Cover page

Title: Parametrical study on the behaviour of steel and composite cellular beams under fire conditions

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ABSTRACT

This paper describes an extensive parametric study on the behaviour of cellular beam under fire conditions.

Different finite element models using shell elements were developed considering both material and geometrical non-linearity; CAST3M [1], ANSYS [2] and another one in SAFIR [3]. They were calibrated on the basis of a new experimental test campaign performed in the scope of the project FICEB+ [4] funded by the Research Fund for Coal and Steel

The comparison between the finite element prediction and actual experimental results showed a good agreement in terms of failure modes, load deflection relationship and ultimate loads. At failure, temperature measured during the fire tests indicated that failure arising by web post buckling of cellular beams in fire cannot be simply estimated by applying temperature dependent reduction factors on strength alone, as given in codes.

A design model representing the behaviour of cellular beam in fire conditions has been developed by Vassart [5-7]. This design model is able to predict the complex behaviour of cellular beam in case of fire comprising web-post buckling and Vierendeel bending, as well as standard flexural bending.

The results of the Finite Element Models are compared in terms of critical temperatures and failure mode obtained using the design model.

This paper also contains some tests results that were used to calibrate the FEM model and the comparison between analytical and FEM models.

EXPERIMENTAL TEST CAMPAIGN

Beam geometric and material properties

An overall view of the four beams is shown in Fig. 1. As part of the composite floor plate, beams 1, 3 and 4 were considered to be secondary beams, and beam 2 was considered as a primary beam. They were fire designed according to [8].

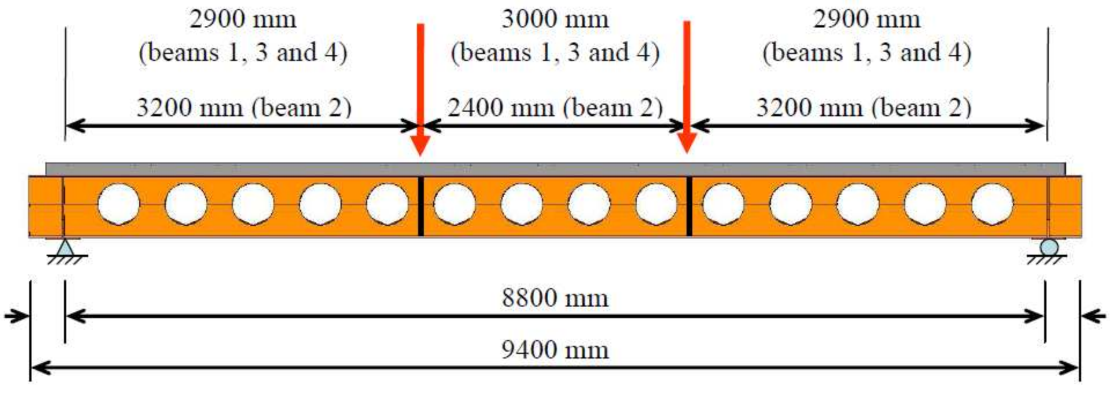


Fig. 1: elevation view of the composite beams

The main geometric and material properties of the beams are shown in Table 1. In addition to the web stiffeners at load points and at its end supports, for beam 4, there was a one side stiffener at each web-post. The upper steel flange was fully connected to the 120mm deep composite slab, which comprised a COFRASTRA 40 ® re-entrant deck, via Nelson headed studs.
The slab width was 2.20 m which equals to the effective width b_{eff} according to Eurocode 4 part 1.1. [9], i.e. 2× L/8. As for the reinforcement steel, a mesh of 252 mm²/m was used.

	Beam 1	Beam 2	Beam 3	Beam 4
Top tee section	IPE 360	IPE 450	IPE 360	IPE 360
Top tee depth h_{top} (mm)	255	275	255	255
Bottom tee section	IPE 450	IPE 450	HEB 450	IPE 450
Bottom tee depth h_{bot} (mm)	300	275	300	300
Stiffener thickness (mm)	20	20	20	20 / 15
Span : L (mm)	8800			
Overall slab length: L_t (mm)	9100			
Slab width : b_{eff} (mm)	2200			
Number of openings	13	13	13	14
Number of circular openings	12	11	12	14
Number of elongated openings	1	2	1	0
Number of semi-infilled openings	0	2	0	0
Cell diameter (mm)	375	335	375	375
Reinforcement mesh	A252			
Number of shear studs	59			
Shear stud diameter (mm)	19			
Shear stud length (mm)	100			
Shear stud spacing (mm)	150			
Mechanical load (kN)	140	160	160	140
Steel grade	S355			
NWC compressive strength (MPa)	31.0	33.0	33.5	29.5

