Short Term Scientific Mission to the University of Sheffield

Scientific Report of Dr. Sébastien Durif

Objectives:

This short scientific mission of 2 weeks (from 06/04 to 20/04) in the University of Sheffield aimed at exchanging on fire engineering in steel construction. There, I worked on the study of the behavior of cellular beams with sinusoidal openings in fire condition. The discussion focused on the failure modes, the influence of support condition and thermal expansion in the stress distribution and failure behavior. Then, the second objective was to discus on the subject of research of Pr. I. Burgess on the membrane action of concrete slabs and the influence of considering different failure mechanism than those commonly used in fire engineering (FRACOF method).

1. Cellular beams with sinusoidal openings in fire conditions

The study described below deals with the behavior of cellular beams with sinusoidal openings in fire conditions. The fire condition considered is the normative ISO fire curve. Indeed, the aspect studied is not the time of failure or the resistance of a beam to a specific fire but the behavior and the failure modes of those beams for elevated temperatures. Usually, in most studied cases, the load imposed on the beams remains constant and corresponds to 30% of the ultimate failure load obtained in cold condition.

a. Study of the failure modes
   i. global lateral and global lateral torsional buckling

Usually cellular beams are laterally maintained on the upper flange, either by the concrete slab or secondary beams. Indeed, those beams are especially subjected to lateral buckling as the presence of openings along the beam's length reduces the torsional stiffness of those beams. The **figure 1** presents an example of cellular beam in fire condition. It can be seen that the beams fail due to global lateral buckling with a kind of torsional buckling.

Figure 1: Large scale fire test of cellular beams

It can be observed on this figure that even with the lateral support of the upper flange, a global torsional buckling appears and the bottom flange tends to rotate out of its plan and goes up to the upper flange. However, this behavior is related to high displacements and high temperatures that correspond to a state beyond failure (loss of strength).

Therefore, in order to study the specific behavior of sinusoidal openings in fire, it has been decided to prevent the beams against lateral buckling on the upper and bottom flanges. The main objective is to study if the failure modes of the opening remain similar to those observed at ambient temperature so as to be able to adapt the analytical model, developed for cold condition, to elevated temperatures.

At ambient temperature it has been observed two failure modes due to Vierendeel mechanism: either the formation of four plastic hinges like a rectangular opening, or a combination of failure of the opening quarters with local buckling and plastic hinges. In all cases, it has been observed that the failure of the beams is linked to the failure of all opening parts with the formation of a mechanism in a single opening. However, in fire condition, it has been observed some differences.

ii. Formation of four plastic hinges

The failure modes are directly linked to the opening shape. For big openings (ratio opening depth over beam height > 0.7), it has been observed the formation of 4 plastic hinges (see figure 2).

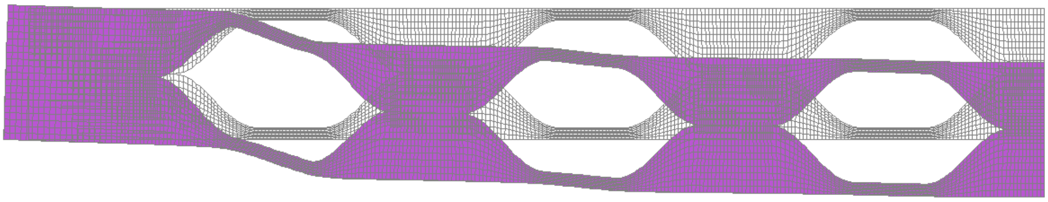

Figure 2: Formation of four plastic hinges in fire condition

The failure observed in this case is clearly linked to the failure observed in cold condition. The study of the stresses at the opening corners is presented in figure 3. This figure gives the equivalent vonMises stresses for five elements on the height of a section at an opening corner. The diagrams of the stresses for each shell element can be compared to the evolution of the theoretical elastic limit that is reduced due to steel temperature. It can be seen that at the time of failure (t = 841s.), all the elements have reached the reduced elastic limit (fy), which corresponds to the formation of the plastic hinge.

