ON THE BEHAVIOUR OF STRUCTURAL STEEL BEAMS UNDER NATURAL COMPARTMENT FIRE

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Abstract

Fire is an extreme action, to which a steel structure may be submitted, and therefore, must be designed to resist.

Traditionally, the fire resistance of structural steel beams has been determined in standard fire tests, with the temperature-time curve ISO834 representing more severe heating conditions compared to that which occurs in many typical natural fire compartments. Therefore to design a steel structure safely and economically, it is necessary to calculate temperature distribution in steel beams under natural fire.

In this paper, the temperature profiles in a steel beams under natural fire are studied first, using spread-sheets written by authors and compared to standard fire. Secondly, two Cardington compartment corner office tests are highlighted, and analysis of primary and secondary steel beams is presented. Simple theoretical natural fire models based on Eurocode EN 1991-1-2 parametric compartment fire are used and a comparison is made using the experimental results from tests conducted at Cardington research centre, UK. Compartment temperatures and cross-section temperature distribution respectively demonstrates that analytical fire models and experimental results are in good agreement in the case of timber cribs fire load.

Keywords: *Natural fire, steel beam, temperature distribution, numerical, Cardington fire tests*

1. INTRODUCTION

Steel construction is becoming widely used in buildings nowadays, for it can reduce substantially the construction time and therefore the global cost.

During the last decades, remarkable progress has been made in understanding the parameters which influence the development of building fires [1], and also the behaviour of fire exposed structural materials and structures [2, 3]. In particular, for steel structures, this progress has resulted in the production of very detailed rules for the design and calculation of structural behaviour and load bearing capacity in fire [4-6].

However, the poor behaviour of structural materials under the conditions of exposure to fire must not be forgotten. It is well known that steel among all materials, suffers a great reduction of yield stress and Young's modulus, under the effect of high temperatures [6-8].

In a steel structure, the failure of a beam is reached when its strength is exceeded at one or more particular points termed plastic hinges, depending on the way it is supported. The development of plastic hinges shows ductile behaviour as energy is dissipated at these points [1, 3].

Extensive research has been carried out in recent years on the numerical simulation using finite element method (FEM) [8, 13] as an alternative to the original plastic hinge analysis method.

Moment redistribution is one of the significant phenomena occurring in heated steel beams and a good understanding of this behaviour under fire conditions is dealt with by investigations on the performance of redundant structures [14].

There is limited research work conducted on natural fire conditions [15-17]. It is therefore useful to study steel beams under such conditions. Temperature distributions in steel beams, needed to be determined prior to analysing the structural behaviour, are studied on the basis of the Eurocode parametric fires [4] using worksheet programs written by authors.

In this paper the authors used the available real fire Cardington compartment tests data with two main types of fire loads deployed for wood cribs and a variety of office materials (computers, desks, plastic files, paper piles…) for test 3 and 6 respectively. Comparisons are made with respect to ISO 834 curve and the two BRE-Cardington real fire tests [18-20].

2. FIRE CURVES

The ISO 834 standard fire curve (Fig.1) is used for the fire resistance design in many countries, in which the temperature increases monotonically with time. In EN 1991-1-2 [4], the gas temperature θ in °C, at time t in minutes, is given by expression (1).

$$\theta_g = 20 + 345\, log_{10}(8\,t + 1) \qquad (1)$$

Where θ_g -is the gas temperature in the fire compartment [°C]; t – is the time [min].

In modern fire safety engineering however, the design of structures is moving from the traditional prescriptive method to the performance-based methodology [14]

Unlike the standard fire curve, a natural fire curve is characterized by 3 phases: a pre-flashover phase, a fully developed phase and a decay phase (Fig.1). Most structural damage occurs during the fully developed fire phase and only the fully developed fire phase and the decaying phase are taken into account. The reference time t_0, figure 1, is regarded as the origin of the temperature-time coordinate system, corresponding to the point of flashover.

