COMPOSITE STRUCTURAL MEMBERS IN FIRE CONDITIONS AND MEASURES OF PROTECTION

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Summary: *In this paper, the results of numerical simulation of 2D non-stationary temperature fields in commonly used composite structural members made of steel and concrete in fire conditions were presented. Simulation is based on the model which includes temperature dependence of physical parameters of materials, specific heat and thermal conductivity. Analysis of composite structural members comprises determination of a heat flux field which additionally facilitates understanding of region and geometry of heat flow, thus enhancing fire protection design. Initial temperature distribution is adopted as uniform, according to Eurocode. Fire conditions were according to ISO 834. The FEM computations for different protection scenario and protective materials for partially encased I section - are conducted in ABAQUS. Obtained results can be used in cost optimization of fire protection measures.*

Keywords: *fire protection, composite structural members, heat flux, temperature field.*

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1. INTRODUCTION

The fire has been considered as a burning uncontrolled process that endangers human lives and health, material assets and environment. The main objective of protection of building structures against the fire includes a set of measures and actions of planning, organizing, financing, implementing and controlling to prevent compaction and spreading of the fire by identifying and eliminating its cause in order to rescue people and property and protect the environment. Good and appropriate fire safety concept involves the use of active protection system (early fire detection, firefighting) and passive protection systems (provision of the required fire resistance of the structure, rearrangement of the object into the specific fire sectors).
Releases of large amounts of the heat which are accompanied by high temperatures affect the capacity of building constructions. As the fire represents a phenomenon that depends on a huge number of parameters, standardization of modeling effects is not simple at all. The International Standard ISO 834 specifies a test method for determining the fire resistance of various elements of construction when subjected to standard fire exposure conditions. These conditions have been defined by a heating curve that represents an average air temperature in furnace as a function of time, measured by thermocouples, monitored and controlled such that it follows the relationship:

$$T(t) = 345 \cdot log_{10}(8t+1) + 20 \tag{1}$$

where: T is the average furnace temperature $[°C]$, t is the time [min].

The Standard time/temperature curve is given in Figure 1.

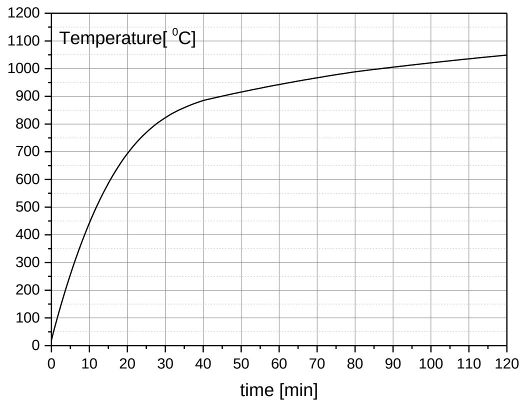

Figure 1. The Standard time / temperature curve in ISO 834

Our national Standard SRPS EN ISO 834 "Fire resistance tests- Elements of building construction" in a very similar way describes the Standard curve. It allows initial furnace temperature in the range 25^0C±15^0C, instead of 20^0C.

Examinations of a building structure in fire condition have been carried experimentally, according to the Standard, but the use of simulation tools also adequately describes real fire conditions [1].
Columns are structural elements that provide support and stability of the entire building. Structural design of columns implies simultaneous action of axial and transversal forces while composite columns members (steel-concrete) are used to accept large vertical loads and bending moments. Structural design of columns becomes far more complex when the fire load is added. It is necessary to provide a certain time of fire resistance of columns to allow safe evacuation of people and extinguishing of fire. The aim is to preserve stability and structural integrity during the fire. Steel parts of columns are more sensitive to increase in temperature because the steel, as opposed to the concrete, has a lower capacity of resistance to heat. Increasing the size of the cross section, adding concrete as an outer layer, results in slower heat transfer from the exterior surfaces to interior sections. The thicker cross section delays column's failure due to effects of the high temperature.
Standard fire test classifies the structure in different class of fire resistance. In steel structures, achieving the critical temperature as limiting criteria has been adopted. The critical temperature represents a temperature interval in which material loses up to 50% of elastic performances and for structural steel amounts 450^0C-650^0C. The limit temperature represents the maximum temperature of material's cross section that makes it unreliable, and for the same material the figure is 900^0C. In both cases material changes the type of crystal structure leading to abrupt change in Young's modulus.
In this paper, using numerical simulation of fire conditions, a temperature and heat flux fields for unprotected and composite circular and square columns with HEB 260 section are calculated. Simulation is based on the physical model which includes conduction, convection and radiation as well as temperature and spatial dependence of specific heat and thermal conductivity.
Apart of the temperature filed, the heat flux field can additionally improve understanding of the fire dynamics, displaying regions and geometry of intense heat flow, enhancing heat protection analyses and the fire protection design.

