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Model Parameter Sensitivity for Structural Analysis of Composite Slab Structures in Fire

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Abstract. The behavior of buildings during fires has recently become a significant issue. Analyzing structures at elevated temperatures is complex and challenging in structural engineering as engineers must take into consideration factors that may not be included at ambient temperatures, namely material and geometric non-linearity as well as time-temperature-varying strength. In this study, the finite element software ABAQUS was applied to model and simulate the behavior of structures in fire events. Steel beams and columns were modeled using two-node linear beam elements, while concrete slabs were discretized using shell elements. A series of verification analyses were conducted to ensure that the analysis produced an acceptable level of accuracy. Furthermore, an extensive sensitivity study was carried out to obtain the appropriate modeling parameters to be used in subsequent numerical analyses.

Keywords: Dynamic analysis; Fire engineering; Heat transfer; Steel composite; Steel structures

1. Introduction

The behavior of steel structures subjected to fire has recently drawn wide attention, particularly since the collapse of the World Trade Center (WTC) in September 2001. Several design codes, such as British Standard (BS) 5950 (BS EN, 2003) and Eurocode EN 1991-1-2 (CEN, 2002), have provisions for fire. Fire safety design generally aims to prevent the collapse of the building under fire conditions, giving occupants enough time to escape safely.

This research concentrates on the performance of composite buildings subjected to a fire. Composite steel frame structures have been widely used in multi-storey building construction as they offer many advantages. In this context, a composite steel frame structure is a structure in which the steel floor beams act compositely with the concrete floor slabs. Such structures have the advantage of being lightweight, and they utilize the composite interaction between the slab and steel beams to enhance their load-carrying capacity and stiffness, thus representing a more efficient use of steel compared to a non-composite frame. Moreover, metal decking on top of the steel beams can act as permanent formwork to eliminate external formwork. Hence, the use of a composite slab reduces

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construction as well as workforce costs.

However, because steel is a sensitive material, its material properties, particularly strength and modulus of elasticity, are significantly reduced at high temperature. Fire insulation, such as spray fire-resistive material (SFRM), is commonly applied to the surface of the steel structure to maintain the stability of the structures during a fire. The main aim of fire insulation is to delay the temperature rise of the steel at elevated temperatures.

In standard fire design, the fire resistance of structures has been evaluated based on the behavior of isolated structures under standard fire tests (BS EN, 1999). It is believed that this approach does not represent the actual behavior of a building in a fire. The behavior of a composite building in a real fire could be seen during the Cardington Tests (Bailey et al., 1999) in the United Kingdom (UK), which indicated that the whole building structure had higher fire resistance than the associated single elements. Significant research has been conducted on the modeling of composite buildings in a fire (Gillie et al., 2001; Nguyen et al., 2015; Jiang et al., 2017). Most previous studies have highlighted and discussed the complexities of modeling structures in a fire. However, there is a lack of detailed research into the influence of parameters on the composite steel frame at high temperature. The present study focuses on this gap. The main objective of this study is to develop and validate numerical models capable of predicting the 3-D behavior of composite steel frames in a fire. A series of sensitivity studies were also performed to investigate the parameters that affect the behavior of composite buildings during a fire.

2. Material Behavior at Elevated Temperature

Knowledge of a material's behavior at elevated temperatures is key to understanding the behavior of structures in a fire. The effect of temperature on material behavior generally consists of the reduction in material properties (yield strength and modulus of elasticity), as well as thermal expansion. The behavior of steel and concrete materials at elevated temperature is more complex than at ambient temperature. Both materials become weaker and more flexible at high temperature. Many theoretical models have been adopted to represent the material behavior of steel and concrete at elevated temperature. In this study, the Eurocode was selected because it is widely used and has been validated by many researchers (Memari et al., 2014; Lin et al., 2015; Selamet and Bolukbas, 2016; Jiang and Li, 2018).

