Fire resistance of axially restrained and partially unprotected Ultra Shallow Floor Beams (USFB®) and DELTABEAM® composite beams

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ABSTRACT: Ultra-shallow floor types such as the USFB® and DELTABEAM® beam 'plug' composite flooring systems are recently developed and have seen many applications in contemporary construction. They involve partially encased steel beams in concrete, with the lower flange remaining exposed. Besides the satisfactory behavior of the system at ambient conditions, understanding their response to elevated temperatures is critical in evaluating their overall performance. Previous numerical studies of the authors have investigated their fire resistance when simply supported. The computational analyses demonstrated that such flooring systems are experiencing severe thermal gradients and bowing. When such beams are axially restrained, the compression due to the restraining may produce second order effects on the bowed beams. On the other hand, the effect of axial restraints is difficult to be estimated because of the temperature's non-uniformity across the cross-sections. For this reason, comprehensive finite element analyses (FEA) were implemented in this paper to simulate the response of such restrained beams subjected to fire. Material properties were modelled according to Eurocodes. The coupled thermal-structural parametric analyses involved different variations of the "shortest" cross-sections. From the FE analyses, useful conclusions are drawn.

1 INTRODUCTION

The "slim deck" and the "slim floor" systems are typical examples of composite shallow floor systems that have been applied recently in the civil engineering industry, while various manufacturing companies developing their own systems. Such systems, which are typically encountered at contemporary multi-storey buildings of any use and will be discussed in this paper, are the Ultra Shallow Floor Beams – USFBs® (ASD metal services, 2014) the DELTABEAM® composite deck floor (DELTABEAM Technical Manual, 2013). While various researchers (Newman, 1995, Both et al., 1997, Bailey, 1999, Mäkeläinen and Ma 2000, Ellobody, 2011 and Maraveas et al., 2012) have studied the response of the slim floor and slim deck systems when subjected to fire, the behavior of systems such as the USFB and the DELTABEAM under elevated temperature effects has not yet been investigated thoroughly. Previous studies of the authors on USFBs (Maraveas et al., 2017) and DELTABEAMs (Maraveas, 2014, Maraveas, 2018) limited to simply supported beams exposed to standard fire. According to these studies and others on partially protected flooring systems (Newman, 1995, Both et al., 1997, Bailey, 1999, Mäkeläinen and Ma 2000, Ellobody, 2011 and Maraveas et al., 2012, Zacharia and Franssen, 2012, Maraveas et al., 2014) these systems develop severe thermal gradients as only the bottom flange is unprotected. These thermal gradients produce bowing (Figure 1).

This paper investigates the effect of axially restrained USFBs and DELTABEAMs via finite element (FE) simulations. Several different types of axial restrain are applied - i.e., different positions of restraining and different restraint factors have been considered. FE models used successfully in authors' previous research (Maraveas et al., 2017, Maraveas 2018) are used.

The simulation results are showing that when the restraint applies at the hot part of the cross-section, the compressive force at a given value produces high compressive stresses at the concrete slab and the slab under pure compression increases the strength and the stiffness of the system.

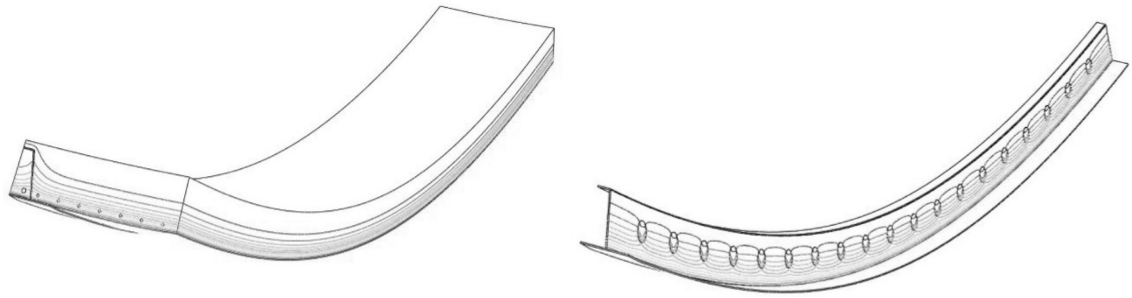

Figure 1. Typical DELTABEAM experienced bowing in fire (left: the composite section; right: the isolated steel beam (Maraveas, 2018)

2 SHALLOW FLOORING SYSTEMS

2.1 *Ultra-Shallow Floor Beams (USFB®)*

For conventional composite floor beams or down-stand composite beams, the thickness of the flanges increases with the increase in span. Consequently, the steel sections are often heavier than needed. The USFB is a new type of composite floor beam, which is fabricated by welding two highly asymmetric cellular tee-sections together, along the web. Profiled steel decking or pre-cast concrete floor units sit on the wider bottom flange, as shown in Figure 2. The top and bottom tee-sections are cut from different parent plane (solid-webbed) beams where the top tee-section is smaller than the bottom tee-section. This asymmetric beam section property reduces the self-weight while increases the moment capacity.