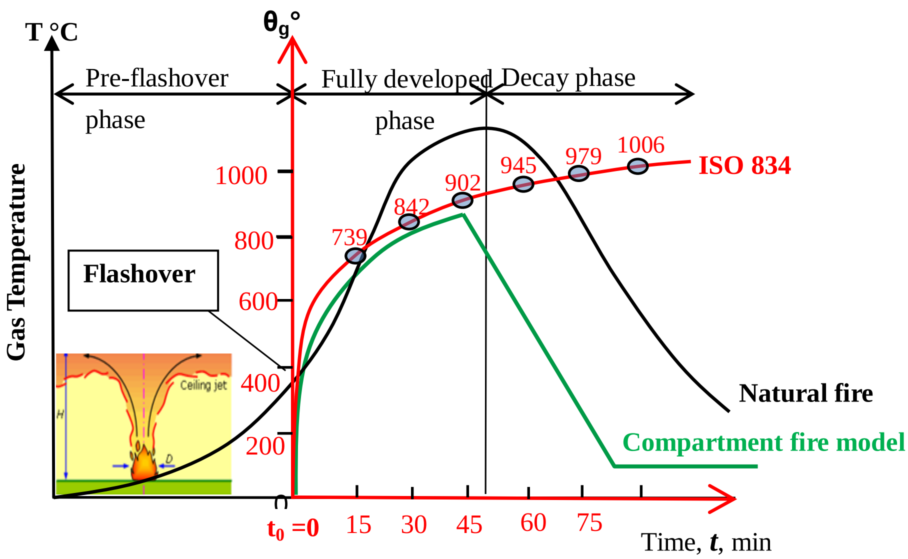

Figure 1. Fire Temperature-time curves – 3 phases real fire vs ISO 834 and natural compartment fire model.

It is clear that the ISO 834 fire curve generally is more conservative than a natural fire curve because the standard curve implies that there is an inexhaustible supply of fuel. If a natural fire is used in a steel structure fire resistant design, it is possible to reduce fire protection [15].

3. NATURAL COMPARTMENT FIRE MODELLING

The compartment temperature during natural fire depends on the amount, distribution, and composition of the combustible materials in the compartment, the enclosure dimensions and ventilation, as well as the thermal properties of the compartment linings [15]. Thus, the natural fire modelling required, takes account of actual fire load, ventilation conditions and thermal characteristics of compartment walls.

3.1 Eurocode compartment fire models

The Eurocode parametric temperature-time curves [1, 4] are based upon three parameters, the design fire load density q_{td}, the opening factor O that accounts for the openings in the vertical walls and the parameter which accounts for thermal properties of the enclosure b.

$$\theta_g = f(q_{t,d}\ , O, b) \quad ;$$

With

$$q_{t,d} = q_{f,d}.{}^{A_f}\!/_{A_t}\,[\tfrac{MJ}{m^2}] \quad ; \qquad O = \sqrt{h_{eq}}.{}^{A_v}\!/_{A_t}\,[\,m^{\frac{1}{2}}]\begin{cases}\geq 0.02\\ \leq 0.2\end{cases} ; \qquad b = \sqrt{c.\rho.\lambda}\ \ [\tfrac{J}{m^2.S^{1/2}K}]\begin{cases}\geq 100\\ \\ \leq 2200\end{cases} \tag{2}$$

- Time temperature in the heating phase :

The evolution temperature during the heating phase is given by:

$$\theta_{g=}20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \tag{3}$$

Where t^* is the fictitious time given $t^*=t\,\Gamma$, t the time in hours and

$$\Gamma = \left(\frac{O/0.04}{b/1160}\right)^2 \tag{4}$$

In the case of Γ=1, Equation (3) approximates the ISO834 standard temperature-time curve [16].

