University
of Ljubljana
Faculty
of civil and
geodetic engineering

BUCKLING RESISTANCE OF A REINFORCED CONCRETE FRAMES IN FIRE CONDITIONS

COST Action TU0904

Integrated Fire Engineering and Response

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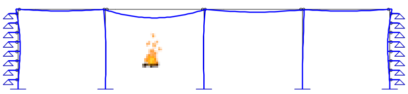
Outline of the presentation

- Problem description
- Temperature – moisture model of a reinforced RC frame construction (columns and beams)
- Mechanical model of a RC frame construction (columns and beams) exposed to mechanical and fire loads
- Numerical results
- Expected goals of PhD work

Problem description

- **Reinforced concrete** (RC) **frames** are widely used constructions
- One of the most important design requirements: **fire resistance** of RC frames
- Failure of columns: **material failure** or **buckling** (geometric properties)
- Deformability increases during fire
- Plastic materials – **post-critical buckling resistance**
- **robustness of structure**

A reinforced concrete frame (*http://www.archiexpo.com/prod/atlas-beton-sa/reinforced-concrete-columns-62424-161123.html* (23.03.2012))



Proposed mathematical model

matehematical modelling of fire analysis

time development of temperatures of *the fire compartment* (1st phase)
+
determination of temperature and moisture distribution *in column* (2nd phase)

mechanical response of column exposed simultaneously to fire and mechanical load (3rd phase)

thermo-hygro-mechanical analysis
2nd phase + 3rd phase

mechanical analysis is separated from thermo-hygro analysis

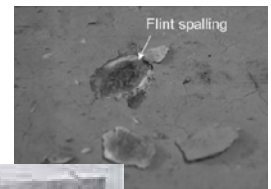
How to define the criteria of concrete spalling?

Concrete spalling

Explosive spaling

- appear at the begining of the fire (5-30min)
- very difficult phenomena
- Consequence of pore pressure **and/or** obstruct tempereture deformations

(Jau et al., 2008)



(Mindeguia et al., 2010)

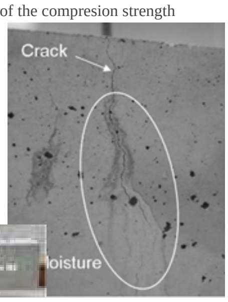
(Dwaikat in Kodur, 2010)

Concrete spalling

Fall of concrete

- Occur at the last state of fire exposure
- Due to losses of the compresion strength

(Jau et al., 2008)



(Dwaikat in Kodur, 2010)

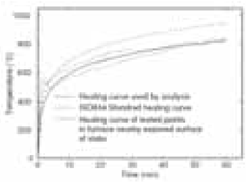
(Mindeguia et al., 2010)

1st phase: Fire scenario

- Determinaton of fire scenario (time and spatial destribution of temperature in fire compartment):

complex CFD methods

standard ISO 834 curve



2nd phase: Heat and mass transport model

- proposed by Davie et al., 2006
- 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)

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

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

- primary unknowns: temperature T, pressure of gaseous mixture of water vapour and dry air P_G and water vapour content $\overline{\rho_V}$
- Solution: finite element formulation (FEM)

3rd phase: Mechanical model

- defines the stress-strain state of the RC column during fire
- the formulation is based on the Reissner's kinematically exact planar beam theory (Reissner, 1972)
- Stress-state state is determined iteratively, where the whole time of the duration is devided into time intervals [t^{i-1}, t^i]
- The RC column is subjected to a conservative, time independent load and a time-dependent growth of temperature
- The contact between the concrete and reinforcement is determined by non-linear constitutive law
- The tangential contact between the concrete and the reinforcement allows for slip and the longitudinal delamination is considered as well

3st phase: Mechanical model – basic equations

Kinematic equations:

$$1 + u^{i\,\prime}(x) - \left(1+\varepsilon^i(x)\right)\cos\varphi^i(x) - \gamma^i \sin\varphi^i(x) = 0$$

$$w^{i\,\prime}(x) + \left(1+\varepsilon^i(x)\right)\sin\varphi^i(x) - \gamma^i(x)\cos\varphi^i(x) = 0$$

$$\varphi^{i\,\prime}(x) - \kappa^i(x) = 0$$

Equilibrium equations

+ boundary conditions

$$R_1^{i\,\prime}(x) + p_X^i(x) = 0$$

$$R_2^{i\,\prime}(x) + p_Z^i(x) = 0$$

$$M^{i\,\prime}(x) - \left(1+\varepsilon^i\right)R_2^{\,i}(x) + \gamma R_1^i + m_Y^i(x) = 0$$

$$R_1^i = N^i\cos\varphi^i - Q^i\sin\varphi^i$$

$$R_2^i = -N^i\sin\varphi^i + Q^i\cos\varphi^i$$

Constitutive equations:

$$N^i(x) - N_c^i(\varepsilon(x),\kappa(x)) = 0$$

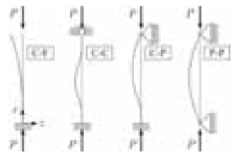
$$Q^i(x) - Q_c^i(\kappa(x)) = 0$$

$$M^i(x) - M_c^i(\varepsilon(x),\kappa(x)) = 0$$

$$N_c^i(x) = \int_{A^i} \sigma^i\left(D^i\right) dA$$

$$Q_c^i(x) = \int_{A^i} \tau^i\left(D^i\right) dA$$

$$M_c^i(x) = \int_{A^i} z^i\sigma^i\left(D^i\right) dA$$



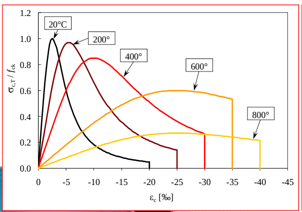
3st phase: Mechanical model – basic equtions

