http://dx.doi.org/10.14311/asfe.2015.041

Proceedings of the International Conference in Dubrovnik, 15-16 October 2015

A FULLY GENERALISED APPROACH TO MODELLING FIRE RESPONSE OF STEEL-RC COMPOSITE STRUCTURES

Jerneja Kolšek [a], Tomaž Hozjan [b], Miran Saje [b], Igor Planinc [b]

[a] ZAG – Slovenian National Buidling and Civil Engineering Institute, Ljubljana, Slovenia
[b] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia

Abstract

In the paper a new generalised three–phase finite–element numerical model for the fire analysis of beam–like steel–concrete composite structures is presented. In addition, the influence of contact stiffness in a standard trapezoidal RC plate to its ultimate fire resistance is presented employing the proposed numerical procedure.

Keywords: steel-RC composite beams, fire, slip, uplift, moisture transfer.

INTRODUCTION

Modelling the fire response of steel–concrete structures is complex from different perspectives, the latter originating mostly from high–temperature material behaviour (especially those of porous concrete) and contact interactions (i.e. effect of the flexibility of the contact connection between the steel and the concrete layer). In terms of contact interactions the review of the scientific literature has demonstrated that the contribution of the steel layer to the structural fire performance is in the fire design procedures frequently neglected and standard numerical models for RC structures ignoring the layered nature of the structure are applied. This is especially true for RC structures with unprotected thin steel sheet, e.g., as in the case of externally strengthened RC structures (tension face-plated, side-plated RC beams or classic trapezoidal steel-RC floor slabs). Although neglecting the influence of the layer of a thin steel sheet may seem reasonable at first glance, an underestimation of the actual structural fire resistance should be expected. More importantly, potential life-threatening events, such as a sudden premature de-bonding ('peel off') of the steel strengthening layer at unsupported edges, could be overlooked. To avoid these uncertainties, numerical models accounting for both the RC and the steel layers should be developed. Only a few of such can be found in the literature and they are often not sufficiently generalised to describe the behaviour of an arbitrary composite beam in fire (e.g., they assume that the interlayer connection is only deformable in the tangential direction while a rigid contact is taken in the normal direction).

The second important source of the high complexity of the problem is the material models, especially those of concrete being heterogeneous multi-phase material. Concrete consists of the solid matrix (the hardened cement paste), aggregates and pores filled with water (liquid, adsorbed or chemically bound), dry air, and water vapour. In fire, mass fluxes of water and gas inside the pores are triggered following evolution of concentration gradients of fluids and their pressure gradients being a result of phase changes (i.e. water evaporation and vapour condensation) and spatial deviations in concrete permeability. As a result, the heat is not only conducted but also convected through the material affecting the evolution of the concrete temperatures. In addition, as a consequence of the physical and chemical decomposition of concrete and of the stress resulting from external mechanical loads or from the restrained thermal dilatations, substantial cracking and consequential deterioration of the mechanical moduli of concrete as well as the increase of its permeability evolves as well. Together with sufficiently high pore pressures concrete damage can cause concrete spalling and even structural collapse. At date several numerical models are available trying to simulate these complex phenomena. The first group of these is called *the multi-step models* with uncoupled hygro-thermal and mechanical analyses (e.g., Davie *et al.*, 2006). These models are appropriate if negligibly small stress is evolved in the element during fire. As an

alternative, some model proposals are also available for more general cases of concrete structures where the hygro-thermal and mechanical phenomena are coupled fully (e.g. Davie *et al.*, 2010) or indirectly (e.g., Dwaikat and Kodur, 2010).
In this paper the recent improvements in concrete hygro-thermal constitutive models (Davie *et al.*, 2006, Dwaikat and Kodur, 2010) and constitutive models of contact interaction between the layers of composite structures (Kroflič *et al.*, 2010, Kolšek *et al.*, 2013) are brought together and then exploited for the evolution of a novel numerical model for performance-based simulations of fire response of an arbitrary steel-concrete composite beam-like structure. Secondly, the developed model is exploited for parametric studies showing the influence of contact stiffness in a standard trapezoidal RC plate to its fire response and ultimate fire resistance.