Depending on whether the fire is fuel controlled or ventilation controlled, the duration of the heating phase t_{max} is given, in hours, by

$$t_{max=}\max\left\{0.0002 \times {}^{q_{t,d}}\!/_{O}\ ;\ t_{lim}\right\} \tag{5}$$

The introduction of t_{lim} is to avoid an unrealistic short fire duration when the ratio between the fire load and the opening factor decreases. Any object or fire load needs a certain amount of time to burn, even if there is an unlimited presence of air [16]

- Time temperature in the cooling phase :

The time-temperature curve during the cooling phase is given by

$$\begin{aligned}
&\theta_g = \theta_{max} - 625(t^* - t^*_{max}.x) && \text{for} \quad t^*_{max} \leq 0.5\\
&\theta_g = \theta_{max} - 250(3 - t^*_{max})(t^* - t^*_{max}.x) && \text{for} \quad 0.5 < t^*_{max} < 2\\
&\theta_g = \theta_{max} - 250(t^* - t^*_{max}.x) && \text{for} \quad t^*_{max} \geq 2
\end{aligned} \tag{6}$$

In which $t^* = t\,.\,\Gamma$ and $t_{max} = \left(0{,}2.10^{-3}.q_{t,d}/O\right).\Gamma$

$x = 1$ $\quad$ $if\ \ t_{max} \geq t_{lim}$, Ventilation Controlled

or $x = t_{lim}.\Gamma/t^*_{max}$ $\quad$ $if\ \ t_{max} < t_{lim}$, Fuel Controlled

For the fuel controlled situation, a new fictitious time $t^*=t\,\Gamma_{lim}$, is used to compute the evolution of the temperature during the heating phase.

3.2 Input data for BRE-Cardington compartment fire tests

- **BRE-Cardington full-scale fire tests**

To generate data on the overall steel structures, the BRE has recently completed at Cardington a series of full scale fire tests in its Large Building Test Facility (LBTF), on eight storey steel-framed building [18]. The so called BRE's-Cardington building is an eight storeys (33m) steel framed construction with five bays (5x9m=45m) by three bays (6+9+6=21m) in plan figure 2 [19].

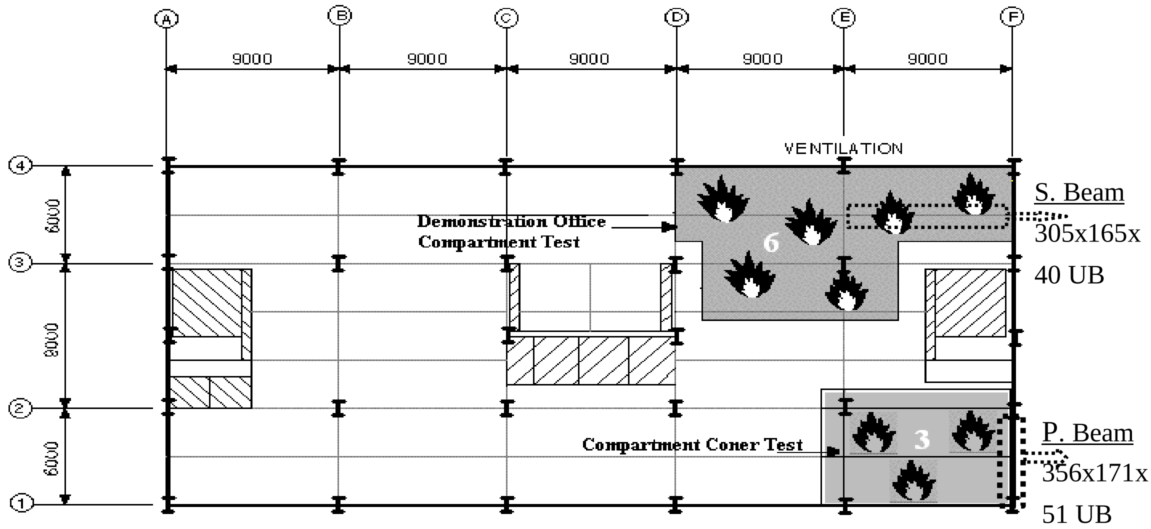

Figure 2. LBTF Cardington test3 &6 locations

Test3, 6, figure 2, involved compartment compartments of different sizes subjected to natural fire fuelled by timber cribs and modern office furniture respectively.

- **Fire simulation - design value of the fire load**

It is calculated based on the characteristic value $q_{f,k}$ as defined annex A EN 1991-1-2 [4]

$$q_{f,d} = q_{f,k}.\, m.\, \delta_{q1}\delta_{q2}.\, \delta_n \tag{7}$$

With: m combustion factor, the value of which is between 0 and 1 (0.8 for cellulosic materials);

δq1 factor that accounts for the risk of fire activation due to the compartment size;

δq2 factor that accounts for the risk of fire activation due to the of occupancy;

δn factor that takes into account the effect of active fire fighting.

