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Integrated fire dynamics and thermomechanical modeling framework for steel-concrete composite structures

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Abstract. The objective of this study is to formulate a general 3D material-structural analysis framework for the thermomechanical behavior of steel-concrete structures in a fire environment. The proposed analysis framework consists of three sequential modeling parts: fire dynamics simulation, heat transfer analysis, and a thermomechanical stress analysis of the structure. The first modeling part consists of applying the NIST (National Institute of Standards and Technology) Fire Dynamics Simulator (FDS) where coupled CFD (Computational Fluid Dynamics) with thermodynamics are combined to realistically model the fire progression within the steel-concrete structure. The goal is to generate the spatial-temporal (ST) solution variables (temperature, heat flux) on the surfaces of the structure. The FDS-ST solutions are generated in a discrete form. Continuous FDS-ST approximations are then developed to represent the temperature or heat-flux at any given time or point within the structure. An extensive numerical study is carried out to examine the best ST approximation functions that strike a balance between accuracy and simplicity. The second modeling part consists of a finite-element (FE) transient heat analysis of the structure using the continuous FDS-ST surface variables as prescribed thermal boundary conditions. The third modeling part is a thermomechanical FE structural analysis using both nonlinear material and geometry. The temperature history from the second modeling part is used at all nodal points. The ABAQUS (2003) FE code is used with external user subroutines for the second and third simulation parts in order to describe the specific heat temperature nonlinear dependency that drastically affects the transient thermal solution especially for concrete materials. User subroutines are also developed to apply the continuous FDS-ST surface nodal boundary conditions in the transient heat FE analysis. The proposed modeling framework is applied to predict the temperature and deflection of the well-documented third Cardington fire test.

Keywords: fire-dynamics; nonlinear finite elements; transient heat; steel-concrete; composite; structural behavior; fire simulation.

1. Introduction

Refined modeling of structural behavior during fire is important for design and damage mitigation aspects. Towards that goal, it is critical to properly apply the needed multi-physics modeling tools to simulate the fire dynamics and the mechanical performance of steel-concrete structural elements under elevated temperatures present in a fire environment. Nonlinear thermomechanical constitutive models

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are also needed due to the large deformations and the temperature-dependent behavior of concrete or steel materials. Damage modeling, due to the large deformations along with stiffness and strength reductions, is also required at the advanced stage of the fire.

Many advanced studies have been conducted over the last decade to characterize the mechanical behavior of concrete and steel structural components under elevated temperatures due to fire. Currently, this area of research remains active because it involves coupled fire and thermomechanical simulations along with damage modeling of materials and structures.

Concrete materials under elevated temperatures can drastically change their effective mechanical and thermal properties. Harmathy (1983, 1988) characterized the thermomechanical material properties of different concrete materials as a function of temperature. The ACI 216 report (1994) reviewed experimental results characterizing the effect of high temperatures on the effective thermomechanical properties of concrete. Ahmed and Hurst (1999) proposed a thermodynamics-based model that accounted for the gas, water, and solid constituents using conservation of energy in a porous medium. Their 2D model was compared with temperature distributions tests on concrete samples. Their model was used to generate the pore pressure, moisture content, and temperature distribution for high strength concrete columns under fire.

The Eurocode 3 (1995) described rules and requirements for the design of steel structures under fire. The code provided design equations for tension members, connections, buckling resistance, moment resistance, shear resistance, and lateral-torsional buckling at elevated temperatures. Outinen and Makelainen (2004) performed small-scale tensile tests using the transient state tensile method to study the mechanical properties of structural steels under high temperatures. Chen, *et al*. (2006) investigated the mechanical properties of high and mild strength structural steels at elevated temperatures. They provided reduction factors over the yield strength and elastic modulus. These factors were compared with four standard codes: American, Australian, British, and European standards. The reduction factors were similar from room temperature up to 540°C. Reduction factors for the yield strengths from the four codes were conservative compared to the test results up to 1000°C. The elastic modulus of high-strength steel from the American, Australian, and European standards were conservative compared to the steady-state tests but unconservative compared to the transient-state tests.

Franssen, *et al*. (1995) performed numerical studies of an early Cardington test performed in 1987 using a two-dimensional (2D) steel frame. They considered the heat flow of detailed composite section models with thermal material properties taken from the Eurocode. Good comparison was shown between the predicted temperature and the test results at the flange, inner and outer web locations for both beam and column sections. Najjar and Burgess (1996) developed a nonlinear analysis approach for steel frames under fire with geometric and material nonlinearities. Their program was extensively verified against other numerical results using the BS5950 steel code. They concluded that the code developed can be used for three-dimensional (3D) analysis of multi-story skeletal steel frames under fire. Li and Jiang (1999) advocated the use of the Clough force-imbalance method for the analysis of steel frames under fire. They pointed the limitation of the displacement-based FE models and the computational effort that may be required for a cross-sectional analysis. Fire tests were conducted on a small-scale single-story two-bay steel frame and the structural response was successfully simulated.