2.1. Steel Material Behavior

At ambient temperature, steel is relatively ductile and has similar strength and stiffness in both compression and tension. These characteristics remain at elevated temperature. However, the material and thermal properties of steel at elevated temperature are different from those at ambient temperature. Eurocode EN 1993-1-2 (CEN, 2005a) presents standard hot-rolled carbon steel temperature-dependent properties, including the stress-strain relationship, thermal expansion, specific heat, and conductivity.

Stress-strain relationships at elevated temperatures are based on the steady-state test at certain elevated temperatures or a transient state test. Kirby and Preston (1988) conducted tests under transient and steady states. At ambient temperature, the steel yield plateau is essential because it defines the design yield strength of the material at a given strain. However, at elevated temperatures, the tests showed strains in excess of 3%, which included the thermally induced strain. Subsequently, Eurocode EN 1993-1-2 (CEN, 2005a) applied the results from Kirby and Preston (1988) to define the stress-strain relationship of carbon steel as a linear response up to the proportional limit, followed by an elliptical transition zone becoming a plateau at the effective yield stress (related to a 2% strain limit)

until the strain reaches 15%, and then a linear decrease to zero stress at 20% strain. Figure 1 presents the stress-strain relationship without strain hardening. Figure 2 shows the reduction factors for yield stress, elastic modulus, and proportional limit. In addition, the thermal expansion can be determined by using the value of 1.4×10^{-5} C^{-1} for practical design (BS EN, 1990).

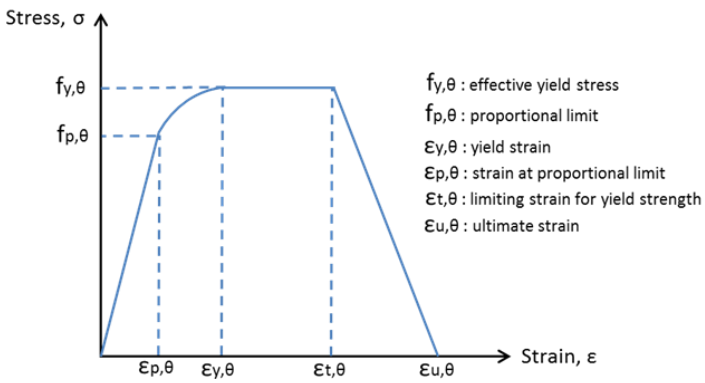

Figure 1 The stress-strain relationships for carbon steel

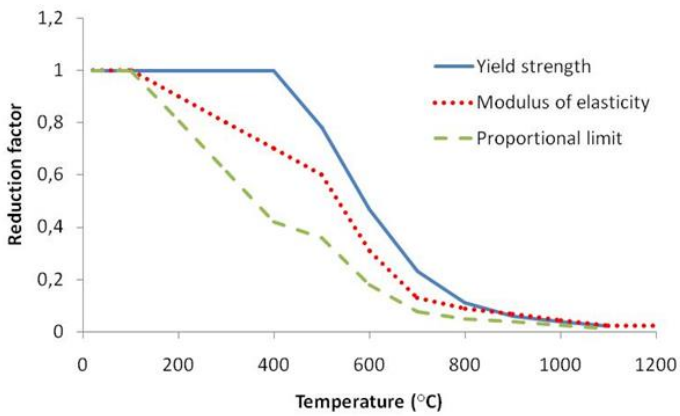

Figure 2 The reduction factors for carbon steel at elevated temperatures

2.2. Concrete Material Behavior

The characteristic behavior of concrete is more complex than that of steel. Moreover, concrete is a brittle material with different stress-strain behavior in compression and tension. Schneider (1988) provides an overview in assessing material properties for concrete at high temperatures. The results of analytical models for strength and stress-strain response became the basis for the model in Eurocode 1992-1-2 (CEN, 2004) and were developed for normal and lightweight concrete.

