22nd International Conference
ENGINEERING MECHANICS 2016
Svratka, Czech Republic, 9 – 12 May 2016

NONLINEAR ANALYSIS OF STEEL CONCRETE COLUMNS FIRE RESISTANCE

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Abstract: *The aim of this work is the design of the steel and concrete composite column subjected to fire considering material and geometrical nonlinearity. The paper presents the detailed analysis of the structural fire resistance in accordance with the Eurocode requirements. On the base of the nonlinear analysis using ANSYS software, the fire resistance of two types of columns – a reinforced concrete column and a steel and concrete composite column - has been investigated. The load of column section is considered alternatively. The Drucker-Prager yield function for the concrete, and Von Mises function for steel, have been taken. The theory of large deformations is regarded in geometrical nonlinearity. The FEM model is made from the solid (SOLID65), shell (SHELL181) and link (LINK180) elements. The comparison studies present the differences of the steel and concrete composite columns in comparison with the reinforced concrete columns, or steel.*

Keywords: fire resistance, material and geometrical nonlinearity

1. Introduction

Experiences from fire cases and their consequences are the main reasons for the developing of the fire safety standards. A list of codes, standards, and other legal documents being used to achieve this aim are based on the simple numerical methods. This paper particularly shows the possibility of solution the fire resistance problem. The fire resistance of the structure could be verified by simplified or exact computational model. From the structural behaviour point of view we consider a plastic model. The definition of the material properties, as well as the load condition, can be defined by deterministic or probabilistic access. Fire resistance of the structure is evaluated by discrete histogram obtained from the probabilistic analysis. The fire resistance of composite steel-concrete structures is calculated according to EN1994-1-2. Three methods are available in order to evaluate the fire resistance: the tabulated data method, the simple calculation models and the advanced calculation models. The tabulated data method is based on observations resulted from experimental study. It is the easiest to apply, but it is limited by the geometrical conditions imposed to the composite cross-section. The simple calculation models compute the ultimate load of the element by means of formulas or design charts, established on the basis of experimental data. The advanced calculation models suppose an advanced numerical analysis of the elements, parts of the structure, or of the entire structure under fire, using specialized software for the mechanical analysis of structures under elevated temperatures.

The nominal standard temperature-time ISO 854 fire curve does not take into account any physical parameter, and can be far away from reality. From the beginning, the nominal curve supposes that the entire compartment is in the flashover phase and the temperature is increased continuously, without taking into account the cooling phase.

The fire is considered an accidental situation which requires, with some exceptions, only verifications against the ultimate limit state. The combinations of actions for accidental design situations are given in the European Standard for basis of structural design EN1990, by the following formulas:

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$$G_k + P_k + \Psi_{1,1} Q_{k,1} + \sum_{i>1} \Psi_{2,i} Q_{k,i} \qquad \text{or} \qquad G_k + P_k + \sum_{i\geq 1} \Psi_{2,i} Q_{k,i} \tag{1}$$

2. Composite steel-concrete structure analysed

The paper presents the calculation of the fire resistance for the composite columns of high rise building. This column is critical structure element with required fire resistance R90 in accordance with Eurocode 4. The composite steel-concrete column consists the steel profile I600 from S235, concrete rectangular section 550/800mm from C30/37 and the reinforcement 8∅28mm from B500B (Fig.1) .

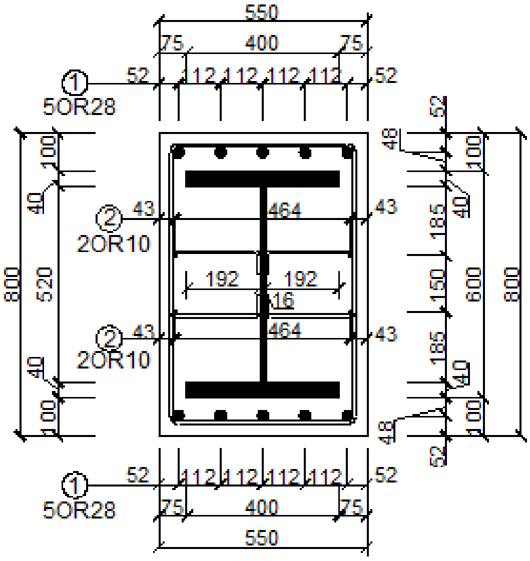

Figure 1: Section of the composite steel-concrete column

3. Geometric and material nonlinearity

The resistance of the composite steel-concrete column was calculated considering the material and geometric nonlinearity depended on temperature. The geometric nonlinearity is based on the theory of the large strain, which is often used for elastic-plastic elements. The motion vector $\{u\}$ is formulated by the position vectors for undeformed $\{X\}$ and deformed $\{x\}$ state

