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FIRE ANALYSIS OF CURVED REINFORCED CONCRETE BEAM

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Abstract
In the present study the fire analysis of a curved reinforced concrete beam exposed to concrete spalling is presented. Due to the complexity of physical and chemical processes in concrete at elevated temperatures, the proposed numerical model is divided into two consecutive mathematically uncoupled phases. In the second phase of the fire analysis a partially coupled numerical model is introduced in order to evaluate the effect of concrete spalling on the behaviour of curved RC beam in fire. In addition, the effect of depth, time development and the length of spalling area on the fire resistance of a curved RC beam is discussed.

Keywords: Curved RC beam, Fire, Spalling of concrete, Moisture transfer.

1 INTRODUCTION

Fire safety of the tunnel structures is an important requirement that in general every engineering structure must fulfil. Insufficient level of fire safety can lead into human loss, material damage and pollution of environment. Tunnel structures are usually made of concrete which is heterogeneous material consisting of solid matrix, water and gaseous mixture of dry air and water vapour. When concrete structures are exposed to high temperatures as can be found in fire physical and chemical processes within concrete structure occur. These can lead to unfavourable effect of explosive spalling of concrete, which can cause premature failure of the tunnel structure. The influence of spalling process needs to be taken into account in order to achieve better assessment of the fire resistance.

This study presents a novel partially coupled strain-based finite-element numerical model for assessing the fire resistance of curved RC beams exposed to spalling of concrete. The idea of the introduced model is to evaluate the time and the magnitude of concrete spalling on the behaviour of curved RC beam in fire conditions. Due to concrete spalling, which is based on the proper parameters (temperature, pore pressure,...), the cross-section of the observed beam is reduced by the layer of concrete that spalls/peels off. The reduction of the cross-section has effect on the mechanical behaviour and also on the temperature field of the analyzed beam and therefore has to be taken into account. In presented study the effect of depth, time development and length of spalling area on the behaviour of curved RC beam in fire situation is presented. The introduced numerical model can be used for the evaluation of the fire resistance of tunnel lining in natural fire conditions.

2 PARTIALLY COUPLED NUMERICAL MODEL

Introduced partially coupled numerical model for the fire analysis of curved RC beam is due to the complexity of physical and chemical processes in concrete at elevated temperatures divided into two consecutive mathematically uncoupled phases. The first phase is dedicated to the determination of time and spatial development of temperatures in the fire compartment. Thus hydrocarbon fire curve (EC1, 2004) is used in the study for describing gas temperatures in the fire compartment, which are used as input parameters for the second phase. In the second phase of the fire analysis the heat and mass transfer in concrete and mechanical part (stress-strain state of structure) are partially coupled. The heat and mass transfer in concrete is based on the model proposed by Davie (Davie et

al., 2006) and in the mechanical part of the fire analysis curved RC beam is modelled with the kinematically exact planar beam model of Reissner (Reissner, 1972). The system of governing equations is solved numerically using the modified principle of virtual work and a strain-based Galerkin-type of FEM (Planinc, 2001).
Further a brief presentation of heat and mass transfer model and mechanical part is given. The algorithm of the partially coupled numerical model for the fire analysis of curved RC beam with concrete spalling involved is described as well.

2.1 Heat and mass transfer model – 1st part of partially coupled numerical model

The heat and mass transfer in concrete is described by the system of equations proposed by Davie et al. (2006). Model considers the transfer of free water, water vapour and dry air caused by pressure and concentration gradients and the conversion of energy, and also takes into account the evaporation of water, the liquefaction of water vapour, the dehydration of the chemically bound water, the capillary pressure and the part of free water, coexisting in an adsorbed state. The governing equations of heat mass transfer model are solved numerically with the Galerkin-type of the finite element method employing 4-noded two dimensional (2D) isoparametric elements. The primary unknowns of the problem are temperature T, pressure of gaseous mixture of water vapour and dry air P_G and water vapour content $\overline{\rho_V}$. For detailed description of the model see (Davie et al., 2006).