Composite steel-concrete structures under elevated temperature were recently investigated. Sanad *et al*. (2000) developed a simple FE model and applied it to analyze the first Cardington fire test. The ABAQUS (2003) FE code was used. Two-noded beam elements were applied for the steel beams and a grillage model for concrete slabs. The steel and concrete material properties included nonlinear temperature-dependent stress-strain relationships. Overall predictions were demonstrated for the deflections and temperature profiles at different points in the tested joist. Some of these predictions were in good agreement with the experimental results while others gave large differences. This may indicated that a more refined model is needed, especially highlighting the need for composite shell elements to represent the concrete slab. Gillie, *et al*. (2001) developed effective section stress-resultants for reinforced concrete slabs under fire conditions. They developed software called Finite Element Analysis of Shells at high Temperatures (FEAST) to generate the effective cross-sectional response. Compressive and tensile concrete material behaviors as functions of elevated temperatures were considered in the FEAST code. Gillie, *et al*. (2001, 2002) employed their previous codes and performed structural analyses for the first and third Cardington tests, termed the Cardington British Steel Corner test. Shell elements with eight-nodes and reduced integration were used for the concrete slab while two-node beam element used for the steel beams and columns. However, no fire simulations for the compartments were performed. Instead, a spatially-uniform surface temperature distribution was used for the concrete slab. The temperature history was measured during the Cardington test. Similarly, each beam was subjected to its linear and spatially-uniform cross-sectional temperature profile also measured from the experiment. The fire cooling down phase was not included in these analyses. Their model showed good ability to predict the deflections as function of the prescribed temperature when compared with experimental data from the first and third Cardington fire tests. Lamont, *et al*. (2001) developed an adaptive heat transfer program HADAPT used in predicting the temperature within the structural elements in the Cardington tests. The code HADAPT was developed for 2D nonlinear transient thermal analysis and used to generate detailed temperature distributions through the thickness of the ribbed concrete slab and metal deck. Heat convection formulation was used with the interface elements between the concrete plate and metal deck in the composite slab. The formulation allowed for studying parameters, such as density, specific heat temperature dependency, moisture content, convection coefficient, and slab thickness, to find out the temperature changes as a function of these variables. Flint, *et al*. (2007) performed numerical analysis to study the mechanical response of a tall building with long span truss floor system under fire environment. They developed a 2D structural model with a multi-floor system using the ABAQUS FE code. A construction type similar to the World Trade Center Towers was used in their computational model. They found that while the long truss span floors did not fail, the structure could collapse because the external/perimeter columns failed due to load redistribution. Bailey (2002) investigated the structural behavior from the large compartment fire test of the full-scale Cardington building. The fire test of the seven-story concrete building was carried out at the Building Research Establishment (BRE) Laboratories at Cardington, Bedfordshire between July and September 2001. A fire compartment, with a floor area of 225 m^2, was constructed between the ground and the first floor and a number of fire scenarios were considered. Limited test results were reported including residual displacements. The observed damage provided useful information on the holistic behavior of concrete buildings under fire. Significant lateral movement of the heated slab was observed in the tests resulting in buckling of the steel cross-bracing and a lateral displacement of the external columns with extensive spalling to the soffit of the slab. Bailey (2002) suggested that the designers should give holistic consideration to the overall structural behavior under fire to prevent premature collapse. Li, *et al.* (2009), Santiago, *et al.* (2008), and Cai, *et al.* (2003) performed experimental and analytical studieds on structure components under fire environment. Latter used 3D finite element to model general composite beam sections subjected to fire. Their generalized composite beam element included geometrical and material nonlinearity including cracking and crushing of the concrete. Also, temperature-dependent thermal expansion and mechanical degradation of the material were used. Non-uniform temperature profiles, variations of constitutive relationships and thermal strains across the section were considered by dividing the cross section into a number of segments. The proposed element was validated by comparing with theoretical and experimental results. Bailey (2003) proposed an extended membrane fire design method to enable the specification of orthotropic reinforcement for the composite slab. The design method gives the designer a tool to specify the most economical planning of reinforcement in the floor slab. A fire design example for a typical building was performed assuming 60 min duration of fire resistance. He found in the example that the ultimate load-carrying capacity of the floor was increased by 23% by placing more reinforcement in the longer span of the rectangular slab panels. The method was compared with the test results and gave very good correlations. Bailey (2004) presented a structural performance-based design approach for steel beams supporting a composite floor allowing designers to specify fire protection to only a proportion of the steel beams within a given floor plate. The new design method enabled an estimate of the membrane capacity of the slab and beam system. This method assumes that the tensile force generated in the beam is transferred to the supporting composite slab and resisted by the compressive membrane force generated around the slab's perimeter. The new design method showed a good match to the BRE corner fire test carried out on the Cardington steel-framed building. Huang, *et al.* (2004) presented some comparisons between a simple design method and finite element modeling for composite floor slabs in fire condition. They investigated the influence of thermal curvature, the effect of changing the edge support conditions and the influence of the proportion of steel reinforcement on the structural behavior. They found out that the tensile membrane action can be important in carrying the loads at high temperatures and deflections. Also, the tensile membrane action occurred depended on the aspect ratios of the slabs. The simple design method usually predicts a greater fire resistance than the detailed computer modeling due to tensile membrane action. The membrane action can be a useful tool as a part of a performance-based fire engineering design approach. Elghazouli and Izzuddin (2001) examined the behavior of composite steel-concrete building floors under fire conditions. They performed the numerical modeling for the structural behavior in the Cardington fire tests. A grillage model was used for the concrete slabs with geometric and material nonlinearities. Their numerical results were in general agreement with the experimental results. Izzuddin, *et al.* (1984) developed a new shell element for concrete composite floor slabs. A geometric orthotropy of the composite ribbed section was considered in the proposed element using the modified Reissner-Mindlin formulation. Nonlinear concrete material model was included with nonlinear temperature-dependent compression behavior and softening due to cracking in tension. They provided numerical examples comparing their element with the 3D brick element for uniform-thickness and ribbed plates. The new slab element showed good agreement with the 3D-continuum modeling consumed less computational efforts. In a following companion paper by Elghazouli and Izzuddin (2004), the new element was used in a full-scale analysis of a composite beam-slab floor system under extreme fire environment present in the third Cardington test. However, coupled fire simulation was not performed. Instead, measured temperature history from the test was used in their full-scale analysis.

Although the fundamental conservation equations governing fluid dynamics, heat transfer and combustion were first developed over a century ago, the practical mathematical models of fire are relatively recent due to the natural complexity of the problem such as an enormous number of possible fire scenarios to consider and a limitation of computing power. Fire simulation tools have been developed in some of the studies. The Consolidated model of Fire Growth And Smoke Transport (CFAST) was developed by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (Jones, *et al*. 2005 and Peacock, *et al*. 2005). The Analysis of Smoke Movement in Enclosures (JASMINE) has been developed continuously at BRE over 20 years (Kumar, *et al*. 2002). The Simulation of Fires in Enclosures (SOFIE) was developed under the group of a Consortium including a number of European fire research laboratories and initiated at Cranfield University (Rubini). Fire Risk Evaluation and Cost Assessment Model (FiRECAM) has been developed by the National Research Council (NRC) in collaboration with a number of partners since 1987 (Yung, *et al*. 2001). In addition, Fire Dynamics Simulator (FDS) was written by staff members of the Building and Fire Research Laboratory at the National Institutes of Standards and

Technology (McGrattan, *et al.* 2002, 2005).

This study presents a framework with three sequential parts for the general analysis of concrete-steel composite structures under fire environment. The first part describes the FDS modeling and how the fire-load with proper boundary conditions is applied. The second part introduces a new method to generate the FDS spatial-temporal (ST) solution variables. Optimal ST polynomials are then examined to strike a balance between accuracy and simplicity. The third part describes the different temperature dependent material properties for steel and concrete. These are needed for the nonlinear mechanical constitutive behavior in addition to the nonlinear transient heat FE modeling. The fourth part of this paper includes a transient heat model, using the FDS-ST as prescribed surface values, for the concrete slab. We characterize the ST history at all nodes of the slab. The ST history for the steel is directly calculated from the FDS model. Finally, the thermomechanical analysis of the third Cardington fire test is performed. Predictions for the deflections and temperatures are compared with the test results.

2. Fire dynamics simulation in structures

The Fire Dynamics Simulator (FDS) has been developed at the Building and Fire Research Laboratory (BFRL) at the National Institutes of Standards and Technology (NIST), e.g. McGrattan, *et al.* (2002, 2005) and McGrattan et al. (2002). The program calculates the temperature, density, pressure, velocity, and chemical composition within each numerical grid cell at each discrete time step. It computes the temperature, heat flux, and mass loss rate of the enclosed solid surfaces. The FDS code is formulated based on Computational Fluid Dynamics (CFD) of fire-driven fluid flow. The FDS numerical solution can be carried out using either a Direct Numerical Simulation (DNS) method or Large Eddy Simulation (LES). The latter is not severely limited in grid size and time step as the DNS method. In addition to the classical conservation equations considered in FDS, including mass species momentum and energy, thermodynamics-based state equation of a perfect gas is adopted along with chemical combustion reaction for a library of different fuel sources. FDS has a visual post-processing image simulation program named "smokeview." This study develops different software for post-processing the FDS results and generating the temporal and spatial numerical data needed for the proposed temperature approximation functions.