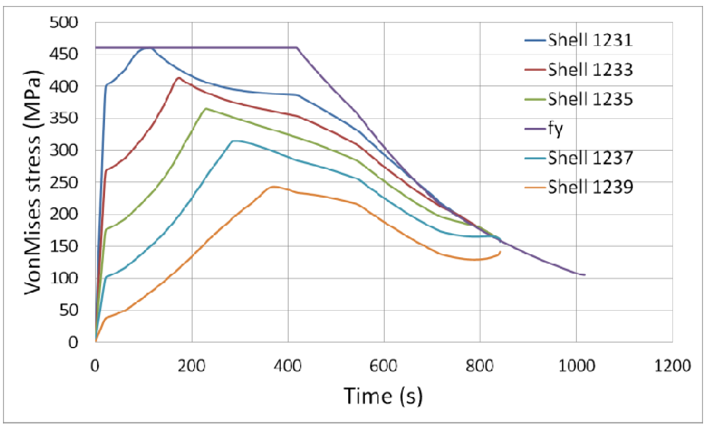

Figure 3: Equivalent vonMises stresses at an opening corner.

iii. local buckling of the quarter of opening and the intermediate web-post

In cases of smaller openings, it has been observed a different behavior. Similarly to ambient temperature, the failures of the opening with smaller depth correspond to the existence of a local buckling. This local buckling appears clearly in the opening quarters were the out-stand fiber is compressed. Thus, we observe out of plane displacement on the upper left and bottom right opening quarter of the first opening (see figure 4).

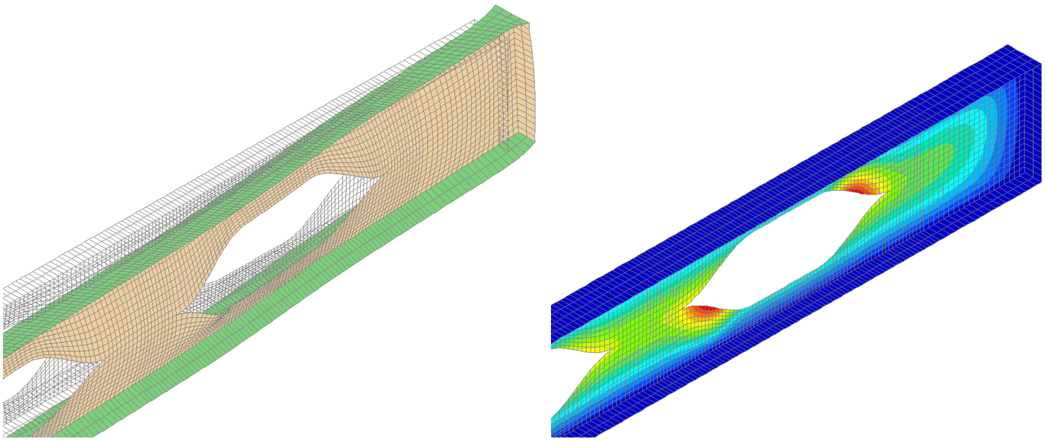

Figure 4: Deflected shape (left), iso values of out of plane displacement (right)

The figure 5 gives the horizontal displacements of the nodes with maximum out of plane displacements on the two related opening quarters and at the mid length of the intermediate web-post.

