FIRE ANALYSIS OF PARTLY DELAMINATED CURVED CONCRETE STRUCTURES

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Fire Engineering Research - Key Issues for the Future II, 6-9 June 2013, Naples, Italy

Introduction, Idea, Motivation

- *FIRE SAFETY ENGINEERING* :
  important part in designing and building of engineering structures;
- *CURVED RC BEAMS:*
  used in industrial structures,
- *REINFORCED CONCRETE:*
  heterogeneous material consisting of solid matrix, water and gaseous mixture of dry air and water vapour;
  chemical and physical processes occur in RC exposed to fire → cause lower load bearing capability and stability of structures;
- NUMERICAL MODEL:
  fire analysis of partly delaminated curved concrete structures (in our case two connected curved RC beams);

- GOALS OF OUR RESEARCH:

  → non linear analysis of 2 connected curved RC beams exposed to mechanic and fire load;
  → consider possible uplift and slip at the contact plane between two connected curved RC beams;
  → evaluate behavior of tunnels in fire condition → based on the knowledge obtained from the fire analysis of 2 connected beams;

Numerical model for fire analysis

THREE BASIC STEPS:

1st step: temperatures of the fire compartment

2nd step: heat and mass transport model

3rd phase: mechanical model

1ST STEP: TEMPERATURES OF THE FIRE COMPARTEMENT

- time dependent change of temperatures in a fire compartment is determined;
- temperatures of the fire compartment are accounted for in boundary conditions in the next step of the fire analysis (hygro-thermal step);

Temperature of the fire compartment

Parametric temperature-time curves:
→ i.e. hydrocarbon fire curve (SIST EN 1991-1-2:2004)
→ simpler method

CFD methods:
→ i.e. FDS
→ more complex method
→ requires appropriate fire scenario

Tunnels:
– vast fire compartment,
– temperatures during fire distributed unevenly,
– CFD needed for fire analysis.

2ND STEP: HEAT AND MASS TRANSPORT MODEL

- defines coupled heat and moisture transfer in concrete exposed to fire
  (three governing equations of mass conservation of free water, water vapour and dry air and a governing equation of energy conservation → Davie et al., 2006)
  → primary unknowns: temperature T, pressure of gaseous mixture of water vapour and dry air P_G and water vapour content $\overline{\rho_V}$, FEM (Matlab)

Free water conservation:

$$\frac{\partial(\rho_{FW})}{\partial t} = -\nabla \mathbf{J}_{FW} - \dot{E}_{FW} + \frac{\partial(\rho_D)}{\partial i}$$

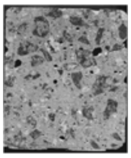
Water vapour conservation:

$$\frac{\partial(\rho_V)}{\partial t} = -\nabla \mathbf{J}_V + \dot{E}_{FW}$$

Air conservation: $\frac{\partial(\rho_A)}{\partial t} = -\nabla \mathbf{J}_A$

Energy conservation:

$$(\rho C)\frac{\partial T}{\partial t} = -\nabla \cdot (-k\nabla T) - (\rho C \mathbf{v}) \cdot \nabla T - \lambda_E \dot{E}_{FW} - \lambda_D \frac{\partial(\rho_D)}{\partial t}$$



3RD STEP: MECHANICAL MODEL

- defines the stress-strain state of two connected curved RC beams during fire

→ kinematically exact planar beam model (Reissner, 1972),
→ new strain-based planar curved beam finite-element (FEM),
→ total strain $D^t = \varepsilon^t + z\kappa^t$ on time interval t can be calculated by the equation $D^t = D^{t-1} + \Delta D^t$ for both beams (layers), ΔD^t - increment of total strain,
→ principle of additivity:
increment of total strain ΔD^t is the sum of strain increments due to temperature, stress and creep in concrete and steel, plus transient strains in concrete: $\Delta D^t = \Delta D^t_{th} + \Delta D^t_{\sigma} + \Delta D^t_{cr} + \Delta D^t_{tr}$
→ the contact between two curved RC beams is determined by a nonlinear constitutive law,
→ geological medium load on outer beam is considered as a uniform load and as springs positioned at the joints of elements of the outer beam.