USFB provides superior structural performance (Tsavdaridis et al., 2013) due to the concrete infill where the ultimate vertical load carrying capacity of the USFB can increase by up to 108% compared to the corresponding non-composite perforated steel beam. Moreover, the shear resistance of the USFB, without using any mechanical shear connectors, such as shear studs, rebars and ducting (Huo et al., 2010) can be provided mainly by contributions from the concrete confinement and the steel flange thickness. The strut action of the concrete confinement through certain web openings reduces the Vierendeel bending effects and improves the vertical shear transfer in the vicinity of the web openings. In addition, it has been demonstrated that there is some residual strength in the concrete preventing the local buckling of the perforated steel beams and the load carrying capacity is somewhat higher than that of the non-composite beam.

The circular or elongated web openings provide a channel for reinforcing tie bars, building services and ducting through the structural depth of the beam, thus minimizing the overall floor depth (Huo et al., 2010). Transverse to the web reinforcing tie-bars can provide longitudinal shear strength by tying the concrete plugs on both sides of the web. Shear studs can be also used, welded horizontally on the web of the steel beams. Full service integration can be achieved when deep profiled steel decking is employed, as pipes or ducks pass through between the ribs of the steel decking; every a few web openings below the metal deck and concrete slab. As the floors are cast, the in-situ concrete passes through most web openings, which may or may not include a tie-bar or duct. In the case of ultra-shallow pre-cast units, all web openings are filled with in-situ concrete, hence service integration cannot be provided, as opposed to the profile metal decking use. This concrete plug forms a unique enhanced mechanism for transferring longitudinal shear force along the beam. The common range of applications for USFBs is for slab depths of 180 to 300 mm, in which the concrete is placed flush with the upper flange. The nature of the choice of UC for the bottom tee-sections and UB for the top tee-sections is that the asymmetry in flange areas can be over 3 to 1. Composite action reduces this effective asymmetry and improves the bending resistance. In practice, the span to depth ratio of USFBs is generally in the range of 25 to 30, which means that serviceability rather than bending or shear resistance will govern. Another study has been conducted on the derivation of dynamic properties of USFBs through FE modal analysis and experimental verification (Tsavdaridis et al., 2009 and Tsavdaridis et al., 2011).

Figure 2. USFB® used with profiled steel decking (top) and with the precast concrete unit (bottom) (Tsavdaridis et al., 2013).

2.2 *Delta composite beams (DELTABEAM®)*

The DELTABEAM system is a steel-concrete composite beam made from welded steel plates with holes in the sides of the webs. These web holes improve the composite action between concrete and steel considerably. The system can accommodate a variety of flooring types, such as precast floors (hollow core slabs) or other composite flooring systems that can be applied to any type of multi-storey building. It can be used in single or multi-span beam arrangements and is available in a variety of thicknesses ranging from 20 cm to 50 cm (excluding concrete thickness). It is suitable for spans up to 13.5 m according to the manufacturer (DELTABEAM Technical Manual, 2013). Some of its advantages are the rapid and easy installation, the reduced construction height, and the cost-efficiency of the system. The configuration and flooring system arrangement of the DELTABEAMs (DELTABEAM Technical Manual) are given in Figure 3.

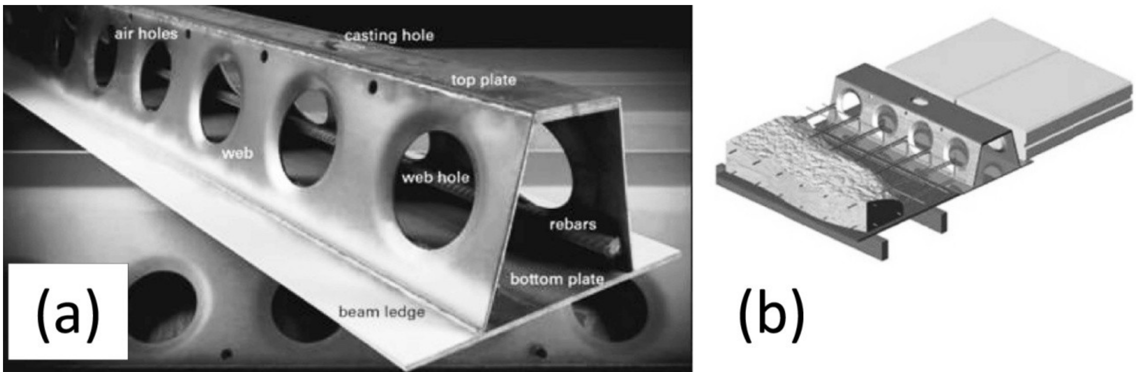

Figure 3. (a) Typical DELTABEAM®; (b) DELTABEAM with pre-cast concrete element (lightweight) and cast-in-place concrete (DELTABEAM Technical Manual, 2013)