1 THE MODEL

The proposed model consists of three uncoupled phases. Firstly, the time development of temperatures of the fire compartment surrounding the structure is calculated. Secondly, the hygro-thermal fluxes within the structure are evaluated and, finally, the mechanical response of the structure during fire is pursued. Within each of the phases, the total duration time of the fire is divided into time intervals $[t^{j-1}, t^{j}]$, and for each of the intervals the basic unknowns of the problem are calculated iteratively.

In the sequel the governing equations of the 2nd and the 3rd phase of the proposed analysis will be summarized briefly. For the sake of simplicity the standard ISO 834 fire curve is selected for these purposes of the 1st phase in this paper. For a detailed description of the proposed model, its governing and its auxiliary equations, the numerical solving procedure as well as corresponding validation analyses the reader is referred to publication of Kolšek *et al*. (2014).

1.1 The heat and mass transfer submodel

The second phase of the model evaluates the time and space distributions of temperatures and pore pressures within the structure. Fourier law of heat conduction is employed for the non-porous steel parts and the model of Davie *et al.* (2006) is selected for the heterogeneous concrete parts. The latter comprises three governing equations of mass conservation of free water, water vapour and dry air:

$$\begin{aligned} \frac{\partial\left(\overline{\rho_{FW}}\right)}{\partial t} &= -\nabla\cdot\mathbf{J}_{FW} - \dot{E}_{FW} + \frac{\partial\left(\overline{\rho_D}\right)}{\partial t}, \\ \frac{\partial\left(\overline{\rho_V}\right)}{\partial t} &= -\nabla\cdot\mathbf{J}_V + \dot{E}_{FW}, \\ \frac{\partial\left(\overline{\rho_A}\right)}{\partial t} &= -\nabla\cdot\mathbf{J}_A, \end{aligned} \tag{1}$$

and the governing equation of energy conservation:

$$\left(\underline{\rho C}\right)\frac{\partial T}{\partial t} = -\nabla\cdot\left(-k\nabla T\right) - \left(\underline{\rho C\mathbf{v}}\right)\cdot\nabla T - \lambda_E\,\dot{E}_{FW} - \lambda_D\frac{\partial\left(\overline{\rho_D}\right)}{\partial t}. \tag{2}$$

In Eqs. (1)–(2), $\mathbf{J}_i$, $\overline{\rho_i}$, E_{FW}, t, $\underline{\rho C}$, k, $\underline{\rho C\mathbf{v}}$, λ_E, λ_D, T denote the mass flux of phase i (FW is free water, V is water vapour and A is dry air), the mass concentration of phase i, the rate of evaporation of free water (including desorption), time, heat capacity of concrete, thermal conductivity of concrete, the energy transferred by fluid flow, the specific heat of evaporation, specific heat of dehydration, and temperature, respectively. The mass fluxes $\mathbf{J}_i$ are derived in terms of pressure and concentration gradients according to the standard Darcy's and Fick's laws. These and all of the other constitutive equations are in the model implemented as proposed by Davie *et al.* (2006) with the exception regarding the time dependent concrete permeability. In contrast to case studies of Davie *et al.* (2006) dealing with problems, where zero 'mechanical' effects in the pressure-driven flow evaluations were expected, such an assumption is no longer valid for general cases of fire exposed structures since the 'mechanical' effects need to be considered explicitly. As suggested by Dwaikat and Kodur (2010), this can be performed indirectly when accounting for the gradients in the initial permeability of concrete, k_0:

$$k_0 = k_{top} \begin{Bmatrix} 10^{2y/D} & y \le x \\ 10^{2y/D}\left(10^{3(y-x)/(D-x)}\right) & y > x \end{Bmatrix}. \tag{3}$$

In Eq. (3) k_{top}, D, y, x refer to initial permeability in the top surface of the concrete section, the depth of the concrete cross-section, the distance from top of the cross-section, and the depth of neutral axis at service load and ambient temperature, respectively. Moreover, at each time station $t > 0$, the permeability of concrete, k is to be evaluated regarding the temperature, T, as well as in terms of the averaged pressure of liquids and gas inside the solid concrete matrix (i.e. pore pressure), P_{pore} (Dwaikat and Kodur, 2010):

$$k = k_0 \left[10^{0.0025(T-T_0)} \left(\frac{P_{\text{pore}}}{P_0} \right)^{0.368} \right]. \tag{4}$$