The surface energy or heat release rate (HRR) per unit area of a fire source can be prescribed and numerically characterized directly avoiding calculating the heat release using chemical combustion reaction. A relatively simple and practical form of the HRR curve is described in Karlsson and Quintiere (2000) and shown in Fig.1. The curve is divided into three parts: the growth phase, the steady-state phase, and the decay phase. The initial fire development is accelerating in the first part and can be described using a quadratic function of time. The second phase is a steady-state phase with a magnitude Q_{max}. The duration of the steady phase is determined by some assumptions on the fire scenario and content of the fire load. The fire decay phase is also dependent on the scenario and content. Without detailed knowledge, this study assumes the decay function as a reflection of the growth phase function. Karlson and Quintiere (2000) provides tables for typical coefficients that can describe different HRR coefficients depending on the items consumed in the fire, such as wood, sofa, electronics, etc.

3. Proposed sequential modeling approach

In this modeling approach, analysis of structures under combined mechanical and fire loads are

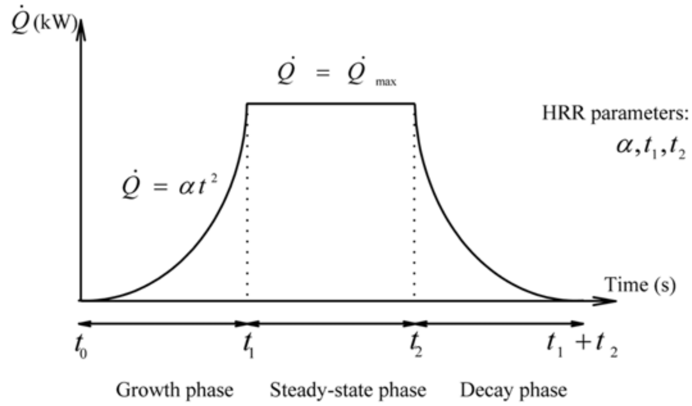


Fig. 1 A heat release rate curve

carried out using the FDS and ABAQUS FE codes. The FDS is first used to solve for the temperature or heat flux on the surfaces as a function of time. A simple heat release rate as a function of time is used to represent the energy released from the surface of the fire source in the FDS model. The solutions for the surface heat and temperature of the steel beams and columns obtained from the FDS fire model are approximated using a fifth-order polynomial in time with coefficients that are spatially dependant. The temperature distributions within the steel beams are assumed to be linear as a function of the upper and lower surface temperatures. However, the 3D temperature distribution for the concrete slabs is more complicated and is determined from a separate heat transfer analysis using the surface heat flux polynomial approximations as boundary conditions. The nonlinear structural analysis is sequentially carried out once the temperature distributions are obtained as a function of time within all points in the structure.

Fig. 2 shows a general framework for the analysis of structures under combined fire and mechanical loading. The proposed approach can be divided into three simulation parts. The first part is the fire simulation where the FDS model is utilized. The FDS model generates a solution of several state variables, such as pressure, temperature, heat, velocity vector. However, our framework is interested in the heat and temperature solution that are related to the structure performance and response. The temperature and heat flux of the interior structural surfaces profiles are used and applied to subsequent simulation parts. The second part is the heat transfer analysis. The objective of this part is to compute

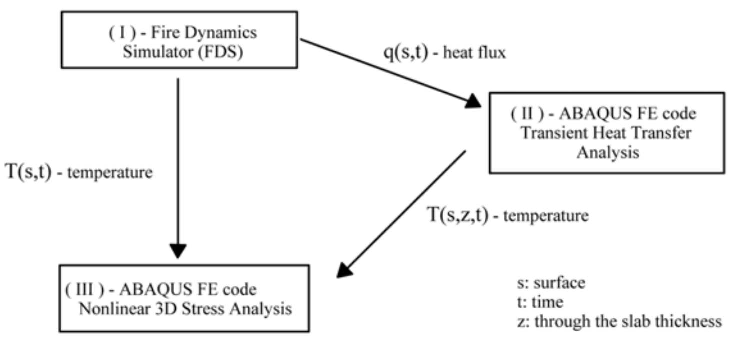


Fig. 2 Proposed sequential fire-heat-structural analysis framework

the temperature profiles for the different structural components, beams, columns, and especially the concrete slabs through their thickness using the heat flux or surface temperature results from the FDS model. The third part is the nonlinear 3D structural analysis. The temperature profiles in this modeling stage is known and imposed spatially as a function of time.

The interior surface boundary file which is one of the FDS result files contains the all interior surface temperature or heat flux values during the fire simulation. The large volume of boundary data generated in a typical fire simulation makes it difficult, if not impossible, to use directly in the subsequent structural analysis. Methods for data reduction and simplified fire-simulation results must be used in order to effectively simulate the refined temperature distribution and at the same time retain the efficiency of applying the temperature profiles. To that end, this study employs a unified approximation for the temperature in beams and columns as a fourth-order polynomial in terms of the structural axial coordinates. The five coefficients of each polynomial are time dependent functions, each in the form of a fifth-order polynomial in time. This can be described for a one-dimensional (1D) element in the s-direction (Fig. 5(a)) as:

$$
\begin{aligned}
T(s) &= A_0(t) + A_1(t)_s + A_2(t)s^2 + A_3(t)s^3 + A_4(t)s^4 \\
A_0(t) &= A_{00} + A_{01}t + A_{02}t^2 + A_{03}t^3 + A_{04}t^4 + A_{05}t^5 \\
A_1(t) &= A_{10} + A_{11}t + A_{12}t^2 + A_{13}t^3 + A_{14}t^4 + A_{15}t^5 \\
A_2(t) &= A_{20} + A_{21}t + A_{22}t^2 + A_{23}t^3 + A_{24}t^4 + A_{25}t^5 \\
A_3(t) &= A_{30} + A_{31}t + A_{32}t^2 + A_{33}t^3 + A_{34}t^4 + A_{35}t^5 \\
A_4(t) &= A_{40} + A_{41}t + A_{42}t^2 + A_{43}t^3 + A_{44}t^4 + A_{45}t^5
\end{aligned}
$$

where, the $A_0(t)$, $A_1(t)$, $A_2(t)$, $A_3(t)$, and $A_4(t)$ are time-dependent polynomial coefficients. A least square type error minimization is carried out to obtain the best polynomial coefficients that minimize the overall error. Once the approximation process is complete, the result is in the form of a coefficients' matrix (5 by 6) for each axial structural element. The total of thirty coefficients is sufficient to provide for the element's spatial and temporal (s,t) temperature during the fire. Figs. 3 and 4 illustrate the proposed temperature approximation compared with the actual FDS simulation results for beam and column type elements and in different fire scenarios. Overall, the proposed polynomial form and its order in time and spatial variables strike an acceptable balance between simplicity and accuracy. This minimal computational storage premium is minute compared to the large numerical database generated during the analysis for a typical member at its grid points. The same polynomial approximation scheme is used to represent the heat and temperature for an interior surface, such as for concrete slabs. In this approach, the surface is divided into several lines where the temperature or heat polynomial approximation in (s,t) are carried out independently. Each of them has a fourth-order polynomial approximation equation for the interior surface heat flux. Fig. 5(b) shows how to divide the slab to axial parts.