3 NUMERICAL SIMULATION

3.1 *Geometry of analyzed beams*

In this paper, a typical USFB and a DELTABEAM have been analyzed. The USFB (Figure 4a), has a total section height of 220 mm and the steel section is comprised of an upper UB254x146x37 tee-section and a lower UC305x305x97 tee-section with span 5 m. The effective width (b_{eff}) has been taken equal to L/8, where L is the span, e.g., 1.25 m. The DELTABEAM (Figure 4b) is a D20-200 (DELTABEAM Technical Manual, 2013) with b=200 mm, B=395 mm, b1=97.5 mm, b2=100 mm, d2=25 mm, h=200 m, Ø=80 mm, upper flange thickness 5 mm and web thickness 10 mm (see Figure 4b for symbols). Its span is 6 m. Its effective width per EN 1994-1-1, 2005 is 1.60 m.

3.2 *Applied loads*

The main load combination for ambient temperature design according to EN1991, 2002 is generally:

$$1.35 \text{ x Permanent} + 1.50 \text{ x Imposed} \quad (1)$$

Which gives a total applied force of 332.55 kN for the USFB (Maraveas et al., 2017) and 180 kN for the DELTABEAM (Maraveas, 2018). For fire design, the main load combination according to EN1991, 2002 is:

$$1.0 \text{ x Permanent} + \psi_2 \text{ x imposed} \quad (2)$$

Where ψ_2 obtains a range of values depending on the type of the structure (always $\psi_2<1$). As it is not possible to determine the result of the combination with this unknown, it has been assumed that $\psi_2=1$. The fire design combination results for these safety factors are approximately 70% of those of the ambient temperature design combination, which is the maximum load that can be required for fire design. The load is uniformly distributed along the length of each beam.

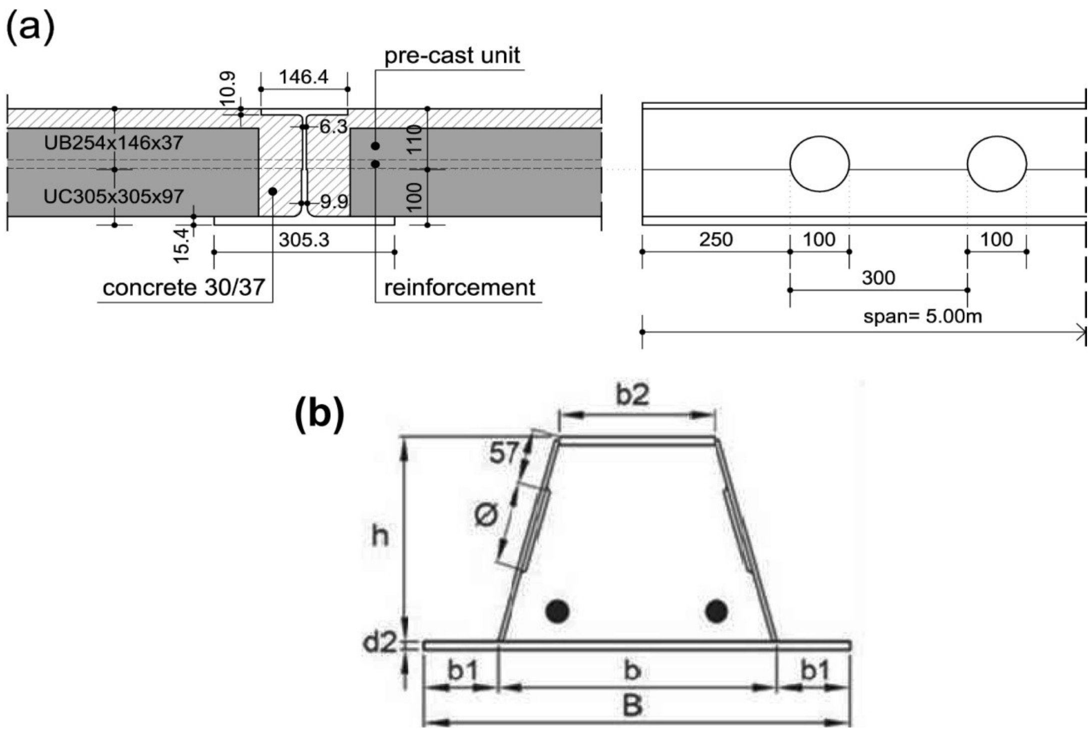

Figure 4. Geometry of studied systems (a) USFB; (b) cross-section of DELTABEAM with cross-section parameters (DELTABEAM Technical Manual, 2013)