Eurocode 1992-1-2 (CEN, 2004) gives concrete temperature-dependent properties, including thermal and mechanical properties. Figure 3 shows a typical stress-strain curve for concrete in compression based on the values in Eurocode EN-1992-1-2 (CEN, 2004). After being heated to the maximum temperature, concrete does not recover its initial compressive strength. Eurocode EN-1994-1-2 (CEN, 2004) recommends that an additional loss of 10% of the value at maximum temperature be applied when the maximum temperature exceeds 300°C. The evolution of the compressive strength is considered to vary linearly from maximum temperature to ambient temperature. Figure 4 illustrates the recommendation of Eurocode EN-1994-1-2 (CEN, 2005b). The dashed line shows the reduction in compressive strength during the heating phase, and the solid line indicates the

reduction in compressive strength when heated to 500°C, followed by cooling to ambient temperature. It can be observed that the reduction of 0.6 at 500°C reduces linearly to a reduction of 0.54 at ambient temperature.

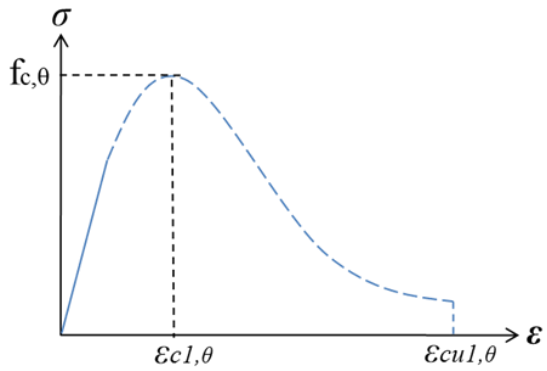

Figure 3 The stress-strain relationship for concrete at elevated temperatures

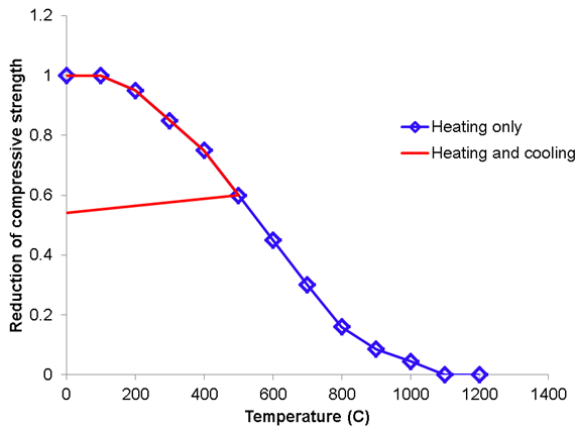

Figure 4 Compressive strength reduction in concrete during heating and cooling

The tensile behavior of concrete at elevated temperature is theoretically difficult to predict. For structural design purposes, Eurocode EN-1992-1-2 (CEN, 2004) suggests that the tensile strength of concrete can be ignored (conservative). In such cases, when the model is slightly vague, the tensile strength may need to be considered in the analysis. Schneider (1988), who provided a condensed survey of the present state of knowledge regarding the high temperature of concrete to estimate the fire behavior of concrete members, reported that the tensile strength of concrete could be assumed to be 10% of the compressive strength.

The thermal expansion of concrete is very complex because the constituent ingredients of concrete behave differently when heated. Thus, the thermal expansion is influenced by many factors, such as type of aggregate, cement, and water-cement ratio. Eurocode EN-1992-1-2 (CEN, 2004) presents a simple formula to calculate concrete thermal expansion. For lightweight concrete, the equation is

$$\Delta l/l = 8 \times 10^{-6}(\theta c - 20) \tag{1}$$

where l is the length at 20°C, Δl is the temperature-induced expansion, and θ_c is the concrete temperature (°C).

3. Modeling Approach

3.1. Structural Element Model

The finite element software ABAQUS v6.13 was used to develop the model of the structure of the composite building. In ABAQUS, there are a number of hexahedron, shell, and beam elements with different characteristics. In this study, steel elements for beams and columns were discretized using a two-node linear beam element in space (B31), which is geometrically simple and has few degrees of freedom. The beam-to-column and secondary beam-to-primary beam connections were assumed to be rigid and pinned, respectively, which is common in practice. These connections result in a structure with greater deformation capacity and less stiffness, which has advantages for the seismic design of the structure.