1.3 The stress-strain evolution submodel

Once the temperature and pore pressure variation in time and space has been obtained, the stress-strain state evolution in the beam during fire is to be defined. To be able to do that, in the mechanical submodel both of the layers of the analysed composite beam-like structure are modelled separately, each by the geometrically exact theory of a planar beam. The related governing equations of the layer 'i ' are ($i = a,b$ with 'a' representing the RC layer and 'b' representing the steel layer):

- kinematic:
- equilibrium:
- constitutive:

$$\begin{aligned} &1+u^{i}{}'-\left(1+\varepsilon^{i}\right)\cos\varphi^{i}=0, && R_X^{i}{}'+\mathscr{P}_X^{i}=0, && N^{i}=\int_{\mathscr{A}_x^{i}}\sigma^{i}\left(D_\sigma^{i},T\right)dA-N_p^{i}, \\ &w^{i}{}'+\left(1+\varepsilon^{i}\right)\sin\varphi^{i}=0, && R_Z^{i}{}'+\mathscr{P}_Z^{i}=0, && M^{i}=\int_{\mathscr{A}_x^{i}}z\sigma^{i}\left(D_\sigma^{i},T\right)dA-M_p^{i}. \\ &\varphi^{i}{}'-\kappa^{i}=0, && M^{i}{}'-\left(1+\varepsilon^{i}\right)Q^{i}+\mathscr{M}_Y^{i}=0, && \end{aligned} \tag{5}$$

In Eqs. (5) $(\ -\ )'$, u^i, w^i, φ^i, ε^i, κ^i, R^i_X, R^i_Z, N^i, Q^i, M^i, $\mathscr{P}^i_X$, $\mathscr{P}^i_Z$, $\mathscr{M}^i_Y$ denote the derivative with respect to material coordinate x, the X-displacement, the Z-displacement and the rotation of the reference axis of the layer 'i', its extensional and bending strains (the curvature), the components of the cross-sectional stress-resultants with respect to the fixed basis ($\boldsymbol{E}_X$, $\boldsymbol{E}_Y$, $\boldsymbol{E}_Z$), i.e. the cross-sectional axial force, the shear force and the bending moment, and components of the traction vectors $\boldsymbol{\mathscr{P}}^{\mathrm{i}}$ and $\boldsymbol{\mathscr{M}}^{\mathrm{i}}$ representing static equivalents of surface and volume forces after being reduced to the layer's reference axis, respectively. Moreover, N^i_p and M^i_p are the contributions of pore pressures in the total stress of the layer 'i' (the well-known Terzaghi's principle) which are equal to zero when the non-porous steel layers are considered (i.e. for $i = b$). Furthermore, σ^i and D^i_σ are stress and mechanical strain of a generic particle of the layer 'i', and the relation $\sigma^i(D^i_\sigma,T)$ is the material constitutive law of concrete/steel at high temperatures (accounting also for elastic reloading and kinematic hardening of cyclically loaded and reloaded material). The following equation applies for calculation of $D^{i,j}$:

$$D^{i,j} = D^{i,j-1} + \Delta D^{i,j}. \tag{7}$$

with $\Delta D^{i,j}$ being the increment of the total strain of the layer '*i*' in the time interval *j*. According to the standard principle of additivity of strains we assume that $\Delta D^{i,j}$ is the sum of the strain increments due to temperature, $\Delta D^{i,j}_{th}$, stress, $\Delta D^{i,j}_{\sigma}$, creep, $\Delta D^{i,j}_{cr}$, and (for concrete only) transient strains, $\Delta D^{i,j}_{tr}$:

$$\Delta D^{i,j} = \Delta D^{i,j}_{th} + \Delta D^{i,j}_{\sigma} + \Delta D^{i,j}_{cr} + \Delta D^{i,j}_{tr} \, . \tag{8}$$