3.3 *Material properties*

3.3.1 *Thermal properties and thermal expansion*

In all analyses, the thermal properties and the thermal expansion of the materials followed the specifications of EN1993-1-2, 2005 for structural steel - reinforcement and EN1992-1-2, 2004 for concrete while their variation with temperature is graphically presented in Figure 5. A more detailed explanation of their modeling is given elsewhere (Maraveas et al., 2012).

3.3.2 *Mechanical properties*

The mechanical properties of the materials were obtained by the EN1994-1-2, 2005. In particular, the stress-strain-temperature diagrams are presented in Figure 6a for structural steel and in Figure 6b and 6c for concrete. For reasons of simplicity and given that no effect was noted on the results, the stress-strain-temperature relationship of structural steel was used for the reinforcement bars.

3.4 *Finite element modeling*

All numerical simulations were carried out using the commercial finite element software ABAQUS. For each of the studied composite beams, a 3D model (Figure 7) of the system was created for a coupled thermal-structural analysis (i.e., for both types of analyses the same model was used including the same element type, mesh, etc.). In all simulations, due to symmetry, half of the beam was modeled and the appropriate boundary conditions were applied (i.e., displacement of the nodes on the symmetry surfaces was completely restrained in the perpendicular direction). This simulation approach was selected because it has produced satisfactory results in similar researches (Maraveas et al., 2017, Maraveas, 2018). More specifically, relevant results (Maraveas et al., 2012) for the slim floor system (with which USFB and DELTABEAM composite beams share many common characteristics such as the partial encasement of the steel cross-section with in-situ concrete, exposure of the lower flange, materials with identical or similar properties, etc.) were compared with experimental data and good agreement was observed. The simulation details (element type, boundary conditions, etc.) are identical with these presented in a similar work for asymmetric slim floors (Maraveas et al., 2012), except the axial restraint, which is explained in detail later in Section 3.4.2. In particular, eight-node solid hexahedral elements that allow heat transfer (C3D8) were used to simulate both the concrete and steel parts of the flooring system. The von Mises plasticity model (*PLASTIC command) was used to simulate the plastic behavior of steel, while the damaged plasticity model (*CONCRETE DAMAGED PLASTICITY command) with a dilation angle of 55^{o} was used for the nonlinear response of the concrete. For the models presented in this paper, a full interaction between concrete and steel was considered via appropriate thermo-mechanical contact properties (*CONTACT PAIR option and isotropic Coulomb friction model-*FRICTION option). It should also be noted that steel reinforcement was included in all analyses. Global and local imperfections have not been considered as the steel beam is restrained by the concrete slab.

3.4.1 *Thermal analysis*

Temperature evolution within the cross-sections was calculated for standard fire exposure (EN 1991-1-2, 2002) from below, and convection at ambient temperature (20^{o}C) on the upper surface. A representative cross-section, together with the boundary conditions, is shown in Figure 8. The pertaining thermal analysis parameters (convection coefficient, radiation emissivity, etc.) are identical to Maraveas et al. (2012) and comply with the specifications of the Eurocodes (EN 1994-1-2, 2005). The convection coefficient for the exposed surface was selected to be 25 W/m^{2}K, while its value for the unexposed surface was 9 W/m^{2}K. The value for the radiation emissivity was either 0.5 (bottom steel flange) or 0.25 (composite floor). Contrary to the bottom side, the heat flow due to radiation was neglected for the upper side, while no heat was transferred normally to the axes of symmetry. Perfect thermal contact was assumed between concrete and steel (infinite interface conductivity).