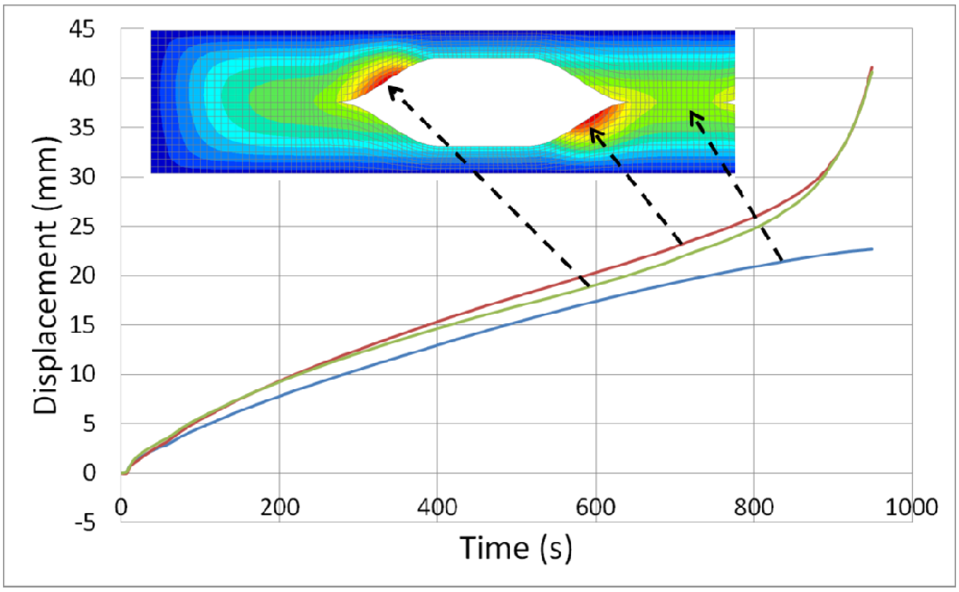

Figure 5: Out of plane displacements of the opening quarter and intermediate web-post

As a consequence, it can be clearly observed that the local buckling of the opening quarter is influenced by a kind of general web buckling. This global buckling may be influenced by a global compression in the web due to thermal expansion.

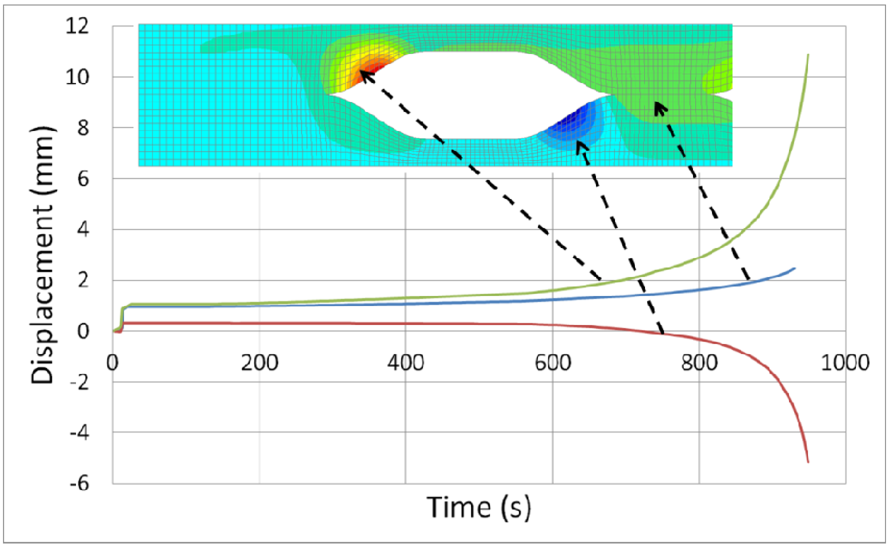

Figure 6: Out of plane displacements for the opening quarter and the intermediate web post without thermal expansion

Indeed, if the calculation is led without any thermal expansion (see figure 6), the deflected shape changes and corresponds more to the one observed at ambient temperature. The out of plane displacements of both opening quarters appear in this case anti-symmetric (see figure 6). Therefore, the thermal expansion seems to have a significant influence, even if we consider bi-supported beam without any axial restraint.

b. Influence of thermal expansion

This part aims at explaining the origin of global compressive stresses in the web due to thermal expansion. All the beams tested are not axially restrained, thus, the beams can freely expand. However, during the heating of the beams, it can be clearly observed a global compression of the web, which reduces at the failure time for important temperatures. The figures 7 to 10 show in function of the time and steel temperature, the distribution of principle stresses around an opening. Tensile stresses are represented in red and compressive stresses in blue.