4. Engineering materials under elevated temperature

The mechanical properties of steel and concrete under elevated temperatures are needed in the

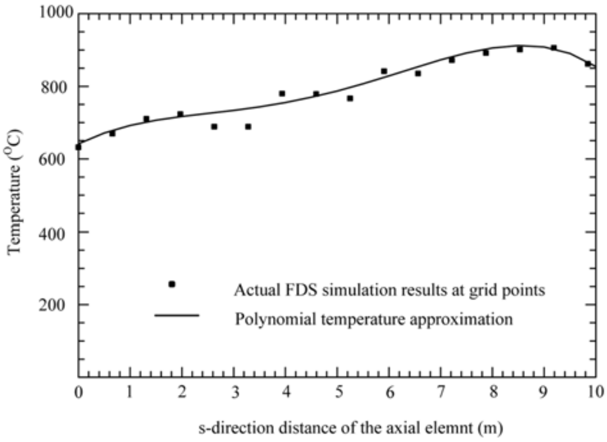


Fig. 3 Temperature comparison between FDS results and polynomial approximation at a certain time

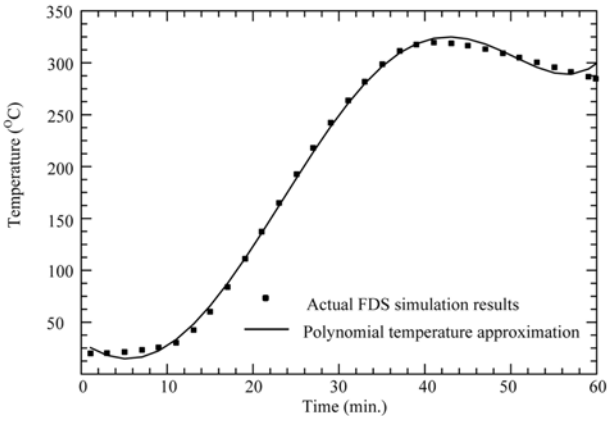


Fig. 4 Temperature comparison between FDS results and polynomial approximation at a certain location

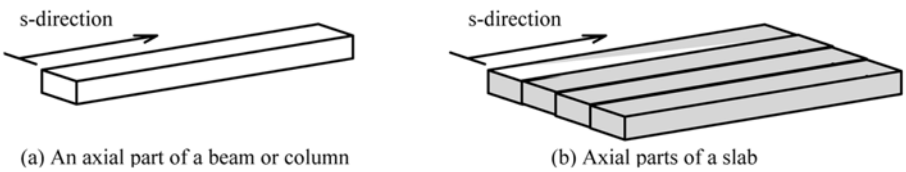


Fig. 5 Axial structural parts for fourth-order polynomial approximation

thermomechanical analysis described based on prior experimental work. The mechanical degradation of these construction materials and their thermal expansion as a function of temperature is required in order to properly carry out the proposed nonlinear stress analysis. In addition, the dependence of the effective specific heat on temperature for the concrete is needed in the transient heat transfer analysis. The material in steel beams and columns can be modeled using incremental elasto-plastic constitutive models. Degradation of the stress-strain response as a function of increasing temperatures should be incorporated with the nonlinear material models. Fig. 6 shows the axial stress-strain curves for steel under uniform temperatures. The coefficient of thermal expansion (CTE) for steel is not constant but increases as temperature increases. The CTE for steel can be calculated from Eq. (1) proposed by the ACI Committee 216 (1994) as:

$$\alpha_{CTE} = (11 + 0.0036 \times \theta) \times 10^{-6}[1/°C] \tag{1}$$

where, θ is temperature in Celsius degrees.

Accurate modeling of the mechanical behavior of concrete under elevated temperatures is also important in order to capture its degradation. Concrete compression and tension stress-strain curves used in this study are shown in Figs. 7 and 9 respectively. While the compression behaviors are

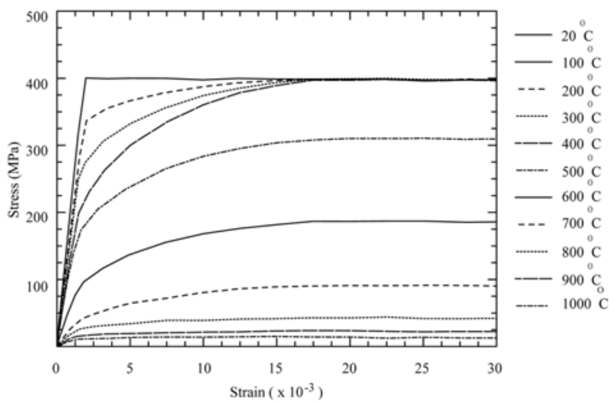


Fig. 6 Steel uniaxial stress-strain curves at elevated temperatures (Adapted from Eurocode-3, ENV 1993-1-2:1995 (1995))

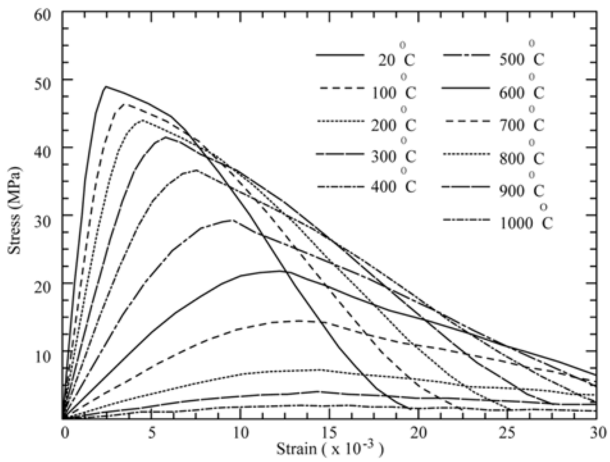


Fig. 7 Concrete compression stress-strain curves at elevated temperatures (Adapted from Eurocode-2, ENV 1992-1-2:1995 (1995))

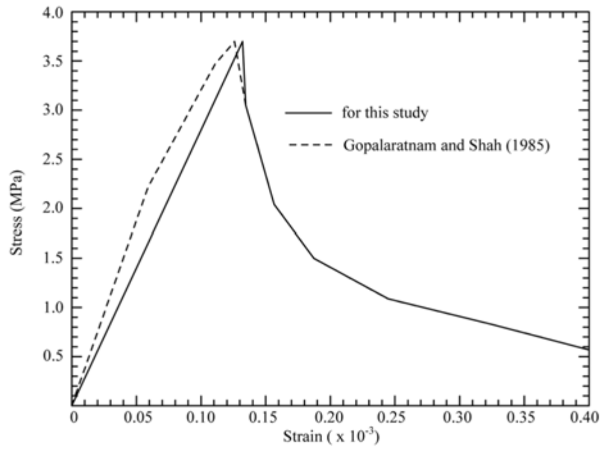


Fig. 8 Concrete stress-strain relationships in tension at room temperature used in this study and experimental data