$$\{u\} = \{x\} - \{X\} \tag{2}$$

The deformation gradient $[F]$ is defined as

$$[F] = \left[\frac{\partial \{x\}}{\partial \{X\}} \right] \tag{3}$$

which can be written in terms of the displacement here $[R_{1/2}]$ is the rotation matrix computed from the polar decomposition of the deformation gradient evaluated at the midpoint configuration:

$$[F_{1/2}] = [R_{1/2}][U_{1/2}] \quad \text{and} \quad [F_{1/2}] = [I] + \frac{\partial \{u_{1/2}\}}{\partial \{X\}} \tag{4}$$

where $\{u_{1/2}\} = (1/2)(\{u_n\} + \{u_{n-1}\})$ is the midpoint displacement.The computed strain increment $[\Delta\varepsilon_n]$ (or equivalently $\{\Delta\varepsilon_n\}$) can then be added to the previous strain $\{\varepsilon_{n-1}\}$ to obtain the current total Hencky strain. The strain increment is also computed from the midpoint configuration.

$$\{\Delta\varepsilon_n\} = [B_{1/2}]\{\Delta u_n\} \tag{5}$$

where $\{\Delta u_n\}$ is the displacement increment over the time step and $[B_{1/2}]$ is the strain-displacement relationship evaluated at the midpoint geometry

$$\{X_{1/2}\} = \frac{1}{2}\left(\{X_n\} + \{X_{n-1}\}\right) \tag{6}$$

This method is an excellent approximation to the logarithmic strain if the strain steps are less than ~10%. This method can be used by the standard 2-D and 3-D solid and shell elements. For the case of nonlinear materials the stress increment can be computed via the elastic stress-strain relations

$$\{d\sigma\} = [D_{el}]\{d\varepsilon^{el}\} \tag{7}$$

where $[D_{el}]$ is the stress-strain matrix and the elastic strain is defined in the form of:

$$\{\varepsilon^{el}\} = \{\varepsilon\} - \{\varepsilon^{th}\} - \{\varepsilon^{pl}\} \tag{8}$$

where ε^{el} is an elastic strain vector, ε - total strain vector, ε^{th} - thermal strain vector, ε^{pl} - plastic strain vector. The incremental theory of plasticity provides a mathematical relationship that characterizes the elastic-plastic response of materials. There are three ingredients in the rate-independent plasticity theory: the yield criterion, flow rule and the hardening rule. The increment of the plastic strain results from the flow rule by Drucker (condition of positive plastic work)

$$\{d\varepsilon^{pl}\} = d\lambda\left\{\frac{\partial Q}{\partial\sigma}\right\} \tag{9}$$

where $d\lambda$ is plastic multiplier (which determines the amount of plastic straining) and Q is plastic potential (which determines the direction of plastic straining). The plastic multiplier $d\lambda$ express from consistency condition of yield function $dF(\sigma,\kappa,\alpha) = 0$

$$d\lambda = \frac{\left\{\frac{\partial F}{\partial\sigma}\right\}^T [D_{el}]\{d\varepsilon\}}{-\frac{\partial F}{\partial\kappa}\{\sigma\}^T\left\{\frac{\partial Q}{\partial\sigma}\right\} - C\left\{\frac{\partial F}{\partial\alpha}\right\}^T\left\{\frac{\partial Q}{\partial\sigma}\right\} + \left\{\frac{\partial F}{\partial\sigma}\right\}^T [D_{el}]\left\{\frac{\partial Q}{\partial\sigma}\right\}} \tag{10}$$

The yield function F defines the state, when the plastic strain ε^{pl} is started. Generally the yield criterion can be defined as follows

$$F(\sigma,\kappa,\alpha) = 0 \tag{11}$$

where κ is the hardening parameter (plastic work) and α is the back stress (location of the centre of the yield surface). The yield function was taken by Von Mises for the steel material and by Drucker-Prager for the concrete material in following form- Von Mises yield function

$$F(\sigma,\kappa,\alpha) = \sqrt{3J_2} - \sigma_y(\kappa) \tag{12}$$

where J_2 is the second invariant of the stress tensor, $\sigma_y(\kappa)$ is the yield parameter.