At a time of 20 seconds, the load remains constant and steel temperature is at 20°. During all the time, the temperature of the gazes increases following the iso fire curve.

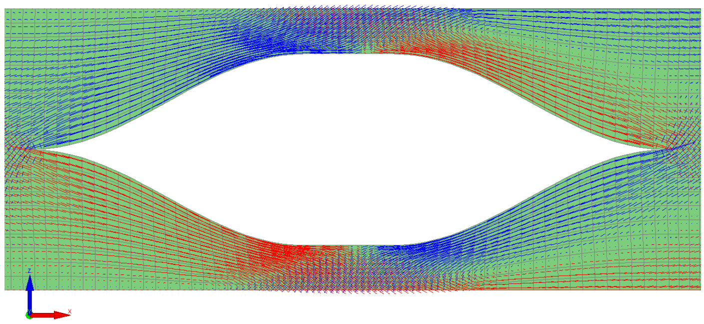

Figure 7: Principle stresses at 20s (steel :20°)

It can be observed on the figure 7 that the distribution of stresses around the opening follows the theory of vierendeel beams which considers a distribution of forces presented figure 11.

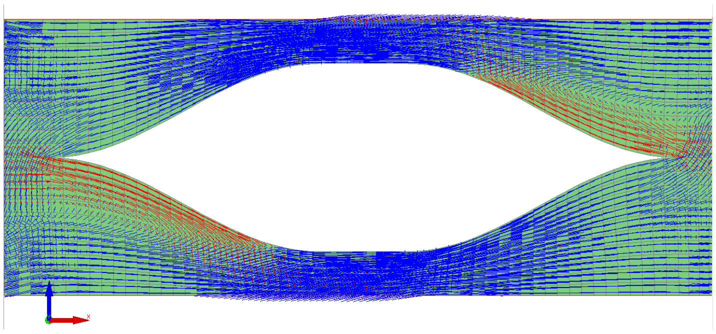

Figure 8: stresses for a time t = 443.5 s (steel: 400°)

It can be seen on figure 8 that for a time of 443 seconds (steel temperature of 400°), the distribution of stresses shows that compression increases in the whole opening with the increasing of steel temperature.

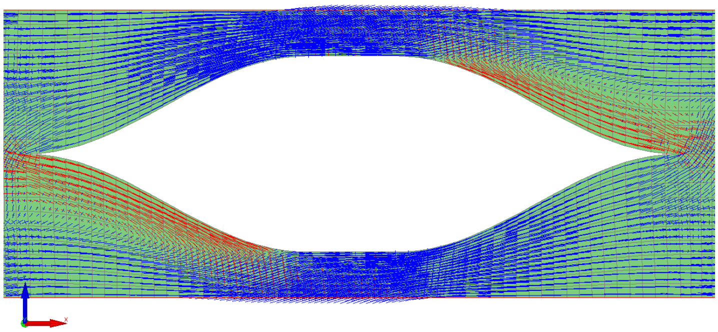

Figure 9: stresses for a time t = 650 s (steel: 550°)

Since the time of 650s, it can be observed (see figure 9) that the compressive stresses in the web reduce. At the time of failure it can be observe that the distribution of stresses is similar to the one observed at ambient temperature (see figure 10).

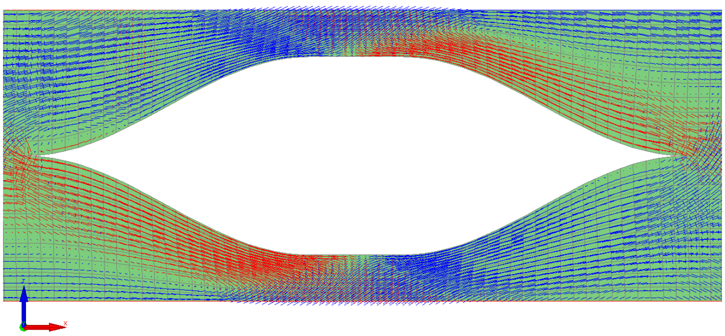

Figure 10: stresses for a time t = 923.5 s (steel: 673°)