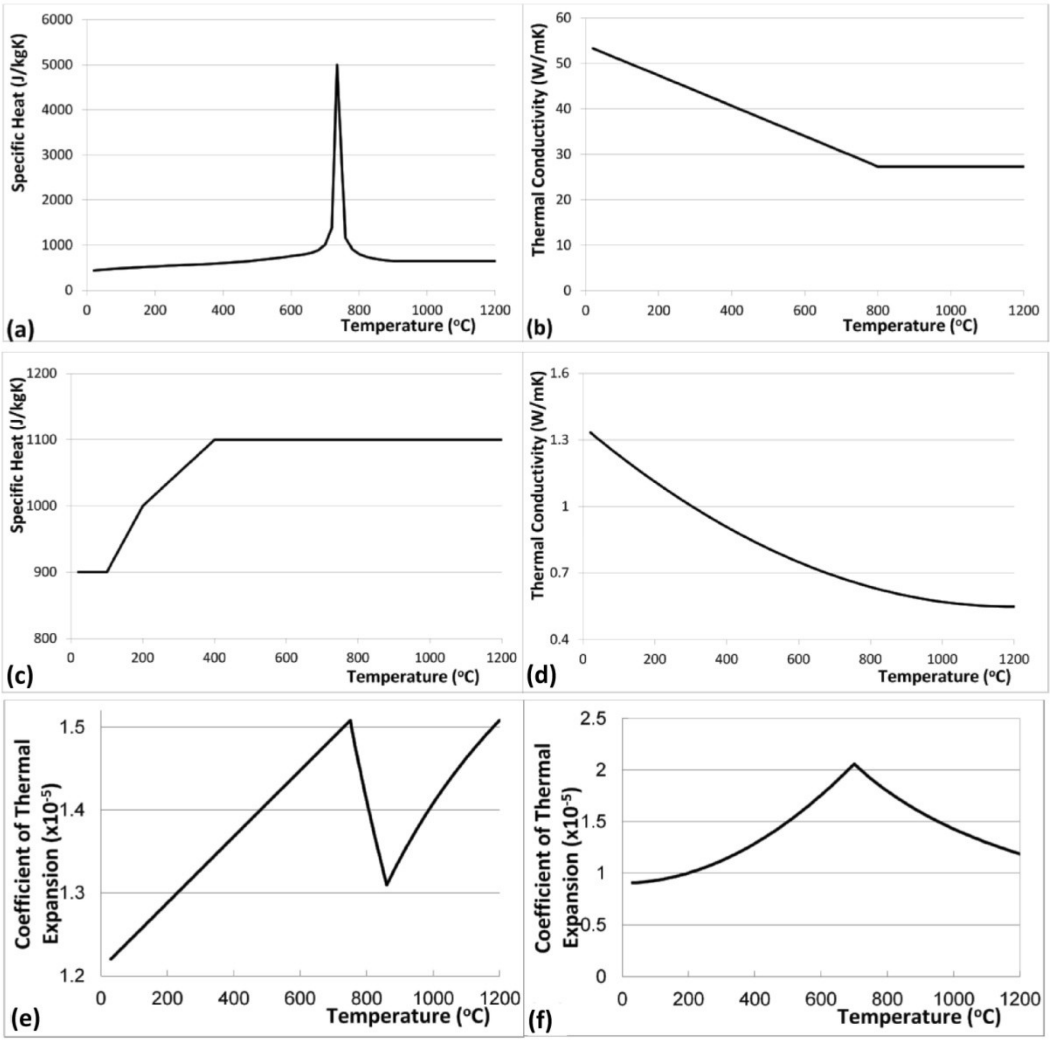

Figure 5. (a) Specific heat; (b) thermal conductivity of steel; (c) specific heat; (d) thermal conductivity of concrete and thermal expansion coefficient of (e) steel; (f) concrete.