2. THERMAL MODEL OF COMPOSITE STRUCTURAL MEMBER

The fire condition is non-stationary thermal process where all three heat transport phenomena, conduction, convection and radiation must be included in the physical modeling. Also, thermal properties like thermal conductivity, specific heat, density and heat transfer coefficient are temperature dependent. In the composite structural members they are spatially dependent too. All these facts make the Fourier heat equation, which describes the process, unsolvable in analytical form even for the simplest cases. Thus, it has been solved using numerical methods.
The conductive heat transfer inside solid parts is modeled using non-stationary Fourier equation. As the whole process occurs at extremely high temperatures relative to exploitation ones, the temperature dependence of the thermal conductivity should be taken into account. On this way the governing equation becomes non-linear. It has been assumed that the whole computational domain is homogeneous part by part which means that all solid parts in the model are homogeneous. As the temperature distribution is considered

only in the cross-section surface, the heat equation in i-th region/sub-domain could be expressed in the following two-dimensional form [2]:

$$\rho_i \cdot \frac{\partial(C_i(T_i)\cdot T_i(x,y,t))}{\partial t} = \nabla(\lambda_i(T_i)\cdot \nabla T_i(x,y,t)) + S_i(x,y,t), \tag{2}$$

where C_i, ρ_i and λ_i are specific heat, density and thermal conductivity of i-th solid sub-domain respectively, T_i is non-stationary temperature field in i-th subdomain and S_i is source term due to radiation. The matching conditions on the interfaces between corresponding sub-domains could be expressed in the following way:

$$\begin{aligned} T_i\big|_{\Gamma ij} &= T_j\big|_{\Gamma ij} \\ \lambda(T_i)\frac{\partial T_i}{\partial n}\bigg|_{\Gamma ij} &= \lambda(T_j)\frac{\partial T_j}{\partial n}\bigg|_{\Gamma ij}, \end{aligned} \tag{3}$$

where Γ_{ij} is an interface between i-th and j-th sub-domain. In the previous equations it has been assumed that thermal contacts between interfaces are ideal. The boundary conditions on the contacts between i-th solid part and air are of the mixed type and could be expressed using the following equations:

$$-\lambda_i(T_i)\frac{\partial T_i}{\partial n}\bigg|_{\Gamma ai} = \alpha_i\cdot(T_{air}(t)-T_i)\big|_{\Gamma ia} + \varepsilon\cdot\sigma\cdot(T_{air}^4 - T_i^4) \tag{4}$$

where α_i is heat transfer coefficient between i-th sub-domain and air, T_{air} is air temperature given by the Eq. (1) and Γ_{ia} is boundary between i-th sub-domain and air. The second term in Eq. (4) is due to radiation heat transfer, and the σ and ε are Stefan-Boltzmann constant and surface emissivity respectively. In the most general case the radiation can be modeled using Radiative Transfer Equation (RTE) in the following form [2]:

$$\frac{dI(\vec r,\vec s,t)}{ds} + (a+\sigma_s)\cdot I(\vec r,\vec s.t) = a\cdot n^2\cdot\frac{\sigma\cdot T^4}{\pi} + \frac{\sigma_s}{4\cdot\pi}\cdot\int_0^{4\pi} I(\vec r,\vec s^{\,'},t)\cdot\Phi(\vec r,\vec s^{\,'})\cdot d\Omega', \tag{5}$$