For either case, the fire load is composed by 20% of plastic, 11% of paper and 69% of timber that is only cellulosic materials and hence m = 0.8.

δq1= 1.5 (Af ≤250); δq2= 1.0 (office);

$$\delta n = \prod_{i=1}^{10} \delta_{ni} = 1.0 \times 0.73 \times 0.87 \times 0.78 \times 1.0 \times 1.0 \times 1.0 = 0.5 \tag{8}$$

A total fire load equivalent to 46 Kg /m2 of timber cribs has been considered with a characteristic value $q_{f,k}$ of 805MJ/m2 , which gives a design value of the fire load :

$$q_{f,d} = 805 \times 0.8 \times 1.5 \times 1.0 \times 0.5 = 483\ \mathrm{MJ/m^2} \tag{9}$$

- **Compartment Fire tests input data**

Table 1 summarises Test3 and Test6 data for parametric fire curve models.

Compartment data		**TEST3**	**TEST6**
Total area of the enclosure	A_t	295 m^2	474 m^2
Floor area	A_f	76 m^2	135 m^2
Total area of the vertical openings	A_v	7 m^2	27 m^2
Opening factor in the vertical walls	O	0.031$m^{1/2}$	0.076 $m^{1/2}$
Height	H	4.0 m	. 4.0 m
Average height of the window openings	h_{eq}	1.8m	1. 8 m
Light weight concrete	ρ	1900 kg/m^3	1900 kg/m^3
	C	840J/kgK	840J/kgK
	λ	1.0 W/mK	1.0 W/mK

Table 1: Data forTest3 & Test6 compartment fires

4. TEMPERATURE TIME CURVES OF BRE-CARDINGTON FIRE TESTS 3 AND 6

Fire curves were produced for two BRE-Cardington tests (3 & 6) showing significant dependence of fire temperature on thermal properties of the enclosure materials.

4.1 Gas temperature profiles in compartment fire test3 & test6

Parametric fire recommended in EN 1991-1-2 [4], is used to simulate both compartment tests 3 and 6 and equations in the heating and cooling phases Eqt.(10), Eqt.(11) are derived .

Temperature evolution in the heating phase:

$$\theta_{g(TEST3)=}20 + 1325(1 - 0.324e^{-0.2(0.506.t)} - 0.204e^{-1.7(0.506.t)} - 0.472e^{-19(0.506.t)}$$

$$\theta_{g(TEST6)=}20 + 1325(1 - 0.324e^{-0.2(3.04.t)} - 0.204e^{-1.7(3.04.t)} - 0.472e^{-19(3.04.t)} \qquad (10)$$

Temperature evolution in the cooling phase:

$$\theta_{g(TEST3)} = 813 - 625(0.506\,t - 0.405)$$

$$\theta_{g(TEST6)} = 959 - 475(3.04\,t - 1.1) \qquad (11)$$

Buchanan [1] has, however pointed out that Eurocode equation gives extremely fast decay rates for large openings in well insulated compartments and extremely slow decay rates for small openings in poorly insulated compartments.

4.2 Parametric fire curves and steel beams temperature profiles

Plots of fire curves for compartment tests 3 and 6 together with ISO standard fire are shown in figure 3.

It can be seen figure 3, that the time to reach the maximum temperature t_{max} (48 mins., 22 mins.), for test3 and test6 is greater than the time tlim (20 mins.). Thus both fire compartments are controlled by ventilation.

