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Beams with corrugated web at elevated temperature, analytical and numerical models for heat transfer

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ABSTRACT

In the case of corrugated web beams, based on experimental results, it was noticed that temperature development along the height of the web has a distinct pattern compared to the flat web beams. The particularity consists of a temperature decrease in the web, in the vicinity of the flange-to-web junction, assigned to the heat transfer by conduction and radiation. On this assumption, starting from the simple relations given in the fire design codes an analytical model is developed considering the heat conduction from the web to the flanges and the radiation heat transfer between web and flanges. The paper presents the results of the proposed analytical method against the experimental results and the numerical simulation. Both analytical and numerical models are compared to the experimental results obtained from the isolated element fire test and the real building fire test. A parametric study on the influence of the geometric dimensions is performed regarding also the time interval for the temperature development. For short term fire exposure, the web exhibits non-uniform temperature along the web height, while for long term fire exposure the entire cross-section tends to a homogeneous temperature.

1. Introduction

Mostly used in bridge engineering, the beams with corrugated webs have increased their use in the industrial structural systems providing not only material savings but also an attractive aspect through the trapezoidal or sinusoidal corrugation of the web. The design of industrial buildings involves the fire design situations therefore the response of these beams at elevated temperature should be evaluated. Due to the shape of the web, the height-to-width aspect ratio and the greater flange-to-web thickness ratio of corrugated web beams in comparison to the flat web beams, the thermal response of such beams implies particularities of temperature development over the steel cross-section. In a preceding paper [1], the authors presented experimental results for both isolated elements and real-scale building tests and this paper is a continuation of the study of elevated temperature influence on beams with corrugated web from the point of view of thermal response.

The aspect ratio of the web of such beams would categorize the cross-section into a thin-walled profile but the thicker flanges makes these beams behave distinctly for both thermal and structural actions.

The temperature development in commonly used flat web steel beam profiles can accurately be determined using the standardized relations recommended in EN 1993-1-2 [2]. The temperature increase with time using the previous mentioned relations depends on the heat transfer by convection and radiation, while conduction is not considered. Owing its small massivity, the temperature in the thin steel part i.e. the beam web, increases at a higher rate than thick parts i.e. the flanges, therefore conduction plays an important role, especially at the junction area between flange and web.

In fire design computation, a great importance is attributed to the temperature distribution which can be regarded as a critical stage of fire design since most mechanical models predict similar deformation/time characteristics according to [3]. As mentioned above, in the case of high conductivity materials i.e. steel, the heat conduction has a great importance for significant temperature difference between two parts of steel cross-section. For the commonly used steel profiles with flat web, the temperature distribution within the parts of cross-section has minor effect along the part thickness and function of the exposure temperatures, it may be regarded either as a uniform temperature or as a thermal gradient through the cross-section [4,5]. Direct exposure to fire of cold-formed steel members exhibit no distinguishable temperature difference due to conduction. In the case of thin-walled steel panels, where the steel profiles are protected, a greater temperature difference is developing between the flange closer to the fire exposed face of the wall and the flange fixed to the unexposed face of the wall leading to conditions proper for observing heat conduction effect [6].