The concrete slab was discretized using a four-node thin shell element with reduced integration (ABAQUS library code S4R). The shell element has five degrees of freedom (three translations and two in-plane rotations) at each node. The steel reinforcement bar is represented by the rebar option in ABAQUS. The shear stud was not modeled directly. Instead, tie constraint was applied to accommodate the fully composite action between the steel beam and the concrete slab.

3.2. Numerical Approach

There are two solution methods in ABAQUS that can be used in this simulation. The first solution is a general static analysis, which is applicable until the determinant of the stiffness matrix equals zero or is negative. However, the main disadvantage of this solution is that the non-convergence problem is difficult to solve when complicated contacts are encountered. The second method is an explicit dynamic analysis, which can overcome the non-convergence problems due to complicated contact but is a very time-consuming process as very small time steps are required.

To resolve the non-convergence problems in the general static analysis, stabilization with the dissipated energy fraction can be used. Numerical convergence problems can be solved with a high dissipated energy fraction. However, the accuracy of the results may be compromised when the fraction is too large. The default energy dissipation factor is taken as 0.2×10^{-4}, which is suitable for most applications. However, the user can determine the value to obtain a certain accuracy if needed.

4. Analysis of Heated Structures

This section presents the application of the finite element software ABAQUS v6.13 to model the building. Benchmark problems obtained from Gillie (2009) were chosen to validate the modeling approach and demonstrate that the analysis captures all the required phenomena at elevated temperature.

Figure 5 shows the benchmark model, which is a simplified version of the UK Cardington Test (Kirby, 1998). Symmetry boundary conditions were applied to all external edges. The Young's modulus and yield strength of the steel beams and columns were 210 GPa and 300 MPa, respectively. The compressive strength of concrete in the slabs was taken as 47 MPa, and the yield strength of the rebar was 450 MPa. These material properties are similar to that of the UK Cardington Test. The steel and concrete properties at ambient temperature are shown in Table 1 and Table 2, respectively.

Initially, the load of 5.48 kN/m^2 was applied to the structure as a gravity load over the slab. Then, the temperature loadings were applied to the shaded area, as shown in Figure 5. At this stage, the secondary beam was heated up to 800°C. Meanwhile, the lower surface of the slab was heated to 600°C with a linear gradient of 4.6°C/mm, resulting in a

temperature of 0°C on the upper concrete slab. Finally, the structures were cooled to an ambient temperature.

Elastic-perfectly plastic structural steel behavior was adopted for the steel elements, and the material properties for steel and concrete at elevated temperature were determined according to Eurocode EN 1993-1-2 and Eurocode EN 1992-1-2, respectively. A damaged plasticity model was applied for concrete based on the work of Lubliner et al. (1989). The default values of the parameters are as follows: the ratio of equibiaxial compressive yield stress to uniaxial compressive yield stress, f_{b0}/f_{c0} = 1.16; eccentricity = 0.1; the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian, K = 0.667; viscosity parameter = 0; and dilatation angle = 40°. It should be noted that the reduction in the compressive strength of the concrete after the heating phase was not considered.