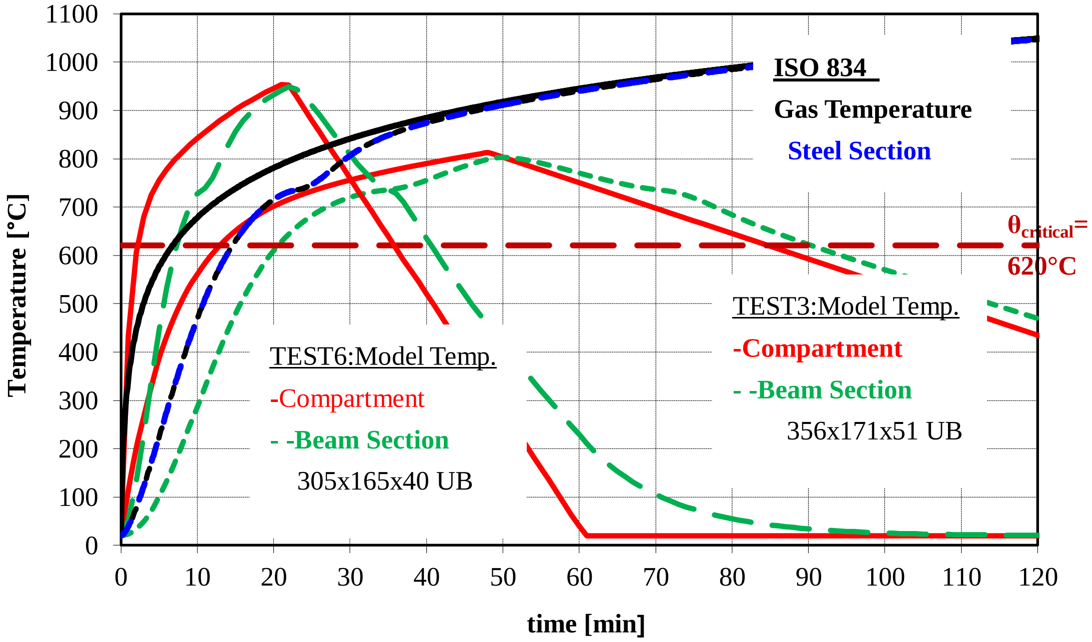

Figure 3. Parametric fire curve for TEST3 &TEST6-
Temperature evolution (Eurocode Models) vs. ISO834

4.3 Natural fire compartment tests

- **Experimental gas temperature in real and steel beams temperature profiles**

Measurements of the temperature in the mid-span beams are shown in figure 4. They are taken in the bottom flanges since they represent the maximum recorded temperatures with regard to web and upper flange.