Table 1 : Geometries and properties of the tested beams

Failure mode

For both beam 1 and beam 3, the failure was due to web-post buckling near the beam supports (Figure 2), which is one of the usual modes of failure observed for such beams in fire situation..
Besides, because of its web-post stiffeners, beam 4 could only have a flexural bending failure, as it behaved like an “ordinary” beam. Hence, as beam 1 and beam 4 had the same cross-section, and as their deflection vs. time graphs are very close, beam 1’s collapse might have been caused by combined web-post buckling and flexural bending.
As for the primary beam, i.e. beam 2, no web-post buckling was observed, which leads to the conclusion that this beam also failed by flexural bending.

Beam 1

Beam 2

Beam 3

Beam 4

Fig. 2: Deformed beams

NUMERICAL MODELING

The parametric study was run conducted using SAFIR (version 2007a), CAST 3M and Ansys.

SAFIR Mechanical model

For the mechanical model of the steel profile, 4-node shell finite elements were used, as shown in Figure 3.

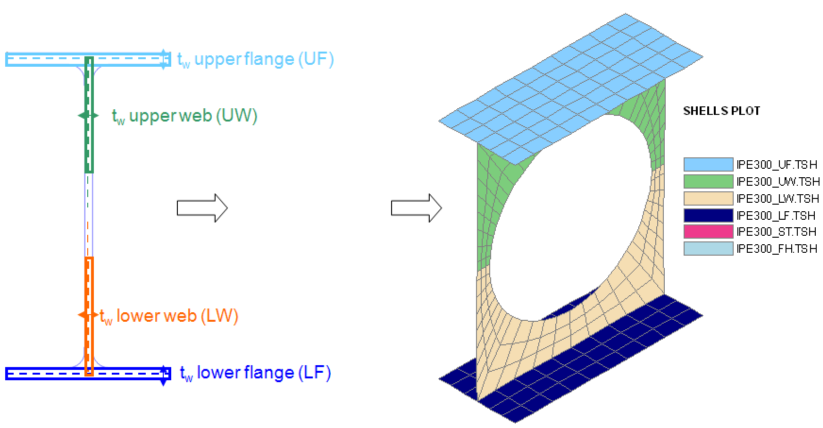


Fig. 3: Mechanical model

The beam was simply supported. Symmetry was used at the mid-span and the lateral displacement of the upper flange was restrained to avoid any lateral torsional buckling (Figure 3).