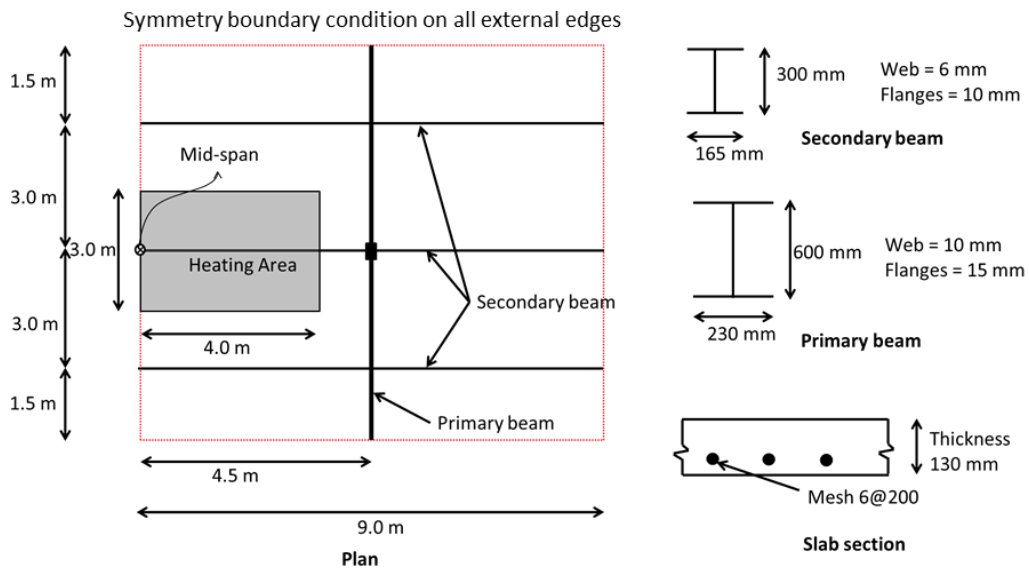

Figure 5 Geometry of the simplified version of the first Cardington Test

Table 1 Steel properties at ambient temperature

Material	E (GPa)	ν	α (C^{-1})	σ_y (MPa)	σ_u (MPa)
Mild Steel	210	0.3	1.4×10^{-5}	300	400
Rebar	210	0.3	1.4×10^{-5}	450	460

Table 2 Concrete properties at ambient temperature

Material	ν	α (C^{-1})	σ_u (MPa)	ε_u
Concrete	0.25	9×10^{-6}	47	0.002

An extensive sensitivity study was carried out to obtain the appropriate modeling parameters to be used in subsequent numerical analyses. The energy dissipation (α_d), mesh size, compressive strength of concrete and thermal expansion were investigated in the sensitivity study. Furthermore, a separate analysis without the presence of a composite slab was performed to understand the mechanisms at work in the composite slab.

4.1. Mesh Size

In finite element (FE) analysis, mesh size is one of the key parameters that can influence the accuracy of the analysis. FE models with a fine mesh produce accurate results but require a longer computing time. However, large mesh size may lead to less accurate results but save computing time. Figure 6 shows the comparison of the mid-span beam deflection as indicated in Figure 5 with different mesh sizes. Mesh size varies from 0.1 m, 0.3 m, 0.5 m, 1.0 m to 1.5 m. It is clear that the general patterns of the deflections are the same in all cases. The maximum deflection occurs during the heating phase when the temperature reaches 800°C (at maximum temperature). It can also be seen that the larger mesh sizes of 1.5 m and 1.0 m slightly under-predict the displacement at temperatures up to 700°C. However, the mesh sizes of 0.5 m, 0.3 m, and 0.1 m give reasonable predictions compared to those in previous studies.

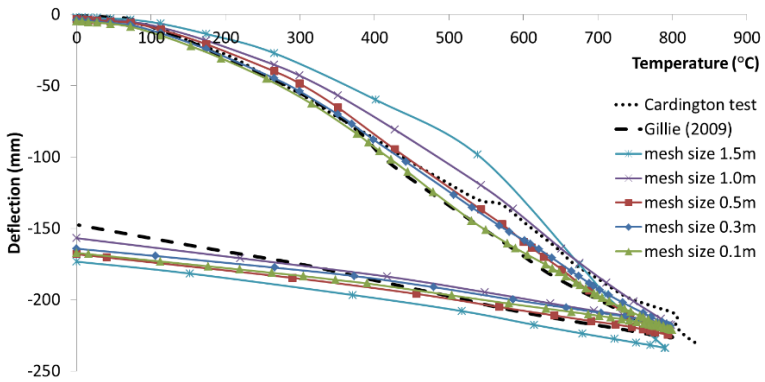

Figure 6 Comparison of mid-span beam deflections with different mesh sizes

4.2. Energy Dissipation Factor

Similarly, the displacements were not sensitive to the energy dissipation factor (αd), as shown in Figure 7. The results above confirm that the modeling approach produces reasonable results. From the results of the sensitivity study, it is appropriate to use the default energy dissipation factor of 0.2×10^{-4}.