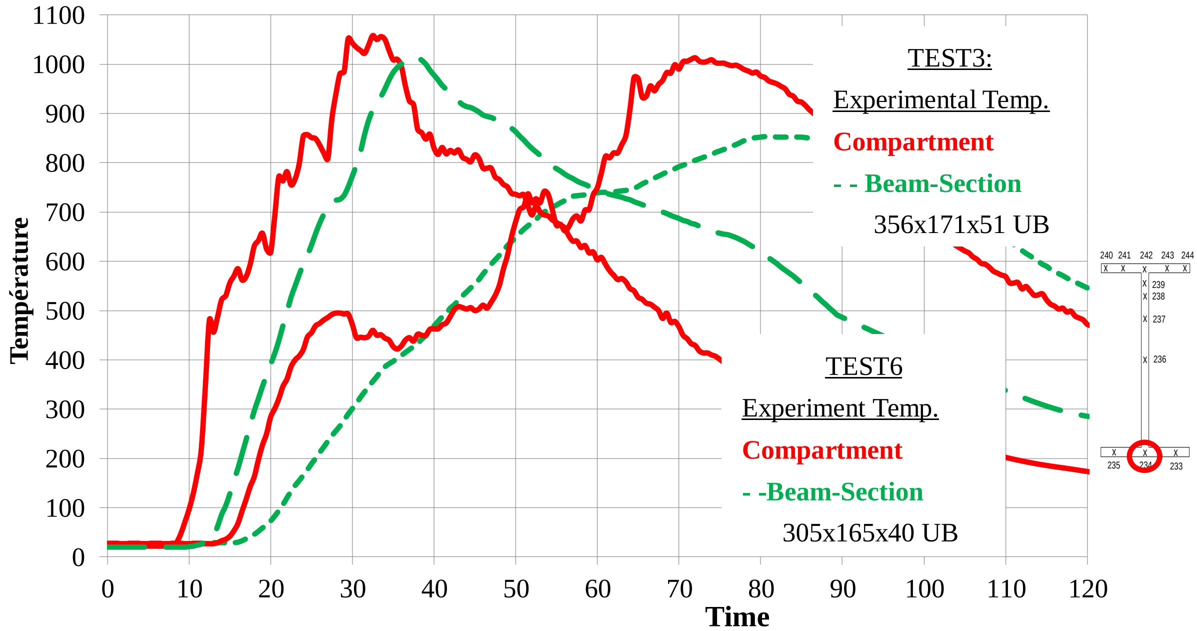

Figure 4. Experimental tests 3&6 - Compartment and steel section temperature profiles

- **Experimental mid-span deflections**

Figure 5 shows the mid-span vertical displacement recorded in both beams from test3 and test6. It observed that during heating phase, the beam with lower displacement is the testt3 primary beam. It is also worth mentioning that in the cooling phase both beams sustained partial recovery Fig.5.

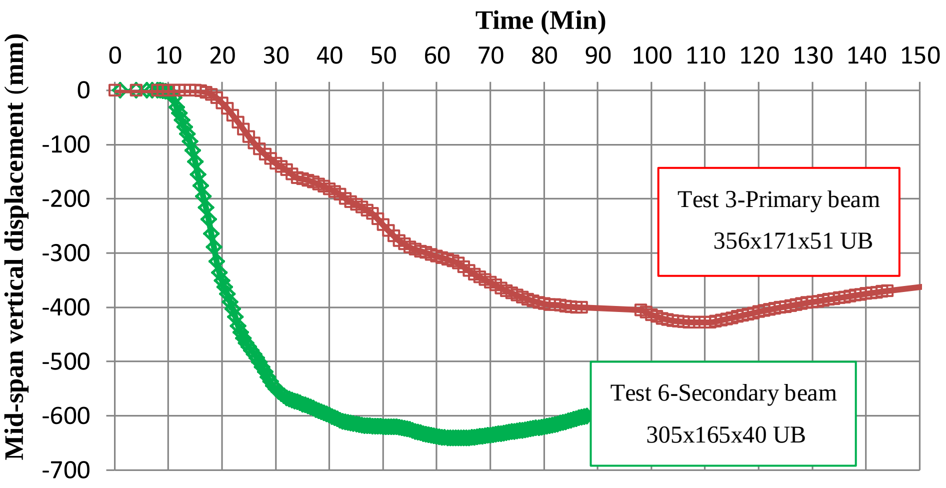

Figure 5: Experimental vertical displacement Test3 et Test6

5. MODELLING OF CARDINGTON TESTS 3 & 6 STEEL BEAMS UNDER NATURAL FIRE

The response of structural steel members under fire conditions is governed by mechanical, thermal properties and deformations [8]. Thermal properties define the temperature profile within the steel cross-section whereas the loss in strength and stiffness is governed by mechanical properties which are temperature dependant. Deformation properties define the permissible mid-span beams vertical displacement under fire loading.

5.1 Basic equations and boundary conditions

The temperature distribution in steel beam can be handled as a one-dimensional heat transfer problem without internal heat source($\dot{q} = 0$), valid for non-combustible member. The one-dimensional heat transfer equation can be written as [13]:

$$\lambda_a(\theta)\left(\frac{\partial^2\theta}{\partial x^2}\right) + \dot{q} = \rho_a . C_a(\theta).\left(\frac{\partial\theta}{\partial t}\right) \tag{12}$$

Where ρa=the unit mass of steel (7850 kg/m3); θ= temperature distribution in member; t= time; x = Cartesian coordinate; Ca=specific heat of steel [J/kgK] and λa= thermal conductivity of steel Figure 6.The temperature field which satisfies Eq. (12) must satisfy the following boundary conditions:
Prescribed temperatures on a part of the boundary; the heat flow by convection and radiation at the boundary assuming that θr=θ∞ (surrounding ambient temperature)

$$q_{cr} = q_c + q_r = (\propto_c + \propto_r)(\theta - \theta_\infty) \tag{13}$$
$$\alpha_r = \sigma.\varepsilon(\theta^2 + \theta_\infty^2)(\theta + \theta_\infty)$$

Where q = combined external heat flow per unit area; α_c is convection coefficient (=25 or 35W/m^{2}K for ISO834 or for Parametric fire); α_r heat flux by radiation between part of the boundary;θ = current temperature; σ=Stefan-Boltzmann constant (= 5.667 x 10^{-8} Wm^{-2}K^{-4});, ε=radiative emissivity (=0.7) of the flame associated with fire.