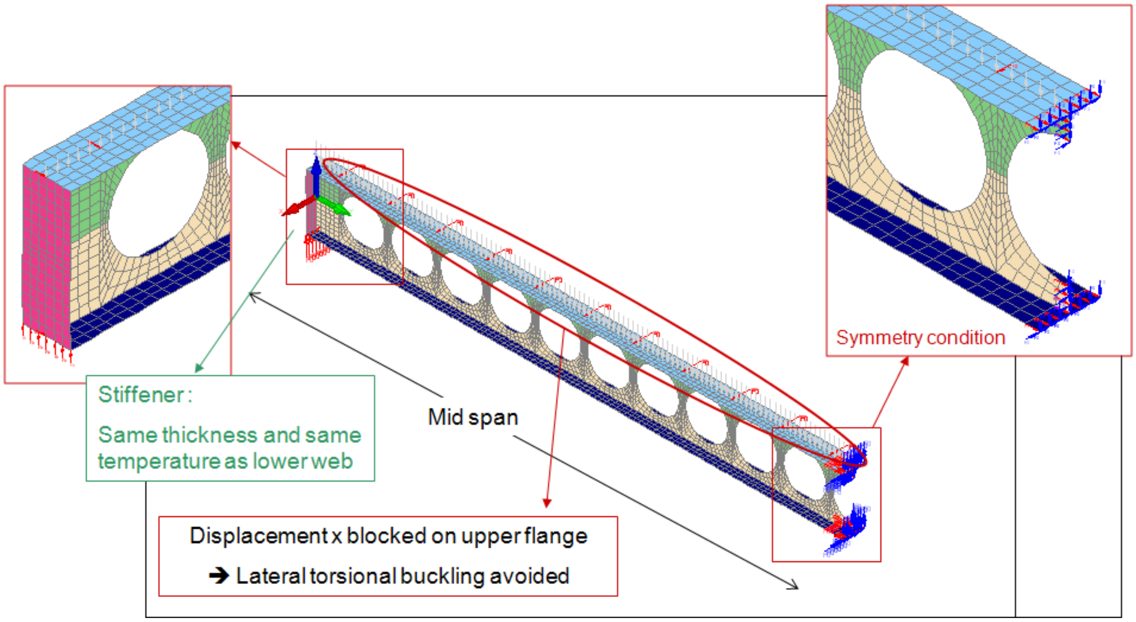


Fig. 3– Boundary conditions for modelled beam

An initial deformation was given to the beam (Figure 4a). This deformation results from the product of a sine curve on the height of the profile (Figure 4b) and of a cosine curve on the length of the beam. The maximum amplitude was 2 mm.

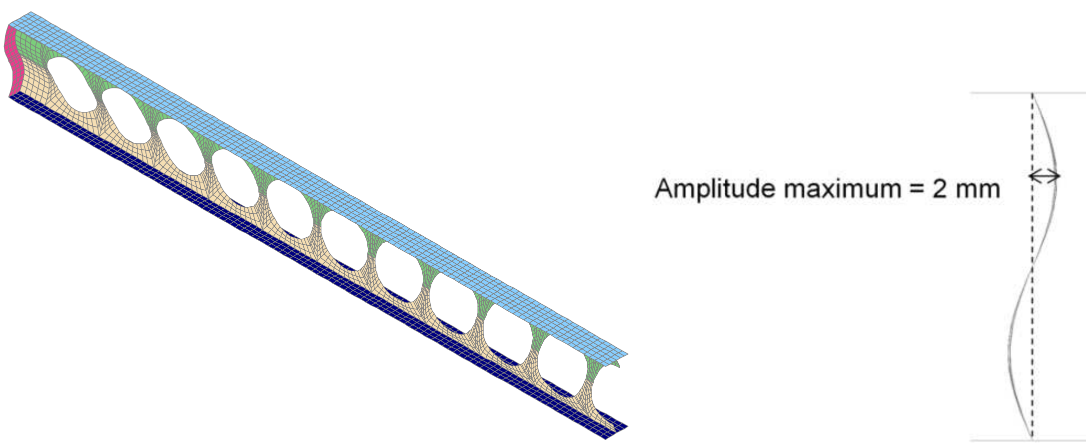


Fig. 4: a) CB with amplified initial deformation (x 15) and b) initial deformation of the web-post

The assumed material properties of the steel were taken according to Eurocode EN1993-1-2 [10], with the variation of different parameters with temperature taken from Eurocode EN1993-1-2.

The Figure 5 shows the comparison between FEM model and the fire test beam 2.