- governing equations of the mechanical model

Kinematic equations:

$$x^i{}' + u^i{}' - \left(1+\varepsilon^i\right)\cos\varphi^i - \gamma^i \sin\varphi^i = 0$$
$$z^i{}' + w^i{}' + \left(1+\varepsilon^i\right)\sin\varphi^i - \gamma^i \cos\varphi^i = 0$$
$$\varphi^i{}' - \kappa_0^i - \kappa^i = 0$$

Equilibrium equations:

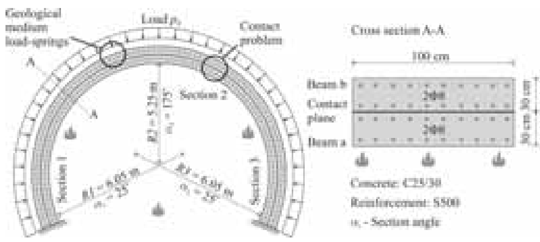
$$R^i_X{}' + p^i_X + p^i_{tX} + p^i_{nX} = 0$$
$$R^i_Z{}' + p^i_Z + p^i_{tZ} + p^i_{nZ} = 0$$
$$M^i{}' - \left(1+\varepsilon^i\right)Q^i + \gamma^i N^i + m^i_Y = 0$$
$$N^i = R^i_X \cos\varphi^i - R^i_Z \sin\varphi^i$$
$$Q^i = R^i_X \sin\varphi^i + R^i_Z \cos\varphi^i$$

Constitutive equations:

$$N^i - N^i_c = 0 \qquad N^i_c = \int_A \sigma^i\left(D^i\right) dA$$
$$Q^i - Q^i_c = 0 \qquad Q^i_c = \int_A \tau^i\left(D^i\right) dA$$
$$M^i - M^i_c = 0 \qquad M^i_c = \int_A z^i \sigma^i\left(D^i\right) dA$$

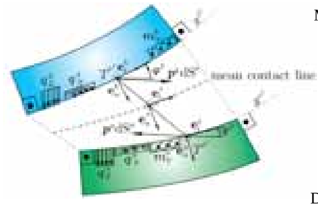
$i - a, b$ beam

NUMERICAL MODEL



CONTACT PROBLEM – CONSTRAINING EQUATIONS

- Curved RC beams are connected with constraining equations:



Mean contact plane/surface:

$$\mathbf{e}^*_n = \frac{\zeta e^a_n + (1-\zeta) e^b_n}{\left\| \zeta e^a_n + (1-\zeta) e^b_n \right\|} = e^*_{nX}\mathbf{e}_X + e^*_{nZ}\mathbf{e}_Z$$
$$\mathbf{e}^*_t = \frac{\zeta e^a_t + (1-\zeta) e^b_t}{\left\| \zeta e^a_t + (1-\zeta) e^b_t \right\|} = e^*_{tX}\mathbf{e}_X + e^*_{tZ}\mathbf{e}_Z$$
$$\zeta = [0,1]$$

Displacement vector: $\mathbf{u}^i, i = a, b$ *beam*

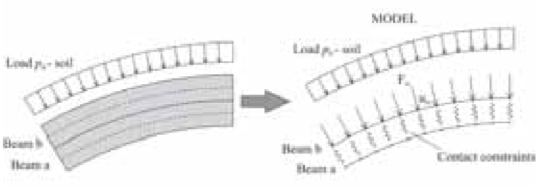
$$w^{i*}_n = \mathbf{u}^i \cdot \mathbf{e}^*_n$$
$$u^{i*}_t = \mathbf{u}^i \cdot \mathbf{e}^*_t$$
$$\Delta^* = u^{a*}_t - u^{b*}_t \rightarrow slip$$
$$d^* = w^{a*}_t - w^{b*}_t \rightarrow uplift$$