Finally, by decomposing the traction (load) vectors of both layers with respect to their external (index '*e*') and the contact (index '*c*') contributions:

$$\mathscr{P}^i = \mathscr{P}^i_e \pm \mathscr{P}^i_c \quad \text{and} \quad \mathscr{M}^i = \mathscr{M}^i_e \pm \mathscr{M}^i_c \, , \tag{9}$$

the equations of the steel and the concrete layers of the composite beam are finally coupled. Since the contact contributions, $\mathscr{P}_c^i$ and $\mathscr{M}_c^i$ (where $\mathscr{P}_c^a = -\mathscr{P}_c^b$ and $\mathscr{M}_c^a = -\mathscr{M}_c^b$), depend on the longitudinal (ΔU) and transversal (ΔW) slips or uplifts between the layers, thus, $\mathscr{P}_c^i = f(\Delta U, \Delta W)$ and $\mathscr{M}_c^i = g(\Delta U, \Delta W)$. Here f and g are functions determined by experiments for the actual type of the contact connection.

2 THE CASE STUDY

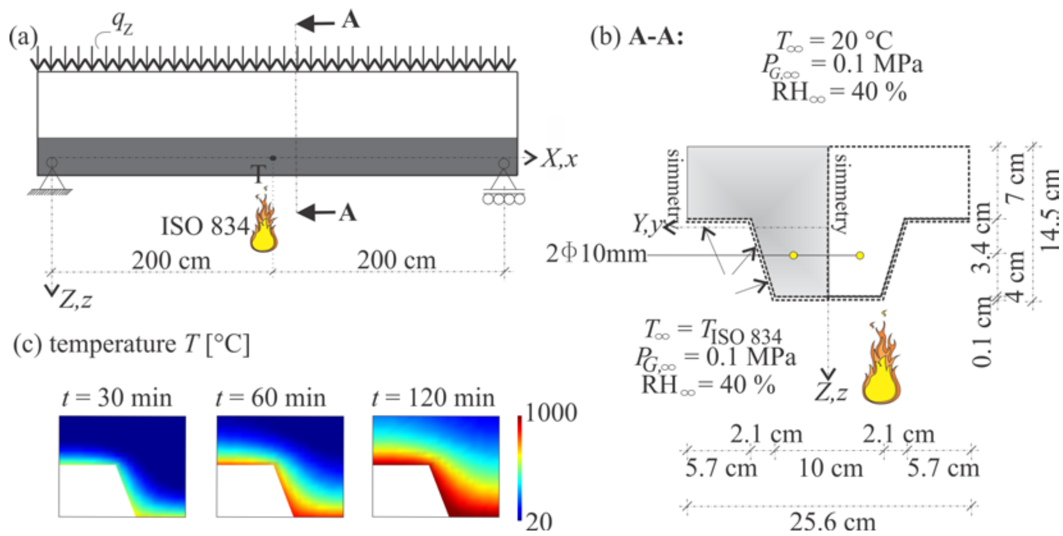

Fig. 1: The case study: Geometrical data, loading data, reinforcement data and the hygro-thermal boundary conditions.

In the sequel we investigate the effect of the contact stiffness on the fire resistance of a simply supported steel-RC trapezoidal composite plate exposed to ISO 834 fire conditions. With the model proposed in Section 1 a typical rib of the slab (Fig. 1) is analysed. In the hygro-thermal step of the calculation, the hygro-thermal properties of a standard normal strength concrete are chosen (see publication Kolšek *et al.*, 2014, for details) and only the concrete part of the cross-section is modelled while neglecting thermal effects of the steel sheet. In the mechanical analysis, the following material data are taken to be valid at room temperature: yield strength of the steel sheet $f_{y,20} = 28$ kN/cm^2, compressive strength of concrete $f_{c,20} = 3$kN/cm^2, and yield strength of steel of the rebars $f^r_{y,20}$=40 kN/cm^2 (note that one rebar is put in each rib of the slab). The high-temperature stress-strain law for steel follows EC3. Since in the EC3 material model, the creep strain in steel is integrated within the plastic strain, creep is not treated in an additive manner in this example. The stress-strain relationship for concrete is taken from EC2 (silicieous concrete). Following the recommendations of Bratina *et al.* (2005) the effects of creep and transient strains in concrete are treated explicitly (see publication Kolšek *et al.*, 2014, for details). Finally, the contact constitutive law at room temperature is selected as:

$$p_{cn,t}^{a,*}(x,z) = A\tau_{cn,t,20,max}(1 - e^{-B\Delta^*}), \tag{10}$$

$$p_{cn,n}^{a,*}(x,z) = A\tau_{cn,n,20,max}(1 - e^{-Bd^*}), \tag{11}$$

where delta Δ^* are slips and denotation d^* represents uplifts at the interlayer contact. Considering the lack of suitable contact law data available in the literature, the above law is only hypothetical and was constructed similarly as in the publication of Huang *et al.* (1999) where bolted connections for composite structures are discussed. The values of parameters A and B were in the equations taken in the same manner as in Huang *et al.* (1999).

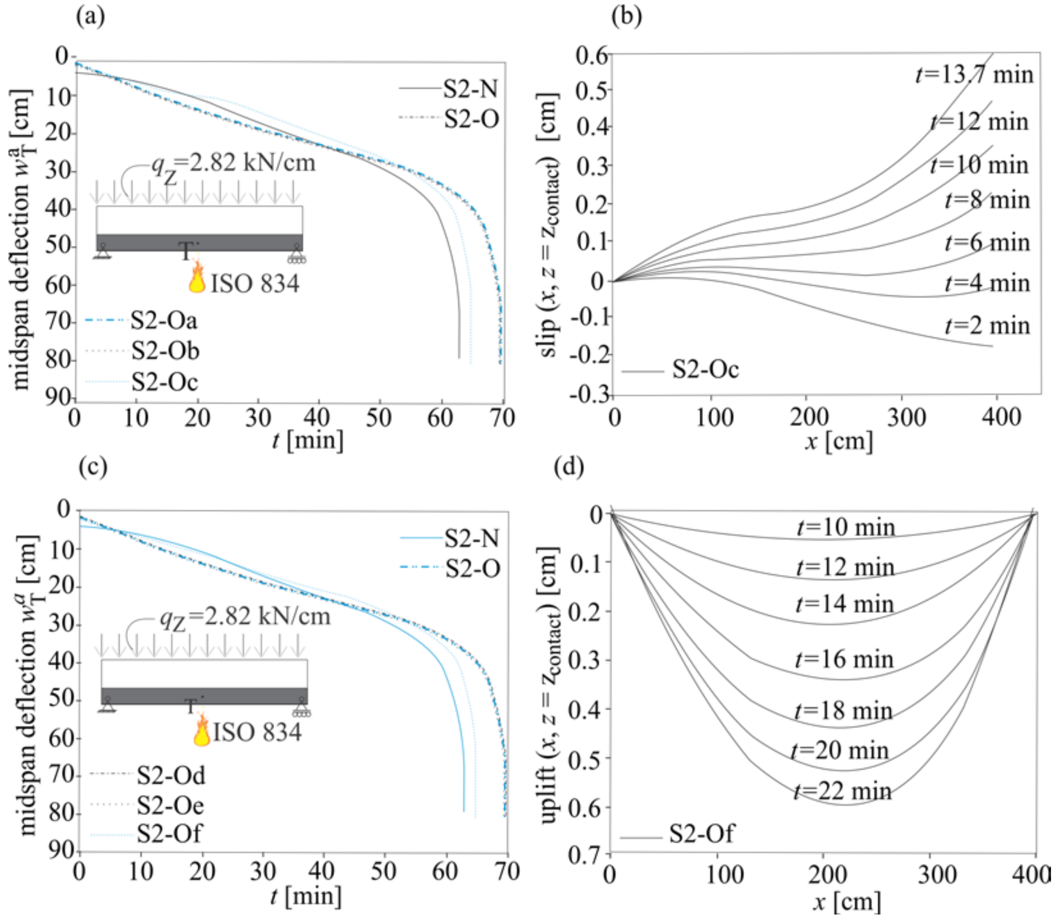

Fig. 2: The time-deflection curves and slip/uplifts evolved along the steel-concrete interlayer contact for cases S2-O to S2-Of.