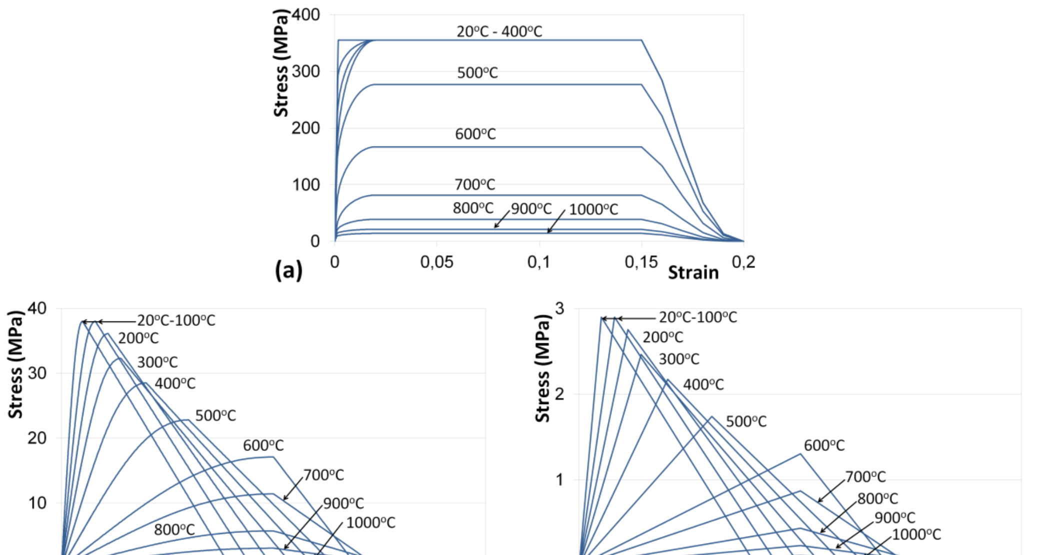

Figure 6. Stress-strain temperature curves of: (a) steel and concrete for; (b) compression; (c) tension

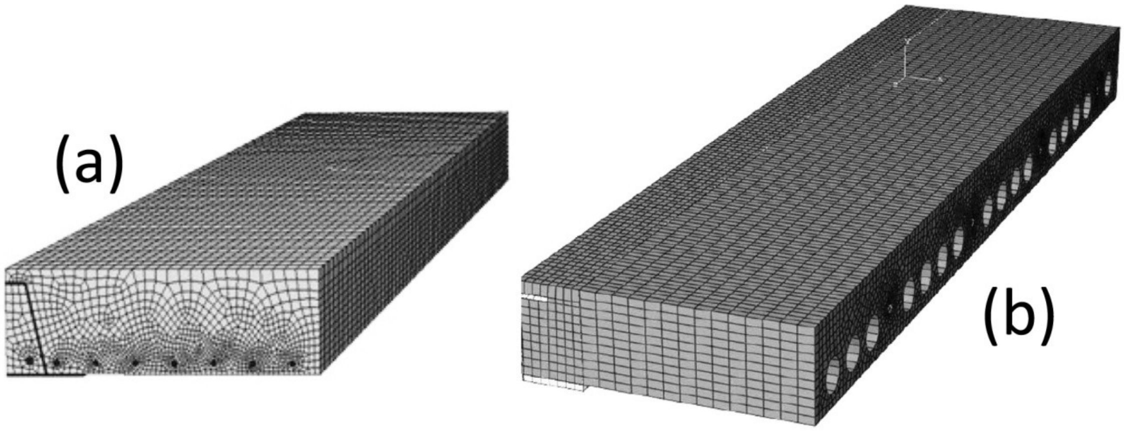

Figure 7. FE models for: (a) DELTABEAM; (b) USFB

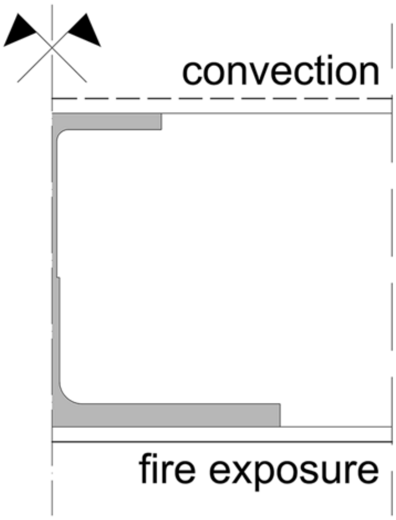

Figure 8. Boundary conditions used in thermal analysis

3.4.2 *Structural analysis*

Besides running a thermal analysis for each of the 3D models (no loading was applied), six other coupled thermal-structural analyses were carried out for each beam type. Both included the static and thermal loading described earlier, but with different restraints:
Analysis 1: Fully axially restrained bottom flange.
Analysis 2: All nodes fully fixed in the axial direction of the beam (equivalent to axially and rotationally restrained).
Analysis 3: Full horizontally restrained centre of gravity of the steel cross-section.
Analysis 4: As analysis 3 but with spring and restraint factor α=0.1.
Analysis 5: As analysis 3 but with spring and restraint factor α=0.5.
Analysis 6: Fully axially restrained top flange.
Where the restraint factor is calculated from the equation:

$$\alpha = Ks / (EA/L) \quad (3)$$

EA/L is the axial stiffness of the beam, Ks is the stiffness of the restraint spring, and α is the restraint factor.

4 RESULTS

The simulation results are presented in Figure 9. It is worth to note that the results of Analysis 6 are identical with these for simply supported beams (Maraveas et al., 2017, Maraveas, 2018).

When the bottom flange is restrained the behavior is almost the same with the axially and rotationally restrained beam (Analysis 1). The compressive force at a given value produces high compressive stresses at the concrete slab and the slab under pure compression increases the strength and the stiffness of the system.