5.2 Simplified method solution for unprotected steelwork

No closed-form solution to the governing non-linear Eq. (12) and its boundary condition non-linear Eq. (13) is possible. For an equivalent uniform temperature distribution in the beam cross-section, the EN 1993-1-2 [5], provides step by step solution of the increase of temperature $\Delta\theta_{a,t}$ in an unprotected steel member during a time interval Δt defined as:

$$\Delta\theta_{a,t} = k_{sh}\frac{1}{c_a\rho_a}.\left(\frac{A_m}{V}\right).\dot{h}_{net,d}.\Delta t \qquad [°C] \qquad (14)$$

Where: k_{sh} is the correction factor for shadow effect; *Am/V* is the section factor as defined by Eurocode 3 [5], representing the ratio of the perimeter of the section exposed to the fire, in meters, and the cross-sectional area of the member, influences the rate of temperature $\Delta\theta$a,t figure 7 .

$\dot{h}_{net,d}$ - is the design value of the net heat flux due to convection and radiation per unit area:

$$\dot{h}_{net,d} = \dot{h}_{net,c} + \dot{h}_{net,r}$$

$$\dot{h}_{net,c} = \propto_c (\theta_g - \theta_m) \qquad [W/m^2]$$

$$\dot{h}_{net,r} = \Phi.\varepsilon_f.\varepsilon_m.5{,}67\text{x}10^{-8}.[(\theta_r + 273)^4 - (\theta_m + 273)^4] \qquad [W/m^2]$$

Where: Φ is the view factor (=1.0); θ_m surface temperature of the beam;; θ_r is the radiation temperature of the environment of the member usually (θ_r= θ_g); ε_m is the surface emissivity of the surface (=0.7); ε_f is the emissivity of the fire (=1.0), [5].

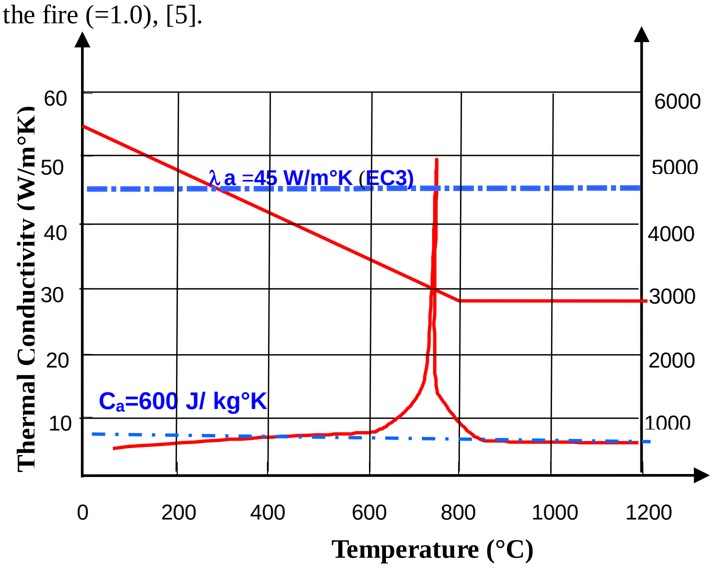

Figure 6. Thermal properties of carbon steel

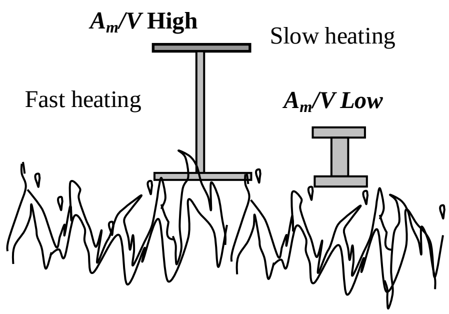

Figure 7. Section factor thermal effects

Temperature profiles for both primary beam-section in test3 compartment fire and secondary beam-section in test6 are presented in figure 3.