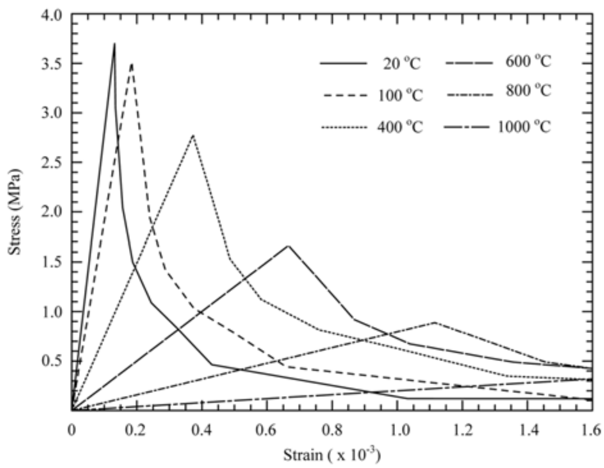


Fig. 9 Re-constructed concrete tension stress-strain curves at elevated temperatures

provided from the Eurocode 2 (1995), tension curves are not provided at the elevated temperatures. As a result, tension stress-strain curves shown in Fig. 9 for elevated temperatures are developed based on room temperature experimental results reported by Gopalaratnam and Shah (1985) shown in Fig. 8. The experimental results are re-constructed such that the slopes in both tension and compression match. The new curve (solid line in Fig. 8)is taken and scaled based on the stress degradation ratios obtained from the compression stress-strain curves as shown in Fig. 8. For example, to construct the tension stress-strain behavior for uniform 100°C, the slope of the room-temperature (RT) tensile curve is multiplied by the compression slope degradation ratio (from RT to 100°C). The ultimate stress for the 100°C curve is also found by multiplying the RT ultimate stress with the corresponding compression ratio. The post-ultimate softening behavior curves are re-constructed in the same fashion using the provided RT tension softening. Fig. 10 shows the concrete thermal expansion with different aggregates as a function of the temperature. An effective heat capacity is taken account of the latent heat of evaporation

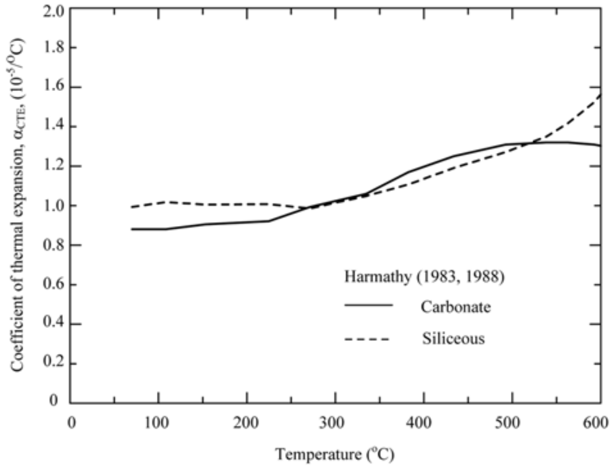


Fig. 10 Thermal expansion coefficient as a function of temperature

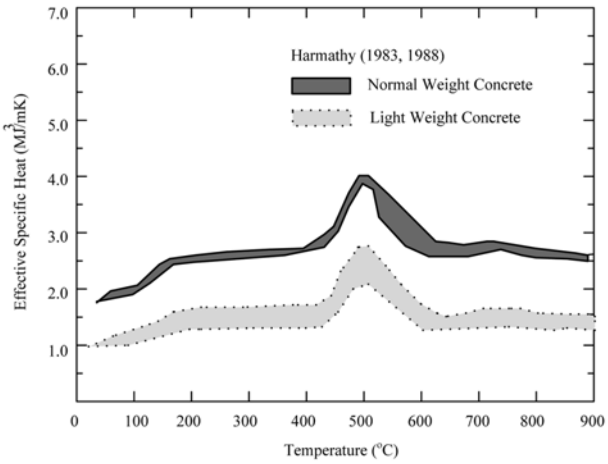


Fig. 11 Upper and lower ranges for effective specific heat of concrete as a function of temperature used in nonlinear transient heat analysis

of the concrete. The effective heat capacity for concrete is shown in Fig. 11. The average values between upper and lower bound experiment data are used in the nonlinear thermal transient analysis (second part of the proposed framework). The carbonate thermal expansion curve in Fig. 10 is used the temperature-dependence of the CTE in this study.

5. Simulations of the third cardington fire test

Full-scale fire tests on a realistic eight-story frame were carried out at the large building test facility at Cardington from September 1995 to June 1996. The overall objective of these tests was to increase our understanding for the complicated structural nonlinear and damage responses during fire. These tests highlighted interactions role between different structural components as their local deformation determine the overall behavior of steel-concrete composite structures under fire. The Cardington test layout performed by the European Coal and Steel Community (ECSC) was shown in Fig. 12. The cross-section of the building covered an area of 21 m × 45 m and had an overall height of 33 m. The beams were considered as simply supported with a composite action with the concrete slab. The structure was mechanically loaded using sandbags distributed over each floor to simulate a typical office dead load. Several fire tests were performed in Cardington using different structural system or compartments and fire sources. Among these tests, the third Cardington fire test was investigated in this paper. The third test involved a corner compartment subjected to a natural fire fuelled by timber cribs. The four columns in this test were protected and the five beams and floor slabs were left unprotected.

The third Cardington fire test was performed on the first floor of the building used to study the behavior of a complete floor system. The compartment area was approximately 80 m^2 and located at the South East corner of the building as shown in Fig. 12. A realistic fire was created by consuming wood-based material with an estimated fire loading of 45 kW/m^2 as reported by Newman, *et al*. (2000). Ventilation was provided by a single 6.6 m × 1.8 m high opening window. All columns, beam-to-column connections, and perimeter beams were fire protected. The secondary beams were equally spaced and have 9 m spans connected to the columns or to the primary beams. The heated primary beam had a length of 6 m. All columns were fire protected along their full height. The composite profiled deck slab had a span of 3 m between the secondary beams (Fig. 12).