2.2 Mechanical part of numerical model – 2nd part of partially coupled numerical model

The mechanical model of the curved RC beam is modelled with the kinematically exact planar beam model of Reissner (Reissner, 1972). Within time interval $[t^{i-1}, t^{i}]$, i = 1, 2,...,n_{cr}, the stress-strain state at time station t^i is calculated iteratively based on the mechanical results at time t^{i-1} and the results from the hygro-thermal analysis (1st part of partially coupled numerical model) at time t^i. The related governing equations of curved RC beam consist of kinematic, equilibrium and constitutive equations:

Kinematic equations:

$$x' + u' - (1+\varepsilon)\cos\varphi - \gamma\sin\varphi = 0,$$
$$z' + w' + (1+\varepsilon)\sin\varphi - \gamma\cos\varphi = 0,$$
$$\varphi' - \kappa_0 - \kappa = 0,$$

Equilibrium equations:

$$R_X' + p_X = 0,$$
$$R_Z' + p_Z = 0,$$
$$M' - (1+\varepsilon)Q + \gamma N + m_Y = 0,$$
$$N = R_X\cos\varphi - R_Z\sin\varphi,$$
$$Q = R_X\sin\varphi + R_Z\cos\varphi,$$

Constitutive equations:

$$N - N_C = 0,$$
$$Q - Q_C = 0,$$
$$M - M_C = 0. \qquad (1)$$

In equations (1) the prime $(\circ)'$ denotes the derivatives with respect to arch length s. Variables u and w are the components of a displacement vector and φ is the rotation of a cross-section at the reference axis. Variable ε and γ are extensional and shear strains, respectively, while κ represents the pseudo curvature (flexural deformation) of the beam reference axis. N, Q and M represent equilibrium generalized internal forces, while N_C, Q_C and M_C denote constitutive generalized internal forces. According to the given stress and strain state on the time interval i–1 and temperature on the time interval i, the mechanical strains $D^i = \varepsilon^i + z\kappa^i$ on the time interval i of any point in the curved beam can be calculated by the equation:

$$D^i = D^{i-1} + \Delta D^i, \qquad (2)$$

where ΔD^i is the increment of the total strains (also known as the 'geometrical deformations') in the time interval i. Considering the principle of additivity of strains we end up with the strain increment, ΔD^i, as the sum of the strain increments due to temperature, ΔD^i_{th}, stress, ΔD^i_{σ}, creep, ΔD^i_{cr}, and transient strains of concrete, ΔD^i_{tr}:

$$\Delta D^i = \Delta D^i_{th} + \Delta D^i_{\pm} + \Delta D^i_{cr} + \Delta D^i_{tr} \tag{3}$$

For a detailed description of each strain increment, see Hozjan *et al*. (2011) and for detailed description of the proposed model a reader is referred to Ružić *et al.* (2015). The non-linear stress-strain relations for concrete and reinforcement steel at elevated temperatures and the rules for the reduction of material parameters due to an increased temperature are taken from European building code EC2 (2005).

2.3 Algorithm of partially coupled numerical model

The criteria for the commencement of concrete spalling and for the evaluation of the depth of the spalled layer are taken according to Gawin *et al*. (2006). The conditions are slightly modified, so the spalling process starts, when the pore pressure reaches maximum value and at the same time temperatures reach values between 200 and 250 ^{o}C. In general the heat and mass transfer analysis and the mechanical analysis are carried out in parallel. When the algorithm detects that the conditions for the start of explosive spalling (Gawin *et al*., 2006) are fulfilled, the change of the finite element mesh with corresponding boundary conditions is executed. The process can be repeated several times within the entire fire analysis. However, since the modified geometry of the cross-section, especially in the heat and mass transfer part, presents a numerical 'shock', an appropriate reduction of time step and adequate resizing of the finite element mesh are needed. The algorithm is simple but necessary for the proper assessment of the fire safety of curved RC beams exposed to concrete spalling. The procedure of the algorithm is shown below; for the sake of transparency the time increment for both parts of the partly coupled numerical model is the same size.

The algorithm of partially coupled numerical model:

- 1st phase
  - The determination of the temperature field in the fire compartment;
- 2nd phase
  - Step 1: time increment [t^{i-1}, t^{i}]:
    - Heat and mass transfer analysis → T, P_{G}, $^{\circ}{}_{V}$;
    - Mechanical analysis → stress-strain state of the curved RC beam;
    - The conditions for the start of spalling is checked;
  - Step 2: Check of conditions for the explosive spalling of curved RC beam:
    - If YES → re-meshing of the finite element mesh and reduction of the time step Δt;
    - If NO → continue to step 3;
  - Step 3: New time step
    - $t^{i+1} = t^{i} + \Delta t$;
    - Repeat Step 1 and 2 until the failure of curved RC beam or the end of fire;

Note. Considering a comparison also uncoupled numerical model is used (Ružić *et al*., 2015). Important difference compared to the partially coupled numerical model is that the parts (hygro-thermal and mechanical part) of the second phase of the fire analysis are performed separately as a continuing process. Therefore the effect of spalling is considered only in the mechanical part of the fire analysis in the form of reduced height of the cross-section. Meaning the temperature state of the cross-section is determined on initial structure and does not change within the analysis.