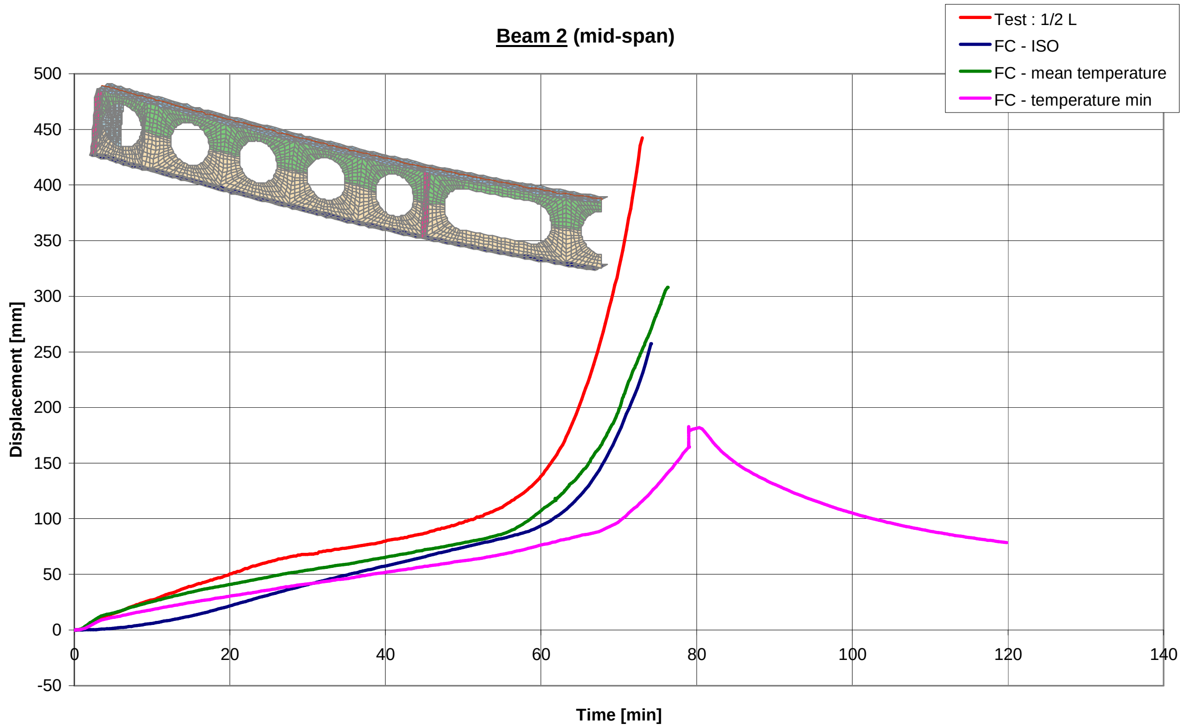


Fig. 5: Time–Displacement diagram of the beam 2 at mid-span

Ansys Numerical Model

The Ansys model was based on a 3D mesh made of shell and beam elements (Figure 6a). As the ribs were neglected in the model, only the concrete part above the steel deck was modelled (Figure 6b). The experimental measured yield strengths were used.

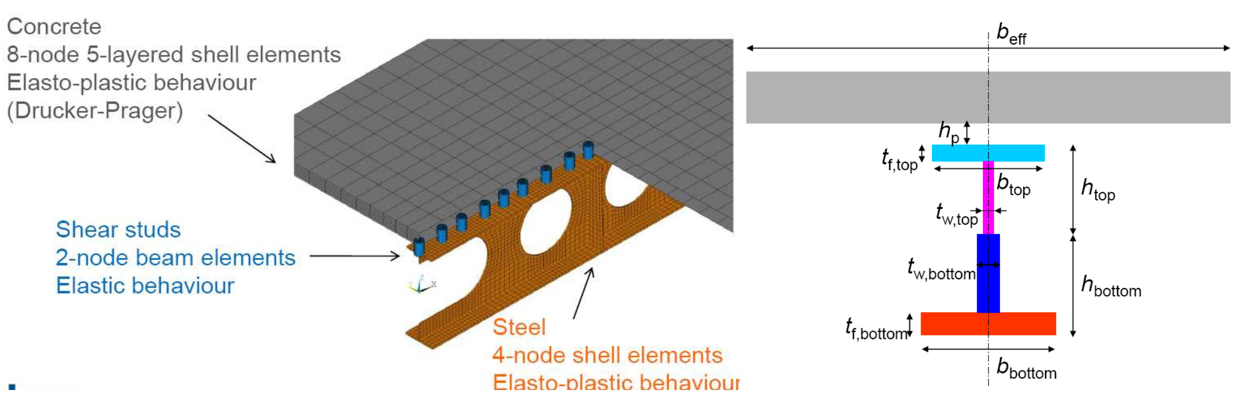


Fig. 6: a)Mechanical analysis model and b)Mechanical analysis cross-section

Due to mid-span symmetry, axial restraints and rotational restraints about the two axes of mid-span cross-section were applied. Support conditions were modelled by restraining vertical displacements. Also, so as to prevent lateral torsional buckling, flange-web junctions in both tees were laterally restrained. The mechanical load was applied to the top steel flange, including self-weight. The analysis was run until numerical failure. Figure 7 shows the comparison between the FEM model and the fire test beam 2.