The proposed fire modeling using FDS was applied to simulate the third Cardington fire test. The FDS model was mainly used to generate the temperature and heat histories on the surface of the structural elements within the fire compartment. Fig. 13(a) showed the FDS model for the third Cardington fire test along with structural elements. The "floor" area was used to distribute the fire source that was specified directly as a heat release rate per unit area (kW/m^2). The grey solid objects represented the concrete slabs and the walls. The black solid elements represented the steel columns and beams. Fig. 13(b) showed the locations where the FE predictions for the displacements and temperatures were compared with the reported experimental data. The temperatures through the thickness of the slab from the transient heat transfer analysis were compared at the location CS1. The other black filled circles were used for displacement comparisons. The grey rectangular indicated the

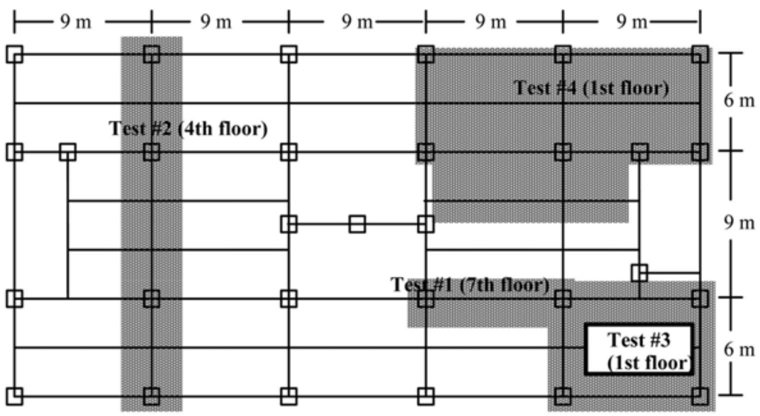
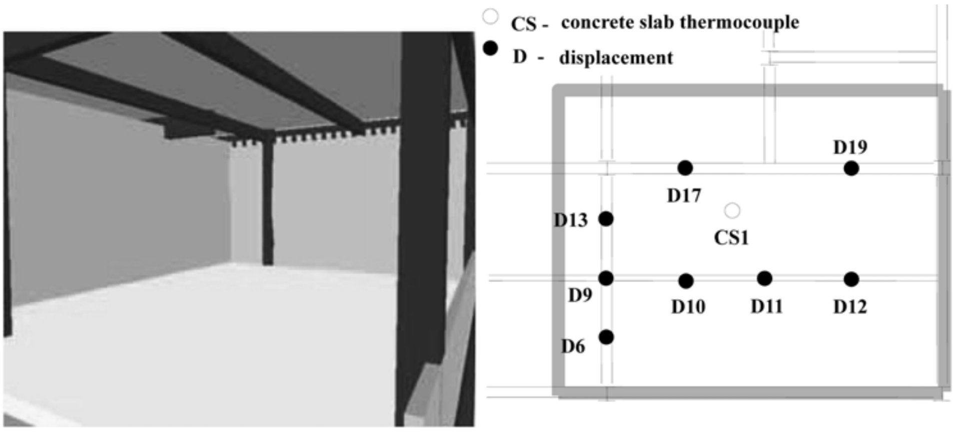


Fig. 12 Layout of the British steel Cardington frame fire tests by the European Coal and Steel Community (ECSC)



(a) (b)

Fig. 13 The Cardington corner fire test modeled by FDS

third Cardington fire test compartment boundary. The applied heat release rate (HRR) was assumed to have a growth rate factor α of 0.0007 based on Karlsson and Quintiere (2000) and a maximum heat release rate per unit area of 162 kW/m^2. These values were used to define the fire source by comparing predicted temperature response in the compartment to averaged measured temperature. The fire load curve used for the third Cardington fire test simulation was shown in Fig. 14. The duration time for growth phase, steady-state phase and decay phase were 8 min, 73 min and 8 min, respectively. The interior surface heat flux profile from the FDS model was applied to nonlinear 3D transient analysis for the concrete slab. The temperature from FDS model results were used to generate continuous ST functions used in the thermomechanical structural analyses of steel beams and columns.

Fig. 15 compared the predicted FDS temperature results with the measured beam temperatures inside the third Cardington test area. The range for the measured beam temperatures was reported by Usmani, *et al*. (2000). The FDS model results showed temperatures for three different locations: A, B, and C.

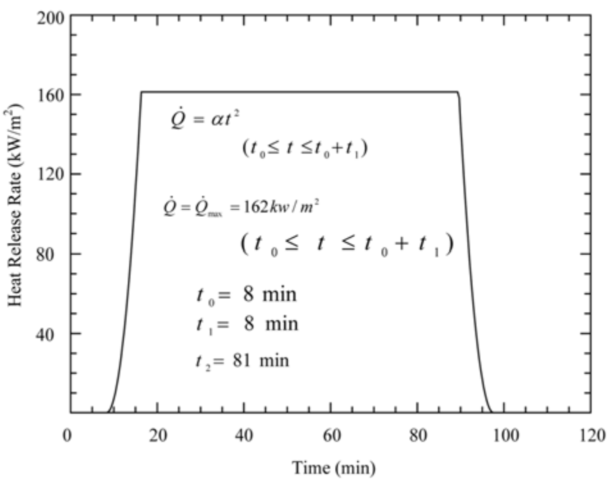


Fig. 14 Fire load curve used to simulate the FDS source in the third Cardington fire test

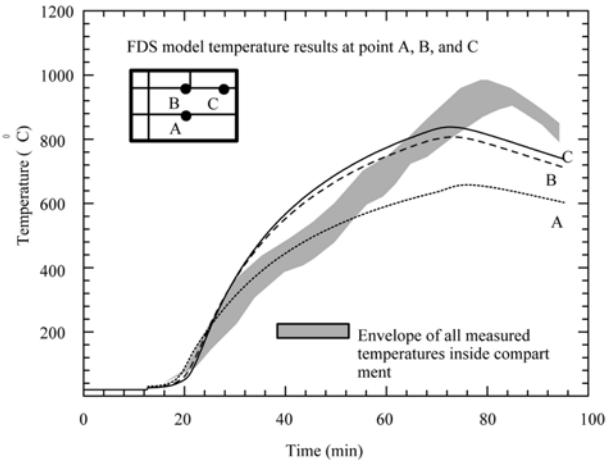


Fig. 15 Predicted temperature histories compared with experimental values for different beams in the third Cardington fire test

The FDS model showed good prediction for low to moderately high temperatures relative to the experimental values.

A separate heat transfer analysis for the third Cardington test was also performed to get the temperature profiles for the concrete slab. The transient heat analysis was modeled using four-node quadrilateral shell elements. The FDS heat flux results were applied as boundary conditions to the bottom surface of the slab while a room temperature was employed to the top surface. The concrete section temperature results from the heat transfer analysis were compared with the experimental data at the CS1 location (Fig. 13). Figs. 16, 17, and 18 showed comparisons between the experimental and model results. Good overall correlation was demonstrated.

