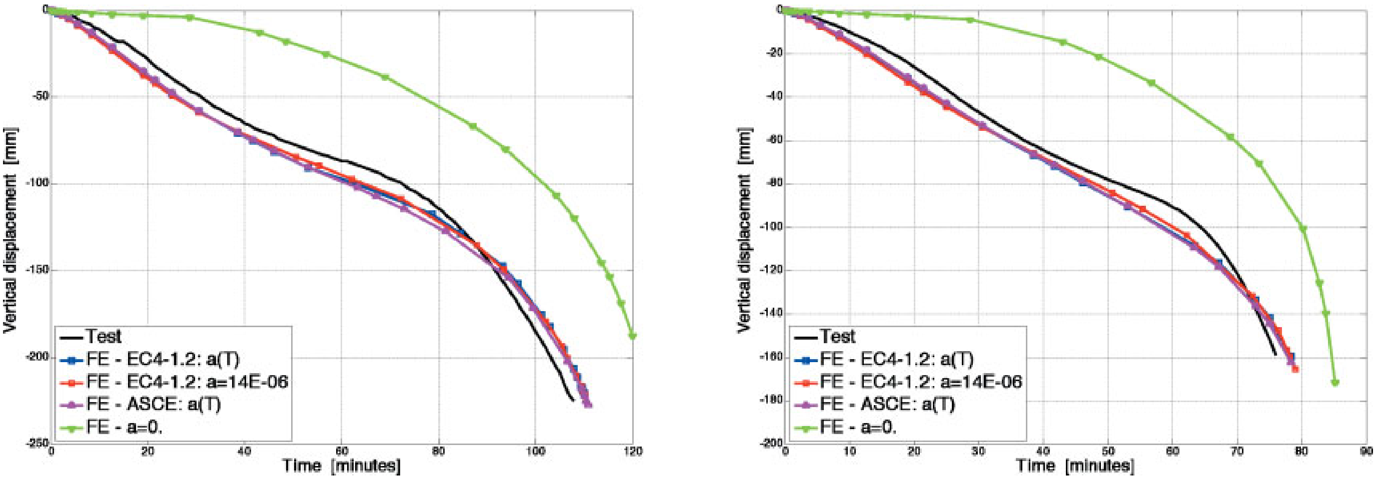

Fig. 16. Time–vertical displacement curves for WFRC 66162 (left) and 67756 (right) (a varies)

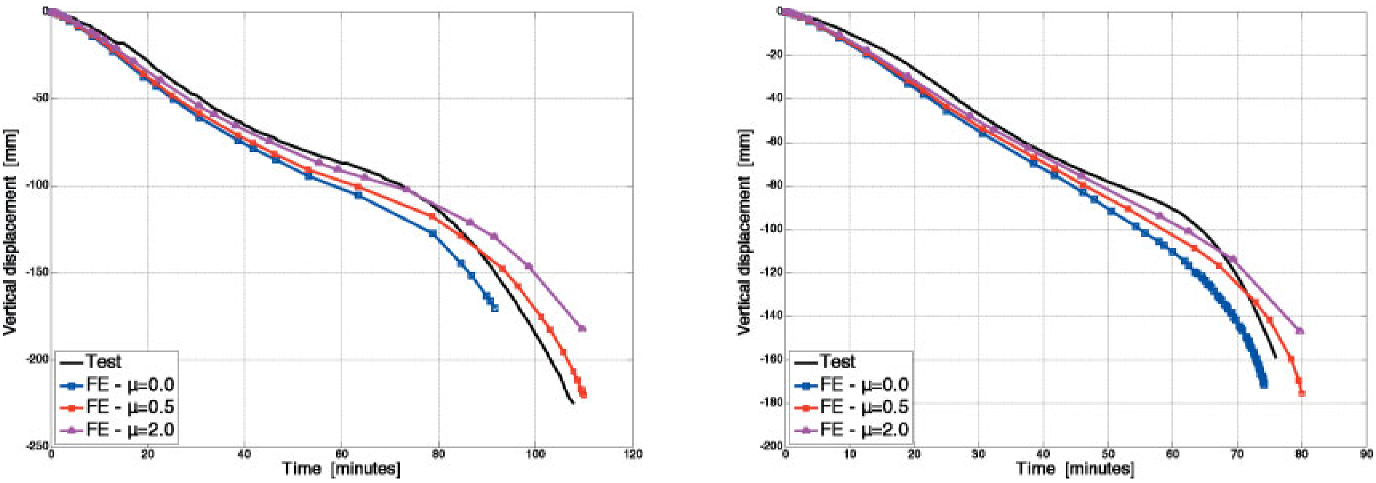

Fig. 17. Time–vertical displacement curves for WFRC 66162 (left) and 67756 (right) (μ varies)

ology using numerical modelling deals with this problem with high accuracy. The thermal and structural numerical results are in good agreement with the corresponding experimental results. Hence, the methodology seems reliable for analysing slim floor structures in fire.

2. There are two sensitivity analyses on the thermal expansion coefficient of steel and the friction coefficient between steel and concrete, which show how these parameters affect the global behaviour of slim floor beams and prove that the data incorporated in the model should be chosen carefully. The expansion coefficient influences the bending of the structure because concrete with lower temperatures resists the steel's deformation, whereas the friction coefficient defines the composite action of the beam.

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