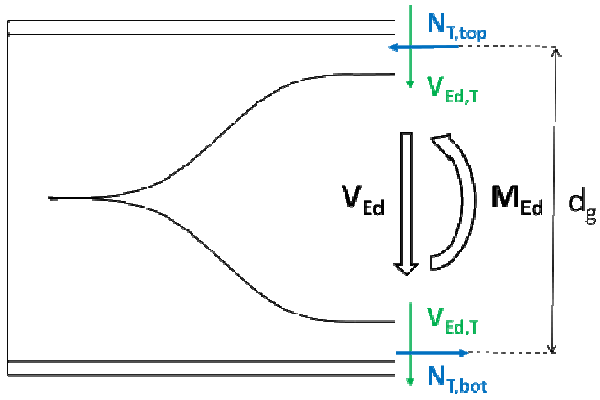

Figure 11: distribution of forces around an opening

c. Study of the analytical model

The study of the analytical model has been done separately. Indeed, the analytical model for cellular beams with sinusoidal openings has been developed by the author for ambient temperatures. However, it has been observed that in the case of small and standard openings, instead of the formation of a mechanism in a single opening, it has been observed that the failure imply the local buckling of opening quarters of several openings and the intermediate web-post. Therefore, in order to compare analytical and numerical results, it has been chosen first to focus the study on models where it has been observed a failure due to the formation of plastic hinges, which imply in this case the formation of a mechanism in a single opening (see figure 2). The table 1 presents the critical temperature obtained theoretically for each opening quarter separately and the critical temperature obtained numerically at the failure of the beam. The steel critical temperature for each opening quarter is deduced theoretically when the plastic hinge is reached.

	Steel critical temperature (°C)	**Iso fire time (seconds)**
Upper left quarter	644	821
bottom right quarter	674	909
bottom left quarter	652	841
upper rigth quarter	681	933
MEAN VALUE	*662.75*	
FEM	652	841

Table 1: Comparison of analytical and numerical results for the critical temperatures

It can be seen on table 1 that the analytical model gives critical temperature close to the one obtained numerically. However, the next work that has to be done is to propose an approach that allow considering the different distribution of stress around the opening when we obtain a plastic hinge, in order to identify precisely the time of failure or the critical temperature of the beam.

d. Forum StiFF: discussion

This forum, organized by the University of Sheffield, represents an event of discussion for different experts from the industry or the University on subjects around fire engineering and steel construction. There, I had the opportunity to discuss with an engineer of the company AkzoNobel that works on the intumescent coating for steel beams. The discussion dealt with the fire protection of cellular beams

The main failure mode of those beams under fire is the intermediate web-post buckling due to the important loss of stiffness of steel under an elevation of temperature. Furthermore, experimental studies led on cellular beams with intumescent coating in fire showed that the temperature of the steel at the intermediate web-post seems to be hotter than for other parts of the beam. This elevation of temperature seems to be linked with the small width of those web-posts, where the failure usually occurs. Therefore, fire design usually needs to have larger web-posts and heavier beams. However, an alternative could be the use of sinusoidal openings, which have larger openings but provide also larger web-posts. Experimental and numerical studies could be led on isolated parts in order to study if in the case of sinusoidal openings, the problem of the elevation of temperature of the intermediate web-post remains a problem or if this shape provides a better behavior when it is protected by intumescent coating.

Some comparison between standard cellular beams and cellular beams with sinusoidal openings in fire condition showed that usually the sinusoidal openings lead to heavier beams. However, in the cases of protected beams, the sinusoidal opening shape may have a better behavior than the circle.

2. Membrane action of concrete slabs : discussion

This short scientific mission has been a good opportunity for me to discuss with Professor Ian Burgess on the behavior of concrete slabs in fire conditions with the development of tensile membrane action. It has been interesting for me to exchange on this subject and learn more about this complex phenomenon.