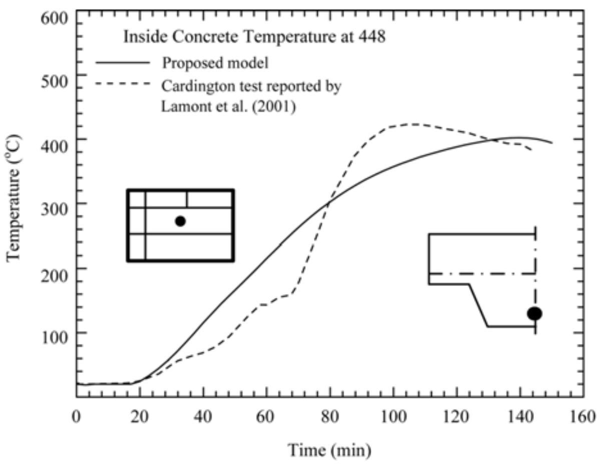


Fig. 16 Predicted temperature history results at a point (448) in the concrete slab from heat transfer analysis of the proposed model compared with experimental data

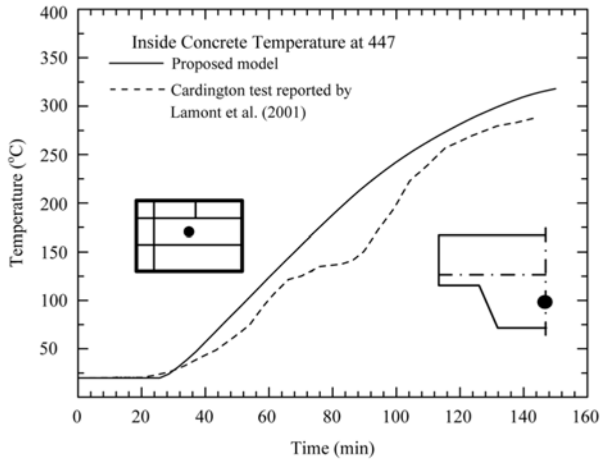


Fig. 17 Predicted temperature history results at a point (447) in the concrete slab from heat transfer analysis of the proposed model compared with experimental data

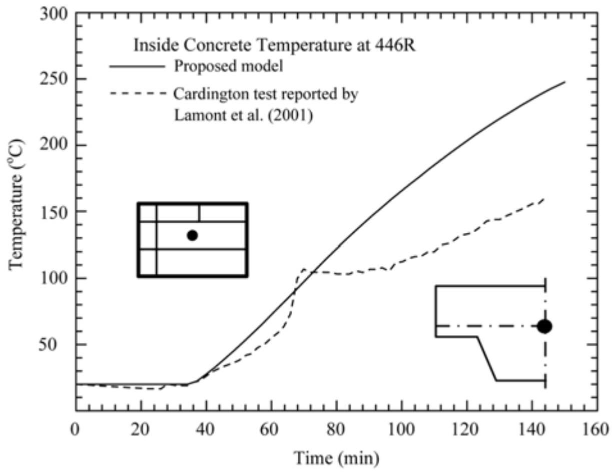


Fig. 18 Predicted temperature history results at a point (446R) in the concrete slab from heat transfer analysis of the proposed model compared with experimental data

The thermomechanical FE model for the Cardington test consisted of 3D beam elements (Timoshenko beam theory) used for the beams and columns. Four-node shell elements were used for the concrete slabs. The temperature history was applied at all nodes of the beam elements and obtained from the previous fire simulation models. The heat transfer analysis provided the temperature history for the shell elements representing the concrete slabs. The predicted vertical deflections were compared with the Cardington experiments reported by Usmani, *et al*. (2000) at several points. Fig. 13(b) illustrated the locations where deflections were measured. Figs. 19 to 22 showed the predicted deflections for four locations compared with experiments. The predicted deflections from the current model capture the

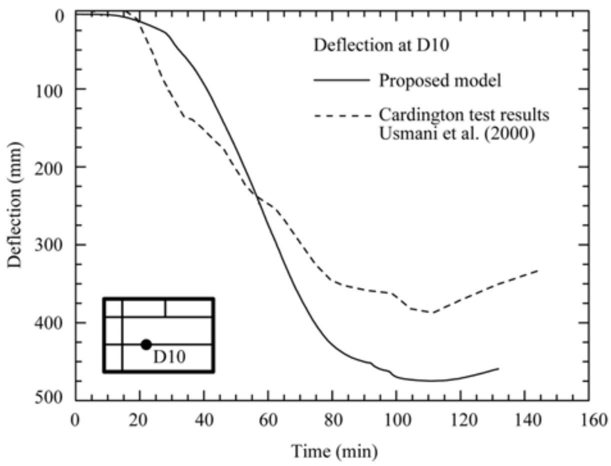


Fig. 19 Predicted beam deflection history (at the circled point, D10) compared with the reported experimental data by Usmani, *et al*. (2000).

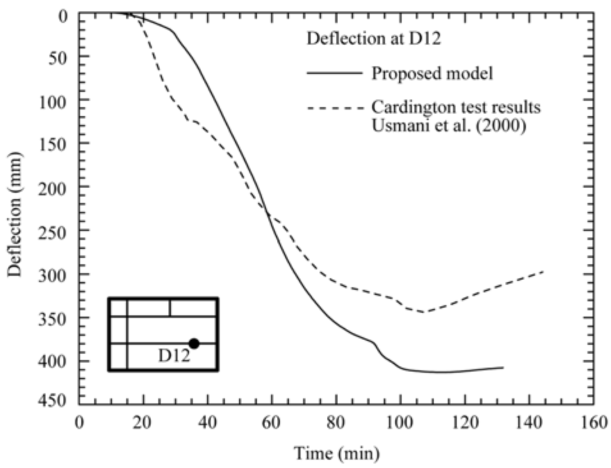


Fig. 20 Predicted beam deflection history (at the circled point, D12) compared with the reported experimental data by Usmani, *et al*. (2000).

overall trends of the test results during both the growth and cooling stages of the fire. However, they tend to show softer than experimental data, those are because the connections between beams and columns are assumed as hinges in the FE models. The model does include the cooling down which can be critical from nonlinear and damage in structural behavior. The current analysis was performed using general purposed four-node reduced integration shell element for concrete slab. Time and location-dependent (spatial-temporal) temperatures predicted from FDS and heat transient analysis are applied for thermal loadings. Slab temperatures in the compartment fire, such as the third Cardington fire test, can be spatially heterogeneous and non-uniform. The proposed integrated frame work can capture this spatial dependency and apply it to the structure in order to capture localized behavior and effects.

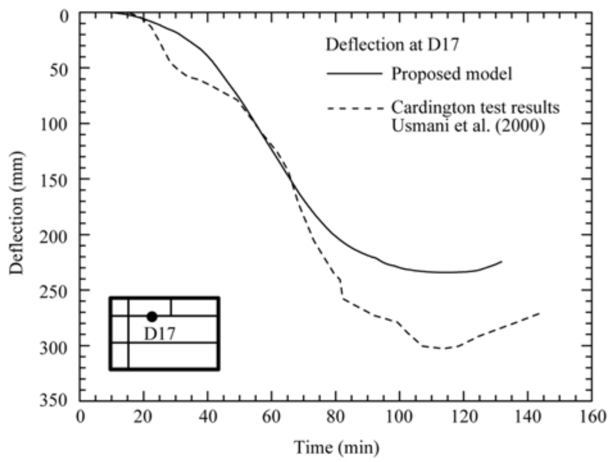


Fig. 21 Predicted beam deflection history (at the circled point, D17) compared with the reported experimental data by Usmani, *et al.* (2000).