3 NUMERICAL EXAMPLE OF CURVED RC BEAM EXPOSED TO SPALLING

In the parametric study curved RC beam exposed to the standard hydrocarbon fire curve as given in EC1 (EC1, 2004) is considered. Geometrical, cross-sectional, material, reinforcement and loading data of the problem are shown in Fig. 1, where also the position of symmetric and asymmetric form of spalling is shown. Other data used in the calculations are: density of concrete 2400 kg/m^3, density of cement per unit volume of concrete 300 kg/m^3, initial temperature 20 ^{o}C, initial pore pressure 0.1 MPa, initial water vapour content per unit volume of gaseous mixture 0.013 kg/m^3, boundary water vapour content per unit volume of gaseous mixture 0.104 kg/m^3, initial porosity of concrete 0.15, initial permeability of concrete $1\cdot10^{-16}$ and saturation water content at room temperature 100 kg/m^3.

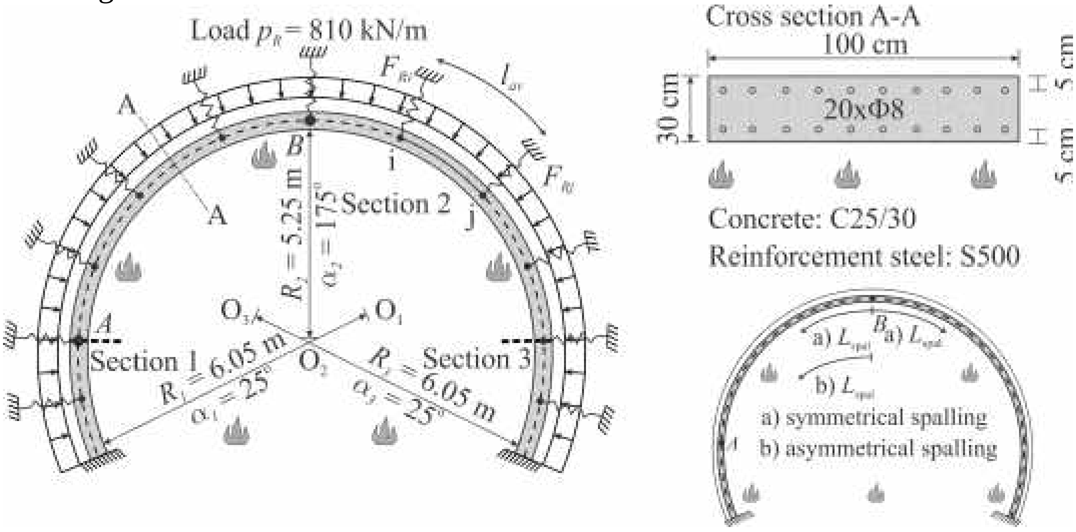

Fig. 1 Geometrical and material properties of the curved RC beam and the examples of spalling

Spalling occurs after 23 min of fire at the depth of d_{spal} = 3 cm from the exposed edge of the observed beam. In the case of symmetric spalling (noted as S), the cross-section of the curved RC beam is reduced on both sides of reference point B and the length of spalling is equal to L_{spal}. While in the case of asymmetric spalling, only cross-sections positioned left from reference point *B* are influenced by the spalling process in the range of L_{spal} (Fig. 1). The aim of the parametric study is to evaluate the influence of the length of spalling L_{spal} on the fire resistance of curved RC beam. The restraining forces F_R (Fig. 1) that represent the effect of soil are activated only when the beam moves toward the soil and are a nonlinear function of the Young's modulus of soil E_{soil}. Full description of constitutive law and determination of F_R is given in Ružić *et al*. (2015). Here, in the parametric study two types of soil are considered E_{soil} = 10 MPa and E_{soil} = 30 MPa.
The distribution of temperatures and pore pressures for partially coupled and uncoupled model are depicted on Fig. 2. For the sake of transparency the results are shown up to 15 cm of a cross-section height.