- **Constraining eq.** $\Delta(x) = u^s - u^c$

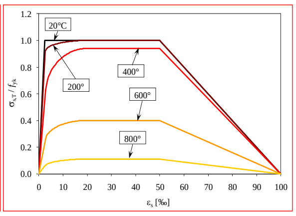
  $p_X^c = p_{X,c}^c(\Delta)$

- **Constitutive laws of concrete and steel** (SIST EN 1992-1-2)

concrete



steel



3st phase: Mechanical model – basic equtions

- Based on the given stress and strain state at the time t^{i-1} and temperature at t^i, the **mechanical strain** $D^t = \varepsilon^t + z\kappa^t$ on time interval t can be calculated by

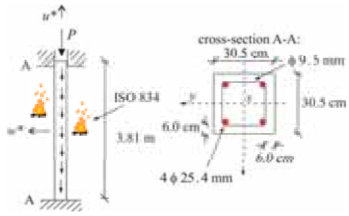
$$D^t = D^{t-1} + \Delta D^t$$

increment of total strain

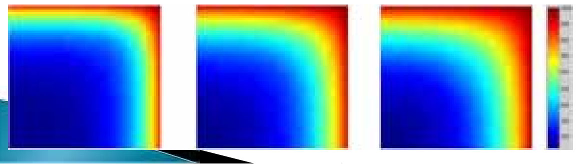
- Considering the **principle of additivity of strains** and the **material models of concrete and steel at elevated temperatures**, we propose that strain increment is the sum of different strains due **to temperature, stress and creep in concrete and steel + transient strains in concrete**

$$\Delta D^t = \Delta D_{th}^t + \Delta D_\sigma^t + \Delta D_{cr}^t + \Delta D_{tr}^t$$

Numerical example - Results of 2nd phase

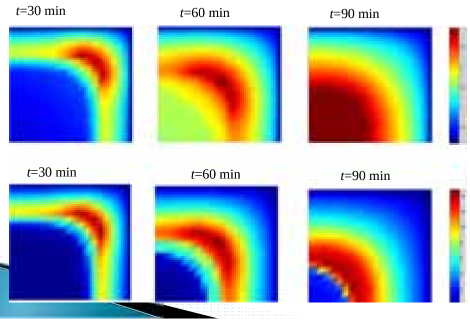


- Distribution of the temperature T [°C]

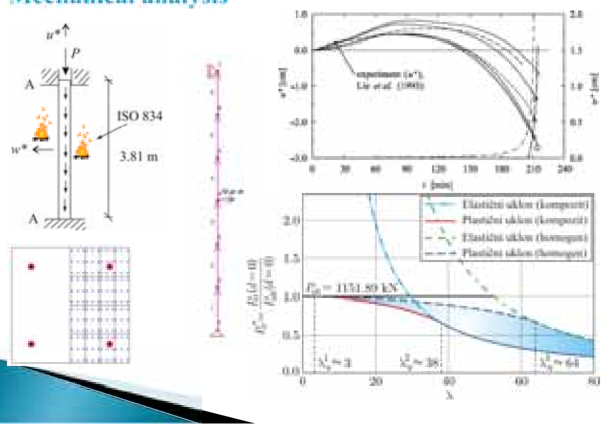


Results of 2nd phase

- Distribution of the **pore presure** and **free water content**



Mechanical analysis



Expected goals of PhD work

- To introduced **a new numerical model for the non-linear geometric and material analysis** of a RC frames exposed to the mechanical and fire load [program environment: **Matlab** (MathWorks, 2011)]
- The validation and varification will be set by comparison to existing experimental tests (*Franssen and Dotrepe*)

- In the post-critical buckling analysis we will consider:
  - plastic buckling due to elastic unloading
  - weakening of the cross-section of the column due to explosive spalling (Dwaikat and Kodur)
  - local buckling of the reinforcement
  - the longitudinal delimination of the concrete-steel contact

Expected goals of PhD work

- **Estimation of the adequacy** of the computational procedure for determination of buckling resistence presented by EC 2
- The results will enable a better understanding of **holistic stability behaviour** of the RC frames in fire conditions
- The findings of the research work will also bring **technical benefits** – with the presented numerical model we will more accurately assess the **fire safety** of RC frames
- New requirements for the design of the new RC structures might be set (development of new design rules)

Thank you for your attention

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