5 CONCLUDING REMARKS

This paper presents a numerical investigation of the behavior of axially restrained shallow beams (USFBs and DELTABEAMs) exposed to fire. According to simulation results, the conclusions below can be drawn:

- When these beams are axially restrained at the 'cold' part of their cross-section, the behavior is identical as the one of simply supported beams.
- When these beams are axially restrained at the 'hot' part of their cross-section, the produced axial forces generate compressive stresses at the concrete slab and the concrete in compression gives higher strength and stiffness to the composite system.
- When the bottom flange is fully axially restrained, the behavior is similar to a fully restrained axially and rotationally beam.
- For most steel elements, the axial restraint is unfavorable and reduces the fire resistance. It has been observed that the partial protected shallow flooring systems have different behaviors and the axial restraint can be favorable.

6 ACKNOWLEDGEMENTS

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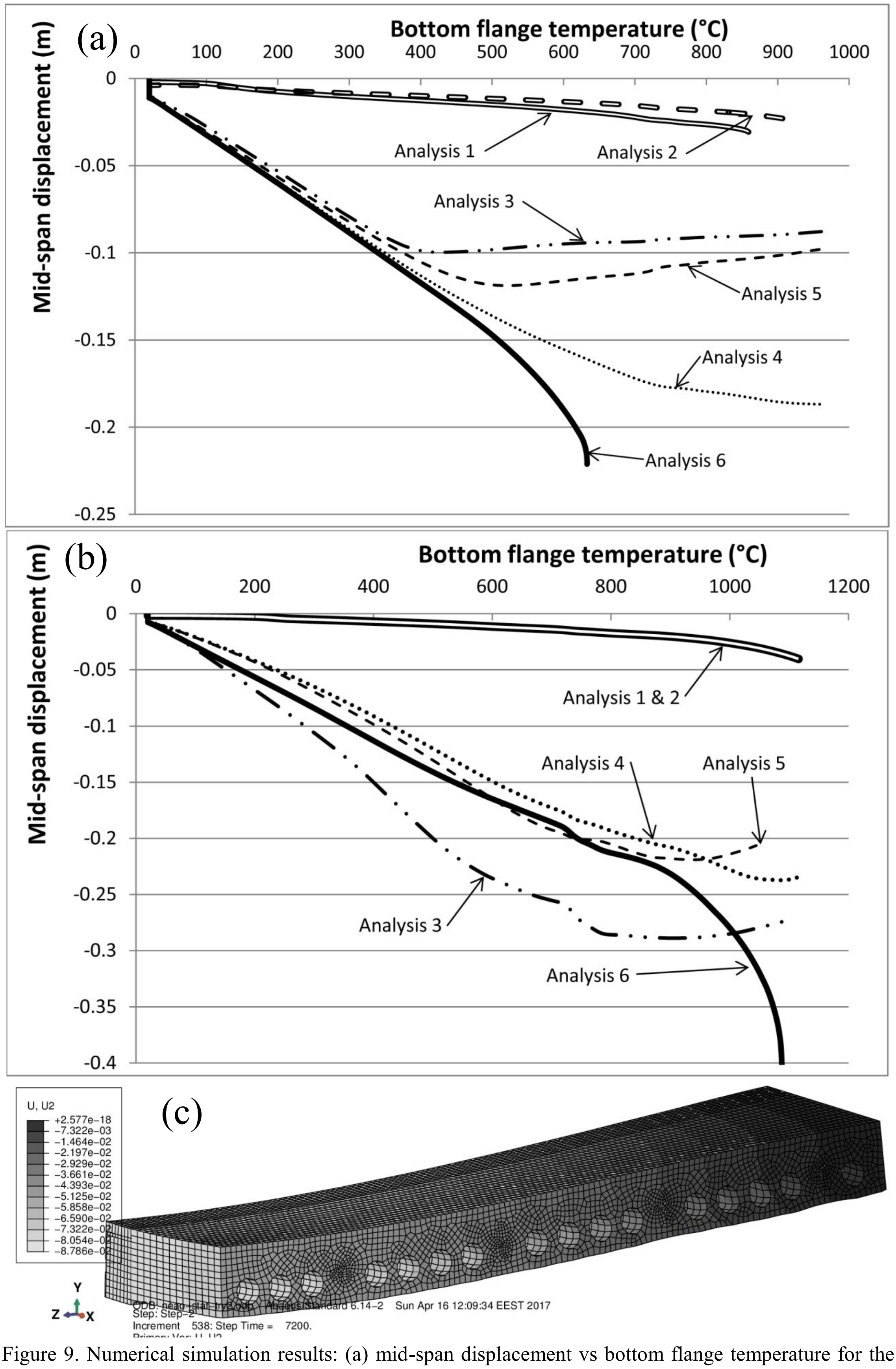