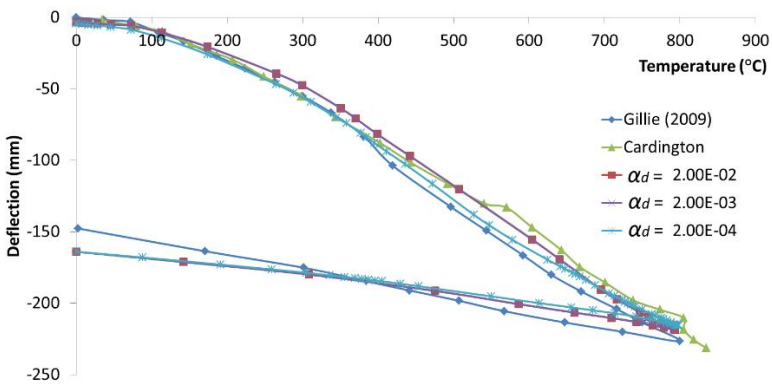

Figure 7 Comparison of mid-span beam deflections with different energy dissipation factors (α_d)

4.3. Compressive Strength of the Concrete Slab

As discussed in the literature review, concrete does not recover its initial compressive strength during the cooling phase. Eurocode EN-1994-1-2 (CEN, 2005b) recommends that an additional loss of 10% of the value at the maximum temperature be applied. However, in this study, it was assumed that there is no reduction in compressive strength after the

heating phase. To understand the effect of the compressive strength of concrete, different compressive strengths from 30 MPa, 47 MPa, and 60 MPa were investigated. Figure 8 shows the comparison of mid-span beam deflections with different compressive strengths of the concrete slab. The result demonstrates that the deflection is not sensitive to the compressive strength of the concrete slab. Thus, it seems that the reduction in compressive strength has a minor effect on the results for this particular structure and for the fire scenarios adopted in this study.

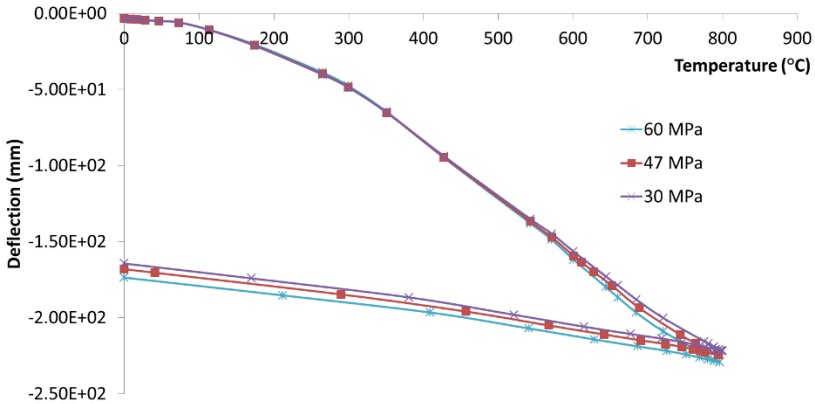

Figure 8 Comparison of mid-span beam deflections with different compressive strengths of the concrete slab

4.4. Thermal Expansion

The intention of this analysis is to study the effect of different types of concrete (lightweight concrete and normal weight concrete) with similar mechanical properties. Two different thermal expansions of 9×10^{-6} (lightweight concrete) and 13×10^{-6} (normal weight concrete) were investigated. As seen in Figure 9, the use of normal concrete increases the mid-span deflection by approximately 5%.