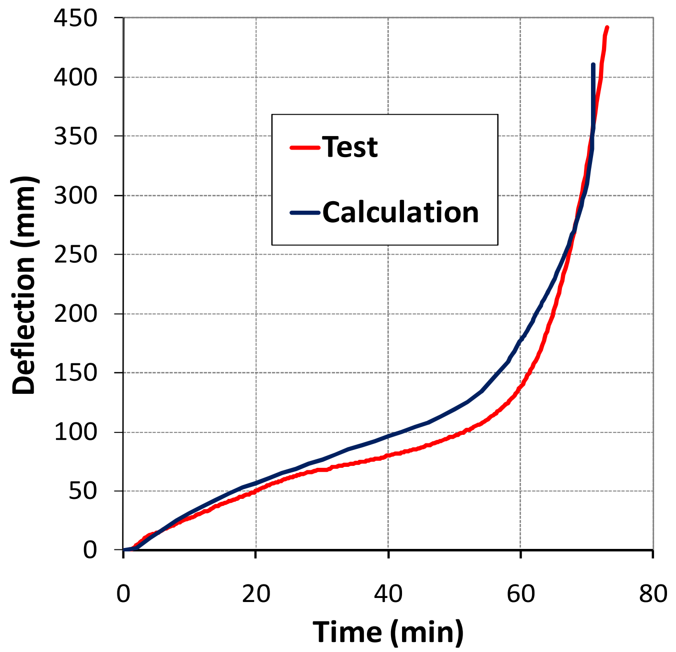


Fig. 7: Time-Displacement diagram of the beam 2 at mid-span

Conclusion on FEM Modelling

A good agreement between the tests and both FEM models is observed, in terms of failure modes and critical temperatures. Thus, theses models can accurately predict the mechanical behaviour of a simply-supported composite cellular beam at elevated temperatures, and can be used for the parametric study which aims to check the relevance of the simplified design method.

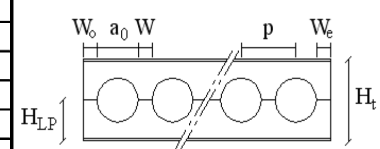
PARAMETRICAL STUDY

This parametrical study was made varying the following parameters:

- steel profile
- geometry of the web-post
- steel strength limit
- loading type
- slab type

Table 2 is summarising the different calculated cases.

	Parameter		minimum value	maximum value	step	number of different beams: PS (Pure steel)	number of different beams: CB (Composite Beam)
general properties	span	L	8 m	20 m	4 m	4	4
	Pure Steel beam or Composite Beam	PS - CB				1	1
	fire curve		ISO fire curve			1	1
	loading	G - Q	PS : 2 concentrated loads - distributed load (load ratio = 0.5) CB : distributed load (load ratio = 0.5)			2	1
steel profile	steel profile	IPE … - HE …	PS : IPE300 - HEA400 - HEM900 CB : IPE300 - HEA400 - IPE300/HEA400			3	3
	steel grade of the profile	f_y	IPE300 : S275 - S355 HEA400 et HEM900 : S355 - S460 IPE300/HEA400 : 355/355 - 355/460			2	2
	total height of the profile	H_t	depending of the steel profile, a_0 and w			1	1
	height lower profile	H_{LP}	depending of the steel profile			1	1
	upper flange thickness	t_{UF}	depending of the steel profile			1	1
	upper web thickness	t_{UW}	depending of the steel profile			1	1
	lower web thickness	t_{LW}	depending of the steel profile			1	1
	lower flange thickness	t_{LF}	depending of the steel profile			1	1
	diameter of openings	a_0	a_0 "normal"	$a_0$max	-	2	2
	position of the first opening	w_0	-	-	-	1	1
	web post width	w	for a_0 "normal" : w_{max} and w_{min} (>50) for $a_0$max : $w_{\text{"optimum"}}$ and $w_{\text{"small value"}}$		-	2	2
	protection	no protection				1	1
concrete slab	concrete slab thickness	h_c	hp = 59mm hc = 61mm	hp = 0mm hc = 120mm	60		2
	overall depth of the profiled steel sheeting	h_p					
	concrete effective width	b_{eff}	min (2 m ; L/4)		-		1
	concrete grade	f_{ck}	C25/30 if S275 and S355 - C30/37 if S460				1
	concrete slab reinforcement	A_s	0.00%				1
	reinforcement grade	f_{sk}	S500				1
	degree of shear connection	h	100%		-		1
						192	192
						= total number of simulations for steel CB	= total number of simulations for composite CB



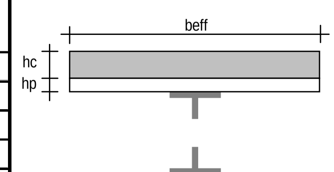


Table 2: Parametrical study cases

Sum-total, 192 simulations are foreseen for pure steel beams and 192 simulations for composite beams.