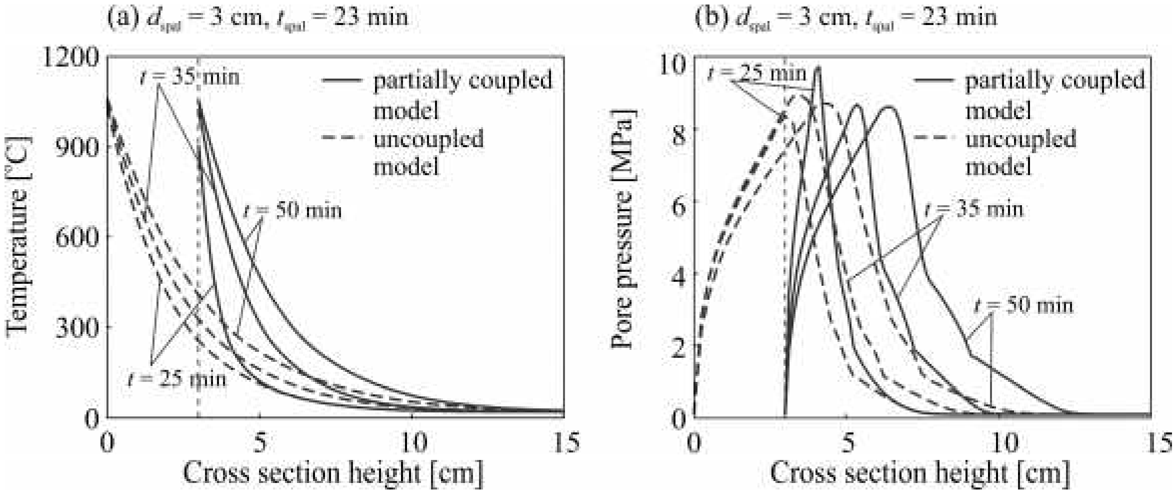

Fig. 2 Distribution of (a) temperature and (b) pore pressure over the height of cross-section at 25, 35 and 50 min

The difference between the distribution of temperatures for partially coupled and uncoupled model is significant, which can be observed in the area of spalling where a huge leap in temperatures for partially coupled model happens. As observed the difference between partially coupled and uncoupled model decreases with the height of the cross-section. Meaning the distribution of temperatures and pore pressure approximately 10 to 15 cm from the exposed edge of the initial section is the same for both models. Proper distribution of temperatures over the cross-section is very important because in the mechanical part of the fire analysis it directly affects the material properties of concrete, and thus the capacity and stability of the arc.
Critical times t_{cr} of the curved RC beam exposed to fire for partially coupled numerical model are given in Table 1. Critical times t_{cr} are more pronounced for the asymmetric form of spalling. As anticipated t_{cr} of the curved RC beam decreases with the length of spalling L_{spal}. Though, a little surprising is the re-increase of the critical time for biggest lengths of spalling. This inconsistency is present in symmetric and asymmetric shape of spalling and for both types of soil. The increased stiffness of soil has positive effect on the critical times of arc for both forms of spalling. For instance, in the case of symmetrical spalling for E_{soil} = 30 MPa the beam fails only for $L_{spal} \geq 600$ cm, while for E_{soil} = 30 MPa failure occurs for $L_{spal} \geq 300$ cm.

Table 1 Critical times t_{cr} for different values of L_{spal} for spalling case d_{spal} = 3 cm

	E_{soil} = 10 MPa		E_{soil} = 30 MPa	
	symmetrical spalling	asymmetrical spalling	symmetrical spalling	asymmetrical spalling
L_{spal} [cm]	t_{cr} [min]	t_{cr} [min]	t_{cr} [min]	t_{cr} [min]
100	> 180	136	> 180	> 180
200	> 180	97	> 180	> 180
300	156	74	> 180	> 180
400	112	62	> 180	150
500	91	59	> 180	106
600	81	68	159	98
700	87	91	136	108

The deformed configurations of observed beam for the length of spalling L_{spal} = 400 cm are depicted on Fig 3. The results are presented for critical time t_{spal} = 23 min when spalling occurs. In general the displacements in horizontal direction are larger than in vertical direction, which is caused by the action of springs that simulate the influence of soil. The effect of asymmetric shape is clearly noticed as the whole deformed shape of curved RC beam is shifted towards the direction of the spalling; in this case to the left side of the arc.