where $\vec r$ and $\vec s$ are position and direction vectors respectively, $\vec s^{\,'}$ - scattering direction, s - path length, a - absorption coefficient, n -refractive index, σ_s -scattering coefficient, I - radiation intensity, T - local temperature, Φ -phase function, Ω - solid angle, $a+\sigma_s$ is optical thickness or opacity of medium. The above non-stationary integro-differential equation should be solved for every pair $\vec r$ and $\vec s$ at every time instant. This makes it extremely difficult and CPU time consuming for numerical solution. To simplify the model, surface-to surface (S2S) approximation is used. In the S2S model the radiation inside all solid parts is neglected and only radiative transport through air from surface to surface is considered. Thus, the presented thermal analysis takes into account heat transfer from hot air to boundary surfaces by convection and radiation followed by heat conduction. Source term S_i in Eq. 2 and radiation intensity I are connected by formula,

$S_i = \frac{\partial (I/c)}{\partial t}$, where c is velocity of electromagnetic radiation.

3. RESULTS OF NUMERICAL SIMULATIONS AND DISCUSSION

Numerical simulations of Eqs. (2)-(5) with the fire condition given by Eq.1, for a single and composite member made of section HEB 260 protected with concrete of circular and square cross sections itch of 1600cm^2, in ABAQUS software package, are presented. ABAQUS's Heat Transfer Solver is used with mesh comprised of type DC3D8 finite element. Two types of concrete layers density of 2400 kg/m^3 and 450 kg/m^3 for protection were used. Temperature dependencies of physical parameters of materials used in simulations in Fig. 2-3 are shown [3,4].

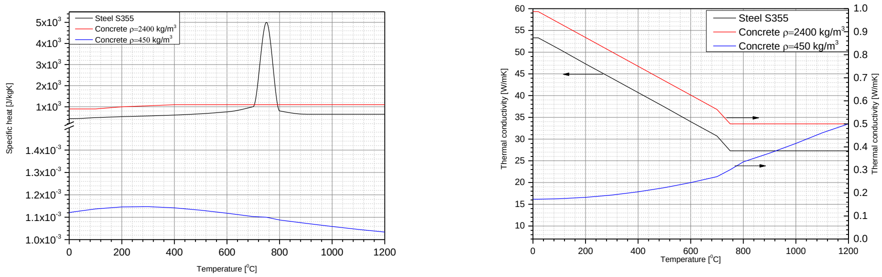

Figure 2. Material's thermal conductivity and specific heat as a function of temperature

The first member used in the simulation was the HEB 260 member without fire protection. Temperature and flux fields, shown in Fig. 3, 120min after fire start, display regions and places of temperature and flux extremes. The highest temperature is at the web's center and amounts to 1048^{0}C. The heat flux at places of joints of web and flange is the highest because at the place the temperature's gradient is the highest.

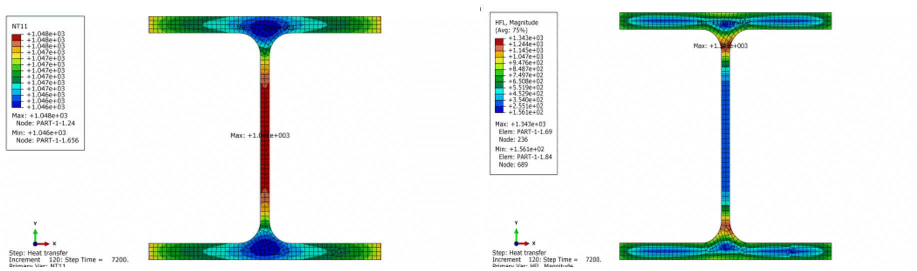

Figure 3. Temperature and heat flux fields of the HEB 260 member after 120min of the fire exposure

It is worth noting that web has the highest temperature the place where the steel column under tensile stress load has the greatest deformations. Thus, fire protection is an imperative. The first model of composite steel-concrete member column analyzed is one of circular cross section, area of 1600cm^2, with concrete density of 2400kg/m^3. The shape is suitable for the thermal analyses because both temperature and flux fields are expected to be isotropic at boundary surfaces, enabling to analyze how the geometry of steel column influences the heat flux into deeper regions. In Fig. 4 the temperature and the heat flux fields are shown, 120min after fire onset.