Figure 9. Numerical simulation results: (a) mid-span displacement vs bottom flange temperature for the USFB; (b) mid-span displacement vs bottom flange temperature for the DELTABEAM; and (c) deformed USFB after 120 min of exposure

REFERENCES

ASD metal services, 2014, Westok, Ultra Shallow Floor Beams, http://www.asdmetalservices.co.uk/en/Products/ASD%20Westok/ASD%20Westok%20Products/USFB.aspx, accessed 22-9-2014.

Bailey, C.G. (1999), “The behavior of asymmetric slim floor steel beams in fire”, J. Constr. Steel Res., 50(3), 235-257.

Both, C., Fellinger, J.H.H. and Twilt, L., 1997, Shallow floor construction with deep composite deck: from fire tests to simple calculation rules, Heron, 42(3), 145-158.

Deltabeam Technical Manual, 2013, downloaded from http://www.peikko.com, accessed 19-12-2013. (in Dutch).

Ellobody, E., 2011, Nonlinear behavior of unprotected composite slim floor steel beams exposed to different fire conditions, Thin Wall Struct., 49(6), 762-771.

EN 1991, 2002 Eurocode 1—actions on structures—part 1–2: general actions—actions on structures exposed to fire. CEN Brussels

EN 1991-1-2, 2002, Eurocode 1: Actions on structures - Part 1-2: General actions – Actions on structures exposed to fire, European Committee for Standardization, Brussels.

EN 1992-1-2, 2004, Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design, European Committee for Standardization, Brussels.

EN 1993-1-2, 2005. Eurocode 3: design of steel structures — part 1–2: general rules —structural fire design. Brussels: European Committee for Standardisation.

EN 1994-1-1, 2005, Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings, European Committee for Standardization, Brussels.

EN 1994-1-2, 2005, Eurocode4—design of composite steel and concrete structures—part 1-1: design for fire, CEN, Brussels

Huo B.Y., D’Mello C, Tsavdaridis KD, 2010, Experimental and analytical study of push-out shear tests in ultra-shallow floor beams. In: 34th International association for bridge and structural engineering (IABSE) symposium, Venice, Italy, pp 31–38.

Mäkeläinen, P. and Ma, Z., 2000, Fire resistance of composite slim floor beams, J. Constr. Steel Res., 54(3), 345-363.

Maraveas, C., Swailes, T. and Wang, Y.C., 2012, A detailed methodology for the finite element analysis of asymmetric slim floor beams in fire, Steel Constr., 5(3), 191-198.

Maraveas, C., Wang, Y.C. and Swailes T., 2014, Fire Resistance of 19th Century fireproof flooring systems: A sensitivity analysis, Constr. Build. Mater., 55, 69-81.

Maraveas, C., 2014, Numerical Analysis of DELTA composite beams in fire, Seventh European Conference on Steel and Composite Structures – EUROSTEEL, Naples, Italy, September.

Maraveas, C., Tsavdaridis, K.D. & Nadjai, A., 2017, Fire resistance of unprotected ultra-shallow floor beams (USFB): a numerical investigation, Fire Technol 53, 609-627.

Maraveas, C., 2018, Fire resistance of delta composite beams: A numerical investigation, Journal of Structural Fire Engineering (Accepted for Publication).

Newman, G.M. 1995, Fire resistance of slim floor beams, J. Constr. Steel Res., 33(1-2), 87-100.

Tsavdaridis KD, D’Mello C, Hawes M, 2009, Experimental study of ultra-shallow floor beams (USFB) with perforated steel sections. Nordic Steel Construction Conference 2009, NSCC2009. 2–4 September 2009, Malmo, Sweden, Reference no. 128, pp 312–319.

Tsavdaridis KD, Giaralis A, 2011, Derivation of dynamic properties of steel perforated ultra-shallow floor beams (USFB) via finite element modal analysis and experimental verification. The 7th national conference on steel structures, Volos, Greece, vol 2, pp 321–329.

Tsavdaridis KD, D’Mello C, Huo BY, 2013, Experimental and computational study of vertical shear behaviour of partially encased perforated steel beams. J Eng Struct 56:805–822.

Zaharia, R. and Franssen, J.M., 2012, Simple equations for the calculation of temperature within the cross-section of slim floor beams under ISO fire, Steel Compos. Struct., 13(2), 171-185.