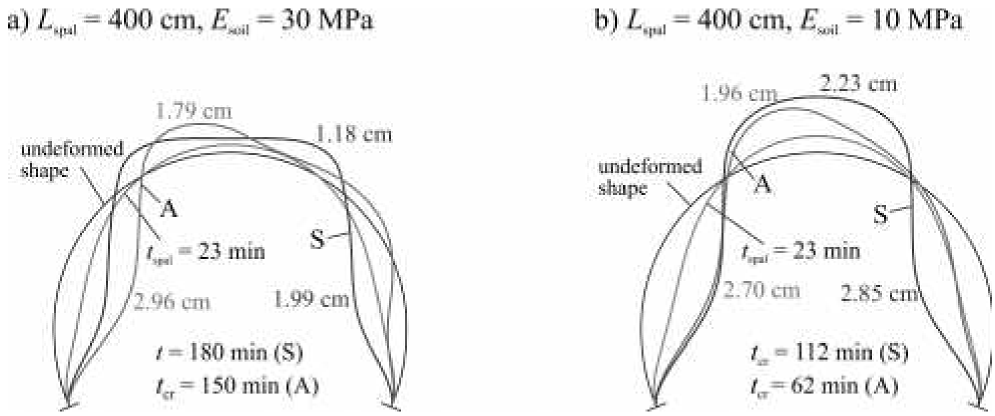

Fig. 3 Displacements in reference nodes A and B for spalling case d_{spal} = 3 cm and two types of soil (a) E_{soil} = 30 MPa and (b) E_{soil} = 10 MPa

In the case of less rigid soil (E_{soil} = 10 MPa) the displacements are more pronounced for the asymmetrical case of spalling, while for more rigid soil (E_{soil} = 30 MPa) the direct opposite holds true (Fig. 3).
At the end of the parametric study the comparison between partially coupled and uncoupled approach is made. The results for critical time t_{cr} of the curved RC beam for the length of spalling L_{spal} = 600 cm and the depth of spalling d_{spal} = 3 cm are given in Table 2. The difference between critical times for partially coupled and uncoupled model is rather high. For instance in case of less rigid soil and asymmetrical form of spalling the critical time for uncoupled model is almost two times bigger from the critical time for partially coupled model. This indicates that for proper assessment of the fire resistance of RC arcs accurate as possible temperature field is needed.

Table 2 Critical times t_{cr} for partially coupled and uncoupled model (L_{spal} = 600 cm, d_{spal} = 3 cm)

E_{soil} = 10 MPa				E_{soil} = 30 MPa			
symmetrical spalling		asymmetrical spalling		symmetrical spalling		asymmetrical spalling	
t_{cr} [min]		t_{cr} [min]		t_{cr} [min]		t_{cr} [min]	
partially coupled	uncoupled	partially coupled	uncoupled	partially coupled	uncoupled	partially coupled	uncoupled
81	142	68	123	159	> 180	98	> 180

4 CONCLUSIONS

A novel partially coupled strain-based finite-element numerical model for assessing the fire resistance of curved RC beams exposed to concrete spalling was presented. The temperature field in concrete was determined with a coupled model of slow transient phenomena involving heat and mass transport and pore pressure increase. Furthermore, the strain-based non-linear beam finite-element was employed in the mechanical analysis. The parametric study of a curved RC beam in fire indicates that adopting the partially-coupled or fully-coupled models is a must in order to adequately assess the structural safety of concrete structures exposed to fire, especially when properties of the concrete (HPC), thermal field and applied loads favour concrete spalling.

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REFERENCES

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, p. 733-763.

Gawin D., Pesavento F., Schrefler B.A., 2006. Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete. Comput. Meth. Appl. Mech. Eng., 195, p. 5707-5729.

Hozjan T., Saje M., Srpčič S., Planinc I., 2011. Fire analysis of steel-concrete composite beam with interlayer slip. Comput. Struct., 89(1-2), p. 189-200.

Planinc I., Saje M., Čas B., 2001. On the local stability condition in the planar beam finite element. Struct. Eng. & Mech., 12(5), p. 507-526.

Reissner E., 1972. On one-dimensional finite-strain beam theory: The plane problem. Journal of Applied Mathematics and Physics (ZAMP), 23, p. 795-804.

Ružić D., Kolšek J., Planinc I., Saje M. Hozjan T., 2015. Non-linear fire analysis of restrained curved RC beams, Engineering Structures, 84, p. 130-139.

EN 1991-1-2, 2004, Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire, 2004.

EN 1992-1-2, 2005, Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design.