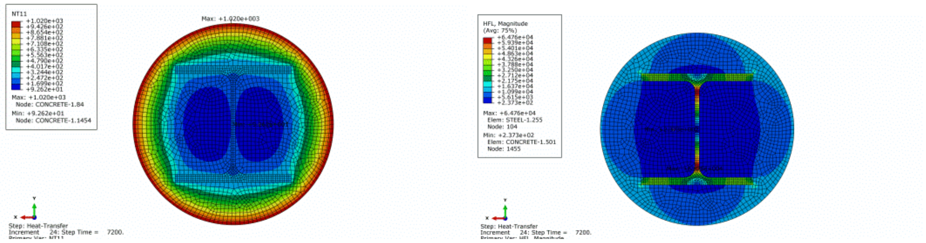

Figure 4. Temperature and heat flux fields of HEB 260 composite steel-concrete column after 120min of the fire exposure

The point of the lowest temperature of 92,62^{0}C is indicated in Fig. 4 and it is placed in concrete in the middle of dark blue colored region. The flux field reveals that regions of elevated heat conduction across concrete are symmetrical relative to the HEB 260 member diagonals (light blue areas in Fig.4). The densest fluxes are along edges of flanges (the lightest blue spots in Fig.4). These points of the HEB 260 member are the nearest to surface of the cross section. These facts indicate that a square cross section of steel-concrete member of the same area and same type of concrete could be slightly better protected. In Fig.5 the results of simulation of a square cross section steel-concrete member are shown.

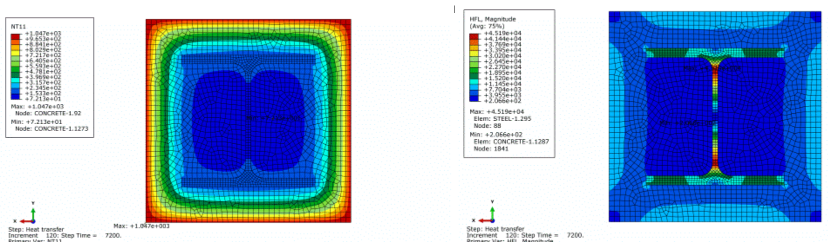

Figure 5. Temperature and heat flux fields of HEB 260 composite steel-concrete column of square cross section after 120min of fire onset

The lowest temperature is 72,13^{0}C and it is placed nearly at the same point as in Fig.4. The heat flux field shows the lowest fluxes in diagonal directions relative to ones in the case of the circular cross section. The lower average temperature is obtained in comparison with the circular cross section, indicating that the square cross section composite members are more suitable for design against fire. Calculation of temperature and heat flux fields for a light autoclaved aerated concrete as protective material is performed and the results are presented in Fig. 6. The area of the cross section is the same as in Fig. 5.

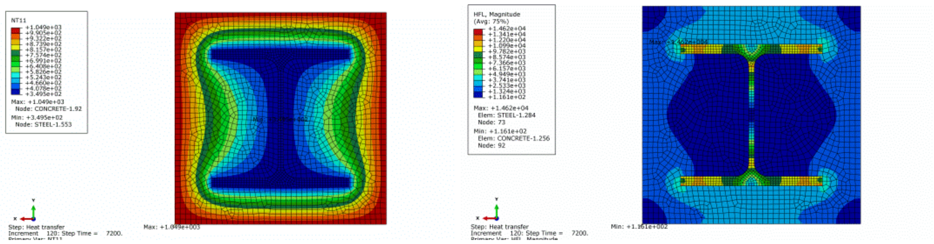

Figure 6. Temperature and heat flux fields of HEB 260 composite steel-concrete column with light concrete of 450kg/m^{3}density after 120min of fire onset

Aerated lightweight concrete is less efficient than much denser because the lowest temperature of the cross section is 349,5 ^{0}C after 120min of fire onset. In the figure presenting heat flux, heat penetrates the structure more in vertical than horizontal direction indicating possible measure of additional protection.

In Fig. 7 a comparison of mean cross section temperature as a function of time of the steel HEB 260 member with and without concrete protection layer of the two cross section types is presented. Also, the same curve for maximal temperature of unprotected HEB 260 member is given.