The membrane action of concrete slabs is full of interest as it can provide substantial additional strength to the structure in fire condition. Indeed, the analysis of large scale tests conducted in many countries revealed that this performance is due to the development of a tensile membrane action in the reinforced concrete slab and the catenary action of the steel beams. A design method has been recently proposed by the FRACOF project (based on C. Bailey and Hayes works).

However, many assumptions have been made to make this design approach. As an example, it considers only one mechanism of failure (see figure 12) whereas at least 4 mechanisms should be studied.

As a consequence, Professor Ian Burgess proposes to come back to the equilibrium of the concrete slab, considering the different possible mechanisms of failure. Through energy equilibrium, he proposes a method of calculation of the additional strength provided by this tensile membrane action in the rebars. Indeed, with vertical displacement, the additional strains in the rebars due to the cracks provide an additional internal energy in comparison to the external work, which leads to an increase of the theoretical load carrying capacity of the slab in order to conserve the equilibrium. The figure 12 presents an example of mechanism with the angle of cracks opening which are taken into account in the calculation of the internal energy.

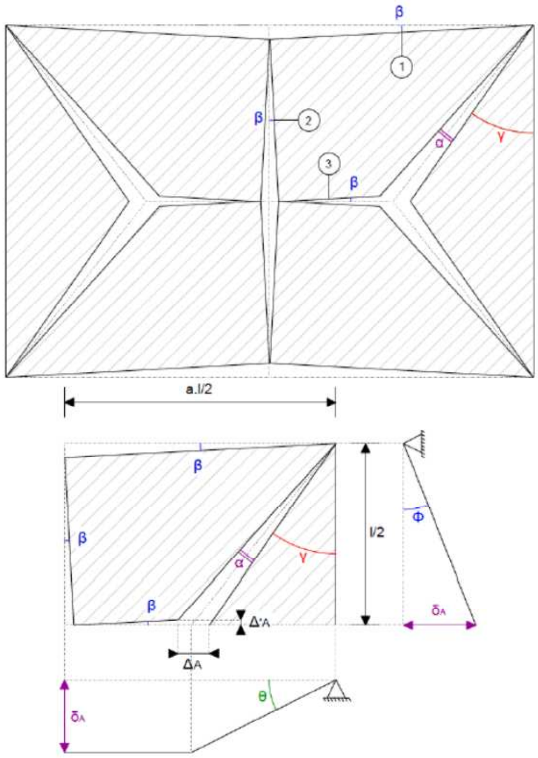

Figure 12: Assumed failure mode for the mechanism A

Furthermore, this new approach points out the evidence of the failure of the rebars which can limit the acceptable displacement.

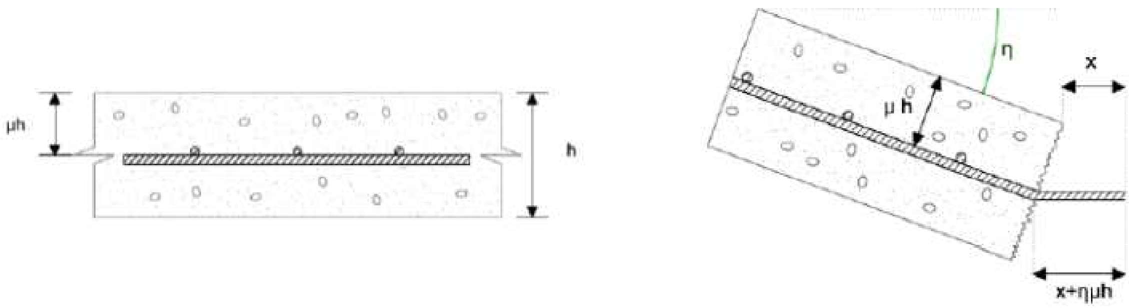

Figure 13: Extension of the rebar; on face of crack

This approach allows identifying the contribution of the rebars in the additional strength of the concrete slab. Furthermore, it shows that the FRACOF method could be in some cases unsafe due to the possible existence of different failure mechanism and failure of the rebars.