$$\mathbf{p}^a dS^a + \mathbf{p}^b dS^b = \mathbf{0}$$
$$dS^a = dS^b \rightarrow \mathbf{p}^a + \mathbf{p}^b = \mathbf{0}$$
$$\mathbf{p} = \mathbf{p}^a = -\mathbf{p}^b = p_X \mathbf{e}_X + p_Z \mathbf{e}_Z$$
$$\mathbf{p} = \mathbf{p}^a = -\mathbf{p}^b = p^*_t \mathbf{e}^*_t + p^*_n \mathbf{e}^*_n$$
$$p_X = p^*_t e^*_{tX} + p^*_n e^*_{nX}$$
$$p_Z = p^*_t e^*_{tZ} + p^*_n e^*_{nZ}$$

Constitutive law: $p^*_t = F\left(\Delta^*\right) \quad p^*_n = G\left(d^*\right)$

GEOLOGICAL MEDIUM LOAD - SPRINGS

- is considered as uniform load along the outer beam,
- affects/limits deformation of two curved connected RC beams,



- deformation of the outer beam is limited by implementing nodal forces - springs F_{ni}

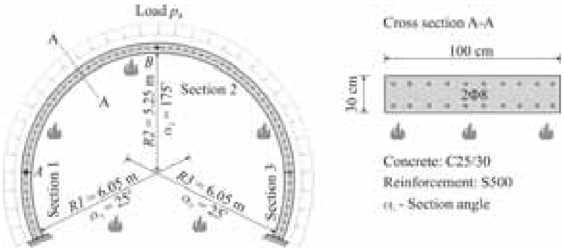
$F_{ni} = K_{soil} \cdot u_{ni}$ → linear relation at the moment

F_{ni} - nodal force of the outer beam in normal direction,

u_{ni} - nodal displacement of the outer beam in normal direction due to mechanical (soil) and fire load.

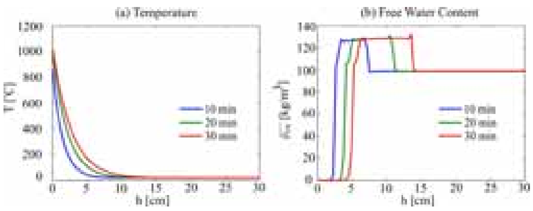
NUMERICAL EXAMPLES (PRELIMINARY TESTS)

Curved RC beam exposed to fire (hydrocarbon fire curve SIST EN 1991-1-2:2004) and uniform load p_R



Geometrical and material properties of curved RC beam.

TEMPERATURE ANALYSIS (2nd step):

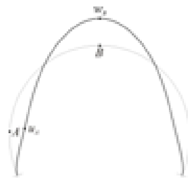


Distribution of (a) temperature and (b) free water content over the height *h* of cross-section at 10, 20, 30 minutes.

MECHANICAL RESPONSE OF CURVED RC BEAM EXPOSED TO FIRE

Load p_R (kN/m)	**N_{el}**	**K_{spring} [kN/cm]**	**t_{cr} [min]**	**w_B [cm]**	**u_A [cm]**
270	32	0	39.9	-2.08	1.14
270	32	1	138	-7.76	3.78
270	32	10	> 180	-0.72	0.61
270	32	100	> 180	-0.33	-0.19
270	32	1000	> 180	-0.10	-0.09
270	32	10000	> 180	-0.02	-0.01

Critical time, displacement components of reference points *A* and *B* for different values of K_{spring}



Scaled deformed shape at critical time, position of reference points *A* and *B*.

Summary, Expected goals

- Non-linear analysis (geometric and material) of partly delaminated curved RC structures exposed to mechanic and fire load;
- Analysis of possible slip and uplift between beams;
- Parametric studies: identification of essential material and geometric parameters, which have effect on stiffness, ductility and stability of partly delaminated curved RC structures;
- Presented model: evaluation of old structures and advice for designing and building of new structures exposed to fire load;
- IDEA-DESIRE: evaluate/detect concrete spalling;

THANK YOU FOR YOUR ATTENTION!