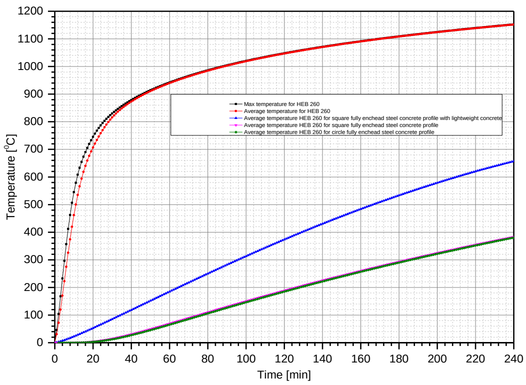

Figure 7. Average temperature of HEB 260 steel cross section (unprotected and protected) as a function of time in fire conditions

The slowest rate of the average temperature increase of the HEB 260 member is in the case of circular and square cross sections of composite members and concrete density of 2400kg/m^3. Even four hours after fire onset, the average temperature is still below 400^{0}C. The same is in case of lightweight concrete but after 120min. In Table 1 and Table 2 comparisons of calculated reduction factors for yields as function of temperature and the type of protection after 120min of fire are shown.

As we can see in Table 1, for temperatures up to 400 ^{0}C there is no reduction of the yield strength $k_{y,\theta}$ of steel member.

Table 2. gives averaged temperature of steel after 120min of fire. One can see that square as well as circular cross section can be used as effective protection against fire both with lightweight and regular concrete. Despite of the same area of the cross section, there are significant differences in the temperature of the circular and square cross-section in favor of square section. It is clear that an unprotected steel profile almost completely loses its mechanical properties after 120 min.

Steel's temperature θ [°C]	$k_{E,\theta} = \frac{E_{a,\theta}}{E_a}$	$k_{y,\theta} = \frac{f_{ay,\theta}}{f_{ay}}$
20	1,000	1,000
100	1,000	1,000
200	0,900	1,000
300	0,800	1,000
400	0,700	1,000
500	0,600	0,780
600	0,310	0,381
700	0,130	0,143
800	0,090	0,105
900	0.068	0,067
1000	0,045	0,029
1100	0,023	0,020
1200	0	0

Table 1.Yields strengths of steel as function of temperature [5].

Type of cross section	Temperature [°C] after 120 min	$k_{y,\theta} = \frac{f_{ay,\theta}}{f_{ay}}$
Steel column HEB 260	1047	0,03
Composite column circular cross section	264	1
Composite column square cross section (ρ_c=2400 kg/m^3)	189	1
Composite column square cross section (ρ_c=450 kg/m^3)	374	1

Table 2. Composite and steel column's average cross-section temperature after 120 min of fire and corresponding yield strengths.

4. CONCLUSION

In this paper, the HEB 260 composite steel-concrete member columns in fire condition according Standard ISO 834 are analyzed. The 2D temperature and heat flux fields for lightweight and regular concrete protection layers of circular and square cross sections are presented. Advantages of the square cross section and weightier concrete over circular and lighter are established and explained. The heat flux field analyses and its possible usage in design of the concrete cross section is demonstrated. The fire resistance of unprotected and protected structural member is obtained.

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SPREGNUTI ELEMENATI U USLOVIMA POŽARA I MERE ZAŠTITE

Rezime *U radu su prikazani rezultati simulacije dvodimenzionalnih nestacionarnih temperaturskih polja kod često korišćenih spregnutih elemenata čelik-beton koja nastaju u uslovima požara. Simulacija je bazirana na modelu koji uključuje zavisnost toplotne provodnosti i specifične toplote materijala od temperature. U analizu je uključeno i određivanje polja toplotnog fluksa koje dodatno ukazuje na oblasti i geometriju toka toplote od samog temperatuskog polja. Temperatursko polje koje odgovara uslovima simulacije u početnom trenutku je uniformno i usvojeno prema Evrokodu. Uslovi požara odgovaraju standardnoj požarnoj krivi ISO 834. Simulacija je rađena za parcijalno ubetonirani čelični I profil sa različitim predloženim varijantama zaštite ražličitim materijalima. FEM analiza je izvršena u programskom paketu ABAQUS. Rezultati rada se mogu primeniti u optimizaciji troškova sistema zaštite od požara.*

Ključne reči*: protiv požarna zaštita, spregnuti elementi, toplotni fluks, temperatursko polje.*