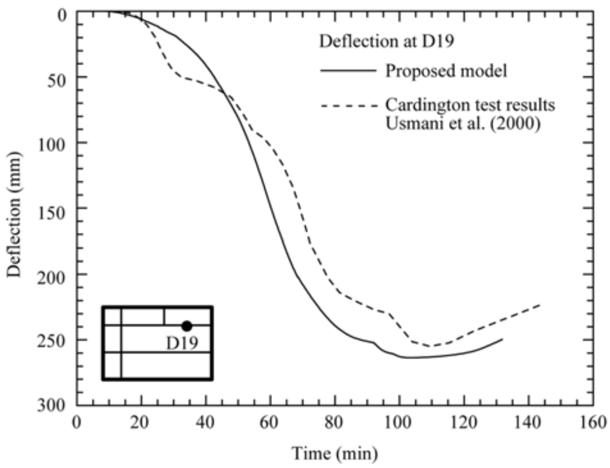


Fig. 22 Predicted beam deflection history (at the circled point, D19) compared with the reported experimental data by Usmani, *et al*. (2000).

Next, we illustrated the importance of performing full-scale fire simulation prior or concurrently with the structural analysis by showing the spatial variation of the temperature and deformations. Fig. 23 showed a table with the non-uniform temperature, deflection, and stresses distributions of the bottom of the concrete slab obtained from the proposed model at 60 and 120 min. The test compartment began to cool down around 100 min after the fire consumed all fire sources as shown in Fig. 14. The contour plots at 60 min and 120 min presented the states during heating and cooling, respectively. The concrete slab temperatures are still increasing, even though the steel beam and air temperatures are going down during the cooling stage. This concrete temperature increment is because the air temperature inside test compartment is relatively higher than the temperature of the concrete slab during this stage. The stresses at the bottom of the concrete slab around steel beam are also increased in compression because

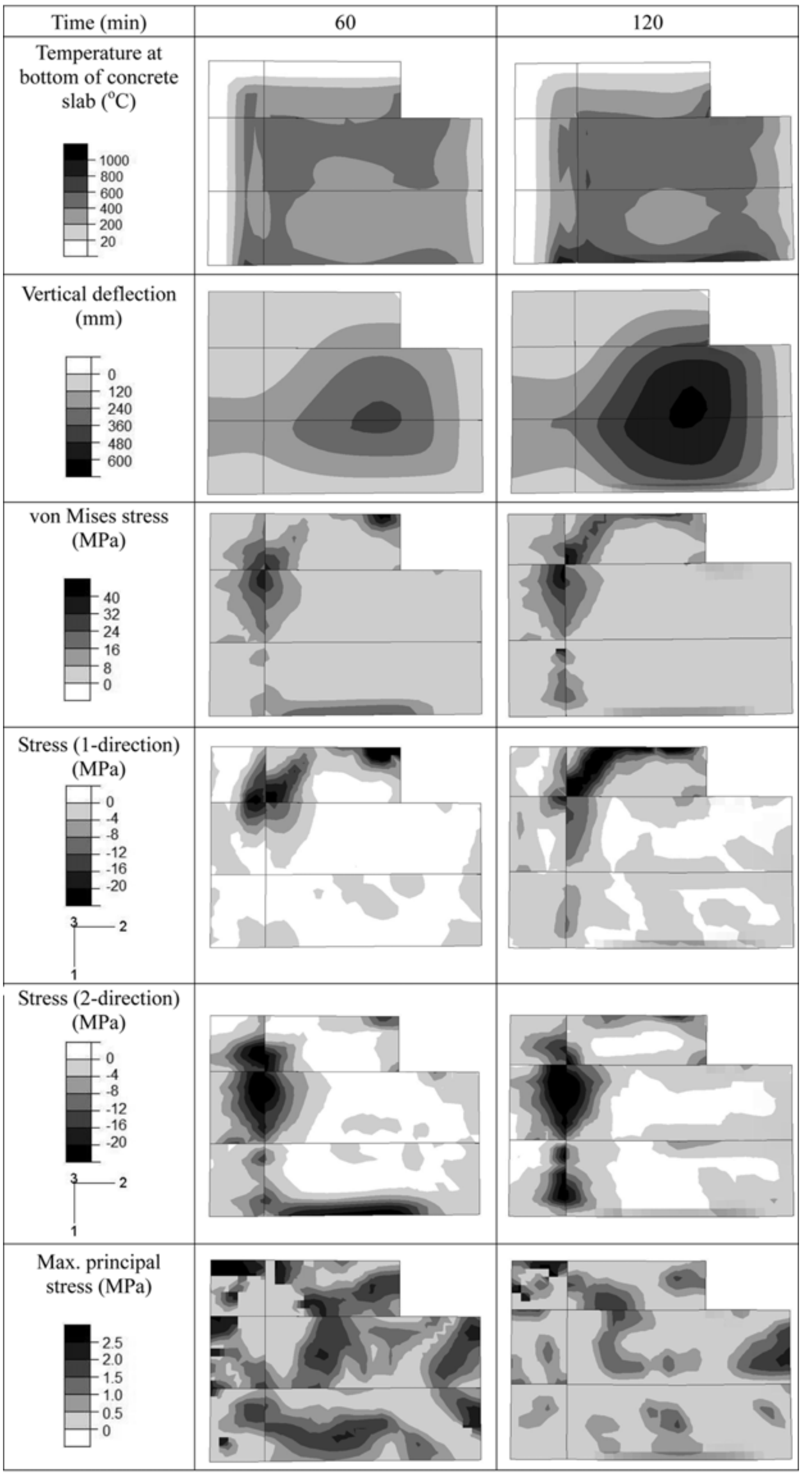


Fig. 23 Predicted spatial distribution of temperature, deflection, and stress contours before and during cooling (topview)

of the relatively big temperature differences between the concrete slab and steel beams. These figures clearly illustrated the importance of performing a full-scale fire simulation to accurately predict the spatial temperature distributions. In addition, the new results highlighted the importance of performing the structural analysis for both heating and cooling fire stages as in the later deformation gradients might also be critical due to damage and geometrical constraints.

6. Conclusions

A new sequential 3D analysis framework is formulated and verified for the thermomechanical response of steel-concrete frame structures under combined thermomechanical loading due to fire. Full-scale simulations using the fire dynamics software (FDS) are performed along with FE structural analysis for both the sequential heat and thermomechanical modeling of the structure under fire. Nonlinear transient heat FE analysis is needed with proper temperature-dependent nonlinear material parameters in order to accurately predict the temperature history within the structure. The concrete chemical reaction during fire is expressed by the change of the effective specific heat as a function of temperature and is shown to have a great influence on the transient heat analysis. A new data reduction scheme has been developed to generate compact ST temperature-dependent polynomial forms from the fire simulations data. Fourth-order polynomials with same order temporal and spatial variables are found to be effective. The new ST approximation, used in the subsequent structural analysis, allows accurate and compact representations of the full-scale refined fire simulation. The proposed analysis framework has been successfully applied to the third Cardington fire test to examine its ability to predict the spatial-temporal distributions and nonlinear structural responses under fire loading during both the heating and cooling stages. In the current analysis modeling, three-part simulations are concurrently carried out. Each simulation is separately but concurrently performed. However, it is possible to conduct fully coupled analysis where fire dynamics and thermomechanical structural analysis are coupled and conducted in a multi-physics analysis framework. This implies a unified formulation and coupling which in theory can be performed. In fact, the current separate formulations can be helpful in the development of this future coupled formulation.

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