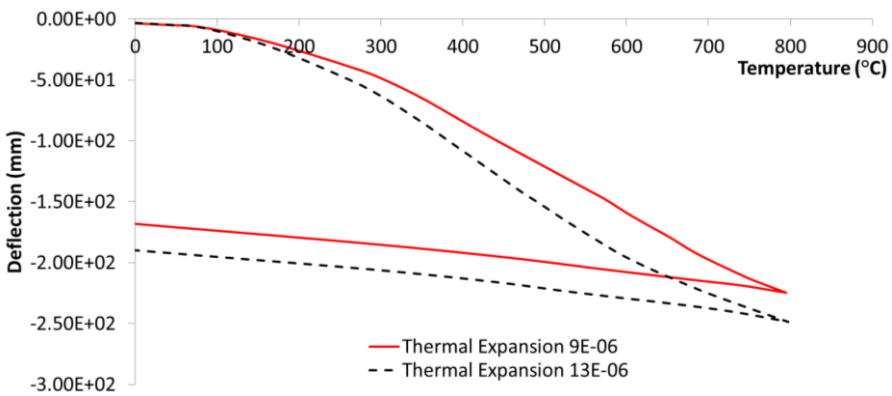

Figure 9 Comparison of mid-span beam deflections with different thermal expansions of concrete

4.5. Effect of the Presence of the Composite Slab

Mid-span beam deflections with and without the contribution of the composite slab are shown in Figure 10. The analysis without modeling the composite slab overpredicts the displacement. However, the composite slab increases the fire resistance of the frame by 50% compared to the frame without the concrete slab. Thus, the composite slab is an essential element in improving the performance of the building during a fire and should not be ignored in the frame analysis.

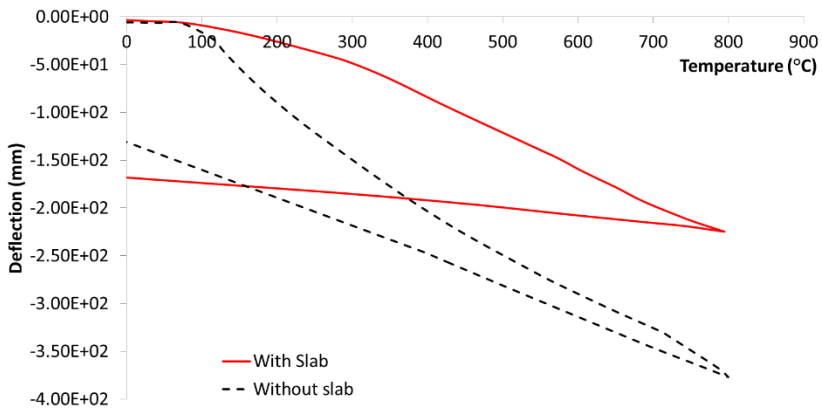

Figure 10 Comparison of mid-span beam deflections with and without the concrete slab

5. Conclusions

This study has described a numerical model generated using ABAQUS. Steel beams and columns were modeled using 1-D line elements, and concrete slabs were modeled using shell elements. A tie constraint between the steel beam and concrete slab was applied to accommodate the fully composite action between the two. The beam-to-column and secondary beam-to-primary beam connections were assumed to be rigid and pinned, respectively.

Because no new experimental study was conducted, a series of validations were carried out to confirm that the results of the analysis provide an acceptable level of accuracy. The results were compared to those of existing experiments. Overall, the results obtained from the analysis demonstrate a good level of agreement with those obtained by others. Therefore, the modeling approach has been validated for important specific aspects of structural behavior of composite buildings in fires.

The results of the sensitivity study indicate that it is appropriate to use a default energy dissipation factor of 0.2×10^{-4}. It can also be seen that the mesh sizes have little influence on the deflection, in which even a mesh size of 0.5 m produces reasonable results. The results also show that the deflection is not sensitive to the compressive strength of the concrete slab. Thus, it seems that the reduction in compressive strength has a minor effect on the results. Furthermore, the presence of the composite slab increases the fire resistance of the frame by 50% compared to the frame without the concrete slab.

However, it should be noted that the beam element used in this study cannot capture all possible failure modes, such as local buckling. An experimental study by Wang and Li (2009) demonstrated the possibility that a steel column can fail prematurely due to localized buckling. Detailed elements, such as solid or shell elements, can be used if detailed beam behavior is needed. In addition, the connections were assumed as rigid and pinned, so connection failure was not taken into account.

Acknowledgements

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