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Nomenclature

A	area of top face of top flange on which heat is radiated [m^2]
A_i	Area of the ith element considered as an emitter
A_m/V	section factor of steel member [m^{-1}]
$A_{m,f}/V_f$	section factor of flange [m^{-1}]
$A_{m,w}/V_w$	section factor of web [m^{-1}]
C	correction factor
K	emission coefficient
L	mean beam length [m]
L_i	length of an element I [m]
ΔQ_1, ΔQ_2	heat fluxes from the web to the top and bottom flanges [J]
$\Delta Q_{1,n}$, $\Delta Q_{2,n}$	intermediate heat fluxes from web to top and bottom flange [J]
ΔQ_i	heat flux from element i-1 to element i [J]
V	volume of the gas between flange and steel deck [m^3]
WTA, (B), (C)	symbol for web thicknesses of 2, 2.5 and 3 mm
b_{f1}, b_{f2}	width of top and bottom flange [m]
c_a	specific heat of steel [J/kg K]
h_{1w}, h_{2w}	partial web height for upper part of web and lower part of web [m]
$h_{1w,n+1}$	intermediate values for partial web height [m]
$h_{1w,0}$, $h_{2w,0}$	initial partial web heights [m]
$\dot{h}_{net}$	net heat flux per unit area [W/m^2]
$\dot{h}_{net,c}$	net heat flux to unit surface area due to convection [W/m^2]
$\dot{h}_{net,r}$	net heat flux to unit surface area due to radiation [W/m^2]
$h_{net,r,A,i}$	radiative heat transfer for element i of the web [W/m^2]
$h_{net,r,B}$	radiative heat flux for the flange [W/m^2]
h_{wL}	width of the web strip with min 5% lower temperature than the maximum temperature point on web [m]
h_{si}	vertical distance from flange to element i [m]
k_{sh}	correction factor for the shadow effect
m_{f1}, m_{f2}	masses of the top flange and bottom flange [kg]
m_i	mass of element i [kg]
m_w	mass of the web [kg]
s	corrugated web length of the web [m]
s_i	distance from half flange centroid to element i [m]
t_{f1}, t_{f2}	thickness of top and bottom flange [m]
t_i	thickness of element i [m]
t_{i-1}, t_{i+1}	thicknesses of the preceding adjacent element and next adjacent element [m]
t_w	web thickness [m]
Δt	time interval [s]
$2w$	wave length of the sinusoidal web [m]
Φ	configuration factor
$\Phi_{A-B,i}$	configuration factor for radiative heat transfer from web to flange
α_c	coefficient of heat transfer by convection [W/m^2 K]
β	angle of incidence of heat radiation [°]
δ_1, δ_2	mean distance of conductive heat transfer from web to top and bottom flange [m]
$\delta_{1,n}$, $\delta_{2,n}$	intermediate values for mean distances of conductive heat transfer [m]
δ_i	distance from element i-1 to element i [m]
ε_A, ε_B	emissivity of the web and the flange
ε_f	emissivity of flames, of the fire
ε_m	surface emissivity of the member
ϕ_A, ϕ_B	surfaces relative orientation angles [°]
κ_{TR}	covering factor
λ	thermal conductivity [W/mK]
$\theta_{A,i}$	temperature of ith element on the web in radiative heat transfer computation [°C]
θ_B	flange temperature for radiative heat transfer computation [°C]
θ_i	temperature of element i [°C]
θ_{f1}, θ_{f2}	temperature of the top flange, bottom flange [°C]
θ_g	gas temperature in the fire compartment [°C]
θ_m	temperature of the member surface [°C]
θ_r	effective radiation temperature of the fire environment [°C]
θ_w	web temperature [°C]
$\Delta\theta_1$, $\Delta\theta_2$	temperature variation of top flange, bottom flange and web [°C]
$\Delta\theta_{a,t}$	the increase of temperature in an unprotected steel member during a time interval Δt [°C]
$\Delta\theta_{a,t,A,i}$	web temperature variation due to radiation of element i [°C]
$\Delta\theta_{a,t,B}$	flange temperature variation due to radiation from web [°C]
$\Delta\theta_{i,i-1}$	temperature variation of element i induced by the heat transfer from element i-1 to element i [°C]
$\Delta\theta_{i,i+1}$	temperature variation of element i induced by the heat transfer from element i to element i+1 [°C]
$\Delta\theta_i$	total temperature variation of element i caused by the heat transfer from element i-1 to i and from i to i+1 [°C]
$\Delta\theta_w$	temperature variation of the web [°C]
ρ_a	unit mass of steel [kg/m^3]
σ	Stephan Boltzmann constant (=5,67×10^{-8} [$W/m^2 K^4$])

The measurements performed by Feng et al. [7] revealed a higher temperature in the flange close to the unexposed face of the wall for the specimens that had continuous web between flanges than the specimens where the flange had a service hole. Another situation which exhibits steel conduction effect was presented by Wang [8] for partially protected beams, where, for a web protected on one quarter of its height, the temperature in the flange had a higher value than for the case of a fully protected cross-section.

The heat transfer principles for furnace tests are clearly described in [3] for both convection and radiation interaction between furnace and elements, while in [9] it is presented the influence of steel type on thermal interaction properties. Moreover, due to high temperature difference at early stages of heating it might be considered that a radiation interaction exists between parts of steel beam.

The paper presents an analytical model which assesses the temperature distribution in a corrugated web steel beam considering the heat conduction from the web to the flanges and the radiation of more heated part of the cross-section, i.e. the web, to colder parts of cross-section, i.e. the flanges. The procedure starts by establishing first the point of highest temperature in the web and then, by dividing the web and the flanges into finite elements, the temperature variation along the web height is determined. The comparison of results is performed with respect to finite element heat transfer analysis and experimental results obtained from the tests performed at Czech Technical University in Prague, presented by the authors in [1].

2. Heat transfer in steel beams

The fire resistance of structural elements during fire is highly influenced by the temperature, thus, the accuracy of predicting thermal field in the cross-section is proportional to the precision of the thermo-mechanical analysis results. The beams with corrugated web may be considered a non-conventional steel profile and, as presented in the following, has a distinct distribution of temperatures than in the case of