- Drucker-Prager yield function for the concrete

$$F(\sigma,\kappa,\alpha) = \beta I_1 + \sqrt{J_2} - \sigma_y(\kappa) \tag{13}$$

where I_1 is the first invariant of the stress deviator, J_2 is the second invariant of the stress deviator, the parameter β and the yield parameter $\sigma_y(\kappa)$ is defined as follows

$$\sigma_y(\kappa) = \frac{6c.\cos\varphi}{\sqrt{3(3-\sin\varphi)}}, \quad \beta = \frac{f_T}{f_c} = \frac{1-\sin\varphi}{1+\sin\varphi}, \quad \varphi = \arcsin\left(\frac{1-\beta}{1+\beta}\right), \quad c = \frac{\sqrt{2}}{2} f_c \tag{14}$$

where C is the cohesion coefficient and φ is the angle of interior material friction.

4. FEM model of the composite steel-concrete column

The FEM model consist of 3.800 solid elements (SOLID65), 784 shell elements (SHELL181) and 1396 link elements (LINK180) in program ANSYS. The material model of the steel elements was defined for the Von Mises yield function and multilinear isotropic hardening stress-strain diagram. In the case of concrete the Drucker-Prager yield function was taken.

5. Recapitulation of the nonlinear analysis

The fire resistance of two types of column - composite steel-concrete (SC) and reinforced concrete (RC) in four models was considered – M1 (SC column loaded by full section), M2 (SC column loaded by steel profile), M3 (RC column only), M4 (S column from I600 only).

Temperature °C	$N_{,\mathrm{fi,Rd,z}}$ kN	$N_{.\mathrm{fi.Ed}}$ kN	Capacity ratio %
20	19224.3108	9027.82477	46.96046
200	17776.4928	9027.82477	50.785185
400	13890.2026	9027.82477	64.9941908
500	10187.6206	9027.82477	88.6156357
700	3547.04101	9027.82477	254.517068
900	1021.70869	9027.82477	883.600662

Table 1: Design values of the normal forces of SC column

6. Conclusions

This paper deals with the analysis of the fire resistance of two types of column - composite steel-concrete (SC) and reinforced concrete (RC) for four models – M1 (SC column loaded by full section), M2 (SC column loaded by steel profile), M3 (RC column only), M4 (S column from I600 only). The load was considered for 20%, 40%, 60% and 80% level of design normal force N_{Rd} and temperature of 200, 400, 500, 700 and 900°C. The limit state was achieved for following situations : model M1 - 40% N_{Rd} and 820°C, M2 - 60% N_{Rd} and 900°C, M3 - 40% N_{Rd} and 700°C, M4 - 40% N_{Rd} and 900°C. The composite steel-concrete column (model M2) loaded by steel profile has the highest level of fire resistance.

Acknowledgement

The project was realized with the financial support of the Grant Agency of the Slovak Republic (VEGA). The project registration number is VEGA 1/1039/12

References

CARVALHOA, L.T. et al. Numerical modelling of steel columns in fire, *Applications of Structural Fire Engineering*, February 2009, Prague, Czech Republic.

CADORIN, J.F et al. : A tool to design steel elements submitted to compartment fires-Ozone V2. Part2: Methodology and application, *Fire safety journal*, Elsevier, 38, 439-451, 2003.

LAUSOVÁ, L. KREJSA, M. Experimentální testování ocelové konstrukce za požáru. *Sborník vědeckých prací VŠB-TUO*, *řada stavební,* VŠB TU Ostrava, 2012, s. 261-268.

KODUR,V. : Guidelines for Fire Resistant Design of Concrete-Filled Steel HSS Columns - State-of-the-Art and Research Needs, *Steel Structures* 7 (2007) 173-182.

PARK,S.H. et al.: Fire resistance of Bar-Reinforced Concrete-Filled Steel Tube Columns, In Proc. *Application of Structural Fire Engineering*, 19-20 February 2009, Prague, CR.

STN EN 1991 – 1 – 2 : *Eurokod 1, Zaťaženia konštrukcii, Časť 1-2: Všeobecne zaťaženia – Zaťaženie konštrukcii namáhaných požiarom*. SUTN Bratislava 2006.