5.3 Beams fire resistance

In this section, steel materials S275 and S355 as a provision for high strength requirement in the actual tests environment and two bare beams, primary with a 6m span and secondary with 9m span, from test3 & 6 respectively, figure 2, are considered.

The steel beams exposed to fire consist of two cross-sections, 356x171x51UB for primary beam and 305x165x40 UB for secondary beam, figure 2 and both are subjected to 3-side heating.

The purpose of the study is to investigate the behaviour of two different type beam models under two different naturel compartment fires.

The uniformly distributed fire design load $P_{fi,d}$ is calculated with a load factor η=0.6:

$$P_{fi,d} = \eta\frac{8}{l^2}.\frac{W_{pl,y}.f_y}{\gamma_{M0}} \qquad (15)$$

The critical temperature $\theta_{a,cr}$ of a carbon steel, of the steel grades S275 and S355, at time t for a uniform temperature distribution in a member is determined for any degree of utilization μ_0 at time t=0 [5]:

$$\theta_{a,cr} = 39.19 ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \quad (°C) \tag{16}$$

With $\mu_0=k_1.k_2.\eta$; k1=0.7 and k2=1 adaptation factors, for non-uniform temperature on the section and along the beam respectively.

6. RESULTS AND DISCUSSIONS

The results of parametric compartment fire analysis are used as part of natural fire input in the heat transfer to obtain temperature profiles for beam-sections. Figure 3 compares the parametric temperature curves presented in Eurocode1 [4] for compartment fire models from test3 and test6. The variations of experimental compartment and steel temperatures with time are shown in figure 4. Both theoretical and experimental maximum recorded steel temperatures are shown in table 2.

Table 2: Results for temperatures and times for fire resistance

Section	$P_{fi,d}$ (kN/m)	K_{sh}x [A_m/V] (m^{-1})	Θ_g/ Θa max (°C)		Θ_{crit} (°C)	$Time_{crit}$ / $Time_{max}$ [min]	Max. Ver. mid-span disp.(mm)
			Analytical	Experimental			
UB356x171x51	42.4	135.8	813/803	1010/852	620	20/48	428
UB305x165x40	10	150.4	959/946	1052/1013	623	8/22.7	629

Theoretical calculations based on analytical Eurocode formulations were conducted on spread- sheet format for automatic use in different data cases and results from thermo-mechanical analyses in the form of critical temperatures and times are summarised in Table 2.

Figure 3 shows that ISO834 gas temperature curve (maximum temperature compartment: 1049.0 ºC at 120.00 min) and subsequent beam temperature profiles remains higher above of the test3 temperature curve and this is true for test6 compartment for a time reference over 20 minutes.

On cooling, the test3 primary beam and the test6 secondary beam, recovered to a permanent displacement of 296 mm and 600 mm respectively, figure 5.

7. CONCLUSIONS

The present paper investigates the structural behaviour of steel beams under natural fires for the purpose of a safe and economical design using compartment fire models. Temperature distributions in steel beams are studied using worksheet programs and obvious difference between the temperature distribution under natural fire and that under ISO 834 curve is highlighted. The standard curve, represents only one of many possible fire exposures, generally provides a very conservative prediction of how a steel beam will perform in an actual fire, therefore it is more reasonable to employ natural fires in fire resistant design.

This study shows that the parametric fire models established on the bases of Eurocode 1 for the tests 3 and 6 compartment fires gives a fair description for both the heating and the cooling phase as compared to the experimental temperature profiles. This is more significant for test3, in which wood cribs has been used as fire load, as the analytical parametric fire model agrees closely with the experiment. A simple overlapping of figure 3 and figure 4 with a shift of 10 on the time reference axis gives a clear understanding to the statement above.

Finally, large-scale tests provide unique data on how steel frames react to real compartment fires. In particular, the Cardington full test program has shown that the fire resistance of the overall structure can be much greater than that of an individual structural member.

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