Results of the parametrical study

The critical temperature and the failure modes were assessed using finite element models and compared with analytical model using the following formula:

$$\frac{\left(Crit\_Temp_{FEM} - Crit\_Temp_{Analytical}\right)}{Crit\_Temp_{FEM}} \times 100 = \Delta$$

This means that when the points are positive, the analytical model predicts a lower critical temperature than the finite element model and so is considered conservative (i.e safe sided).
Figure 8 shows the comparison of the results between FEM and analytical model.

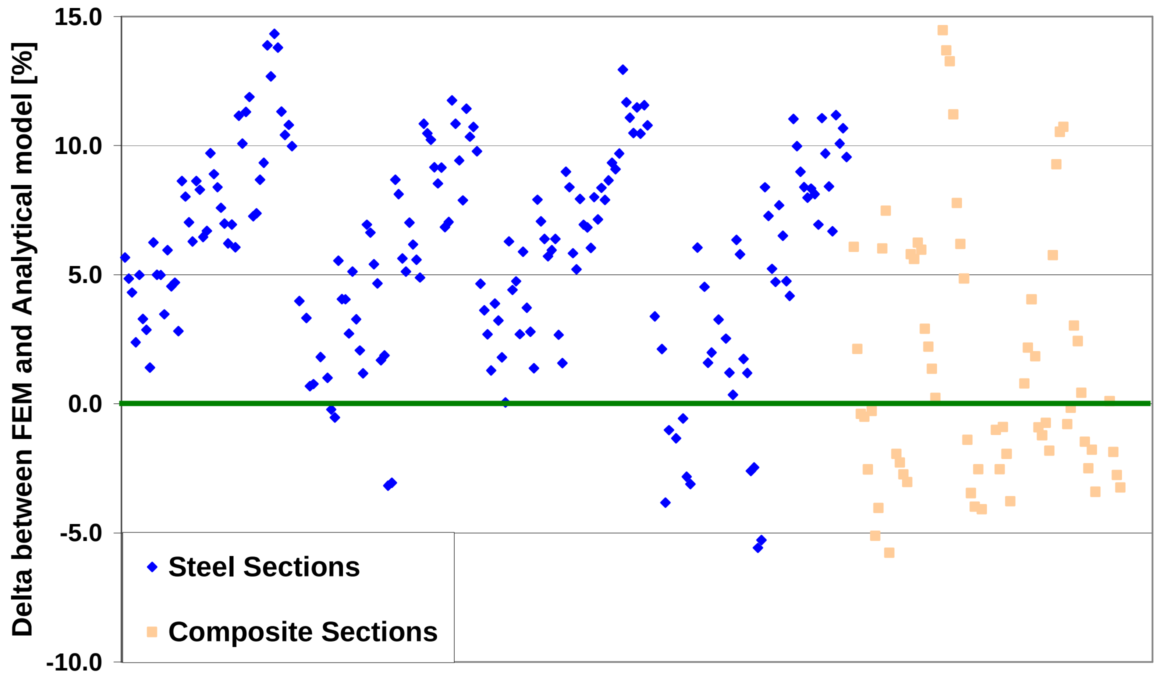


Fig. 8: Time-Analytical model Vs FEM Modelling

Analysing Figure 8, it can be pointed out that the analytical models can predict the critical temperature of steel cellular beams. The analytical model, based on Eurocodes principles, provides safe sided results with acceptable level of accuracy.
It can also be pointed out that the analytical models can also predict the critical temperature of composite cellular beams.
Some numerical simulations still running and points of comparison with analytical models will be added for composite sections. Moreover, the numerical modelling are still analysed because some discrepancies in the results appeared between the different finite elements models for composite sections.

CONCLUSIONS

The different FEM models were able to reproduce with an acceptable level of accuracy the complex behaviour of cellular beams in fire conditions.

On the basis of theses different FEM models, a parametric study was made to validate the developed analytical model.

The analytical model was again validated by this parametrical study and can be used for the prediction of the critical temperature of cellular beam in case of fire. This model takes into account the complex behaviour of cellular beams in fire conditions and is based on the Eurocodes principles taking into account the loss of material properties and stiffness required in the Eurocodes. This model was implemented in a design software called ACB+ and can be downloaded for free on www.arcelormittal.com/sections .

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