Fig. 2 demonstrate results of the parametric studies focusing on the influence of the tangential/longitudinal ($\tau_{cn,t,20,max}$) and normal/transversal ($\tau_{cn,n,20,max}$) interlayer contact stiffness. All studied cases refer to the initial case S2-O where the corresponding values of $\tau_{cn,t,20,max}$ and $\tau_{cn,n,20,max}$ are both defined as 0.59 kN/cm. In cases S2-Oa, S2-Ob, and S2-Oc (Figs. 2a and 2b) $\tau_{cn,n,20,max}$ is then left at value 0.59 kN/cm and $\tau_{cn,t,20,max}$ is varied. Firstly (case S2-Oa) $\tau_{cn,t,20,max}$ is increased substantially to model a tangentially rigid connection and then for cases S2-Ob and S2-Oc $\tau_{cn,t,20,max}$ is reduced to half and fifth of the value selected for case S2-O, respectively. Furthermore, in exploring the effects of normal contact stiffness, in cases S2-Od, S2-Oe, and S2-Of (Figs. 2c and 2d) $\tau_{cn,t,20,max}$ is fixed at 0.59 kN/cm and $\tau_{cn,n,20,max}$ is varied. Three values of the latter are discussed, namely, beside $\tau_{cn,n,20,max}$ = 0.59 kN/cm (starting case S2-O) also $\tau_{cn,n,20,max}$ = 5.9 kN/cm (case S2-

Od), $\tau_{cn,n,20,max}$ = 0.059 kN/cm (case S2-Oe), and, finally, $\tau_{cn,n,20,max}$ = 0.0059 kN/cm (case S2-Of). The results of all of the described studies are displayed in Figs. 2a and 2c (the midspan deflection) and in Figs. 2b and 2d (interlayer slips and uplifts). In all cases (when varying either the tangential or the normal contact stiffness) an only small effect of both parts of the contact stiffness on the deflection and on the ultimate structural fire resistance is observed if the contact is sufficiently stiff (cases S2-O, S2-Oa, S2-Ob, S2-Od, and S2-Oe). If, by contrast, a too flexible connection (like in case S2-Oc or S2-Of) is designed, such that the contact fails prior to the bearing capacity of the RC deck is achieved, a substantial reduction of the fire resistance time occurs. For comparison, results of case S2-N, where only the RC part of the plate without the steel sheet is discussed, is shown as well. It's obvious that the fire resistance of such a beam (S2-N) is noticeably smaller in comparison with analyzed RC-steel beams.

REFERENCES

Bratina S., Čas B., Saje M., Planinc I., 2005. Numerical modelling of behaviour of reinforced concrete columns in fire and comparison with Eurocode2. International Journal of Solid and Structures, 42(21-22), p. 5715–5733.

Davie C.T., Pearce C.J., Bićanić N., 2006. Coupled heat and moisture transport in concrete at elevated temperatures - Effects of capillary pressure and adsorbed water. Numerical Heat Transfer, Part A: Applications, 49 (8), p. 733 – 763.

Davie C.T., Pearce C.J., Bićanić N., 2010. A fully generalised, coupled, multi-phase, hygro-thermo-mechanical model for concrete. Materials and Structures, 43 (1), p. 13-33.

Dwaikat M. B., Kodur V. K. R., 2010. Fire induced spalling in high strength concrete beams. Fire Technology, 46 (1), 251 – 274.

Huang Z., Burgess I., Plank R., 1999. The influence of shear connectors on the behaviour of composite steel-framed buildings in fire. Journal of Constructional Steel Research, 51 (3), p. 219–237.

Kolšek, J., Planinc, I., Saje, M., Hozjan, T. 2013. The fire analysis of a steel–concrete side-plated beam. Finite Elements in Analysis and Design, 74 (15), p. 93–110.

Kolšek J., Saje M., Planinc I., Hozjan T. 2014. A fully generalized approach to modelling fire response of steel-RC composite structures. International Journal of Nonlinear Mechanics, 67, p. 382–393.

Kroflič A., Saje M., Planinc I., 2011. Non-linear analysis of two-layer beams with interlayer slip and uplift, Computers and Structures, 89 (23-24), p. 2414–2424.