PIT Project

Behaviour of steel framed structures under fire conditions

Development of generalised stress- strain relationships for the grillage models of Cardington concrete slab

Research Report

Report R99 SS1

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2. GENERAL NOTES

In the description of the numerical model below the following terms are used :

“The plane” to define the plane of the floor.

“Joist” means a steel beam, and the test Joist means the heated Joist during the fire test.

“Vertical” means vertical to the slab plane.

“In plane” means in the plane of the Long. slab.

“Joist longitudinal direction” or “longitudinal direction” to mean parallel to the Joist length coordinate.

“Transverse direction” to mean at right angle to the Joist longitudinal direction (i.e. in the direction of the longitudinal axis of the ribs Figure 1.

“Reference vertical co-ordinate” is the interface between the Long. slab and Joist .

3. INTRODUCTION

To model the composite concrete slab of the Cardington frame, a generalised stress-strain relationship based on an analytical approach of concrete cross section is developed in this paper. These relationship can then be adopted in the finite element model dedicated to study the behaviour of whole structure under fire condition. The following is a description of the approach used to develop these relationships.

4. SLAB MODELLING

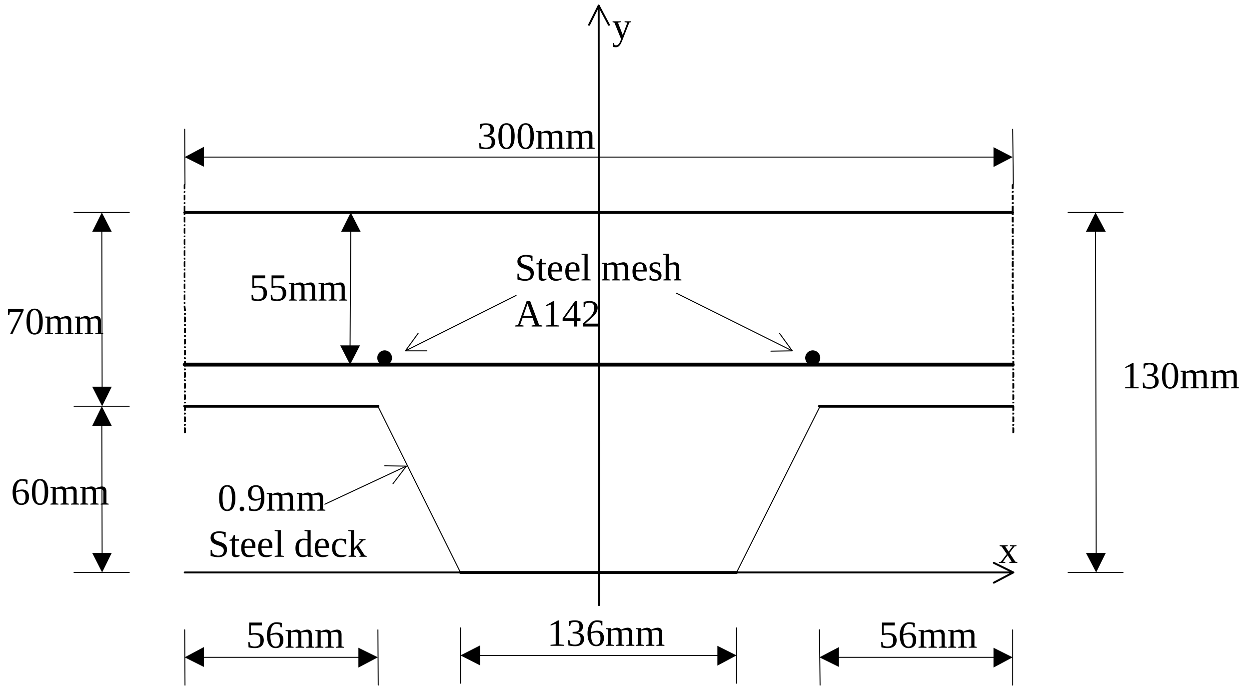
For the reinforced concrete slab of the Cardington building, different parameters have to be considered in slab model. The different behaviours of concrete in tension and compression, the orthotropic behaviour of concrete due to the reinforcing mesh and the decking steel and the development of membrane actions need to be considered in order to provide a realistic representation of the slab behaviour.

A grillage type model of the orthotropic slab seems reasonable here as its stiffness in the direction of the ribs (transverse) is significantly higher that in the longitudinal (parallel to tested joist) direction. The slab is modelled using beam elements corresponding to each rib in the transverse direction and another beam element corresponding to the effective width of the slab is used in the longitudinal direction to act compositely with tested joist. In the transverse (short) direction, slab elements have a trapezoidal shape and the geometry of the concrete section in this direction is shown in Figure 1. The thickness of the steel deck used is 9mm and the reinforcement consists of one layer of A142.

5. SECTION BEHAVIOUR FOR THE REINFORCED CONCRETE SLAB IN TRANSVERSE DIRECTION

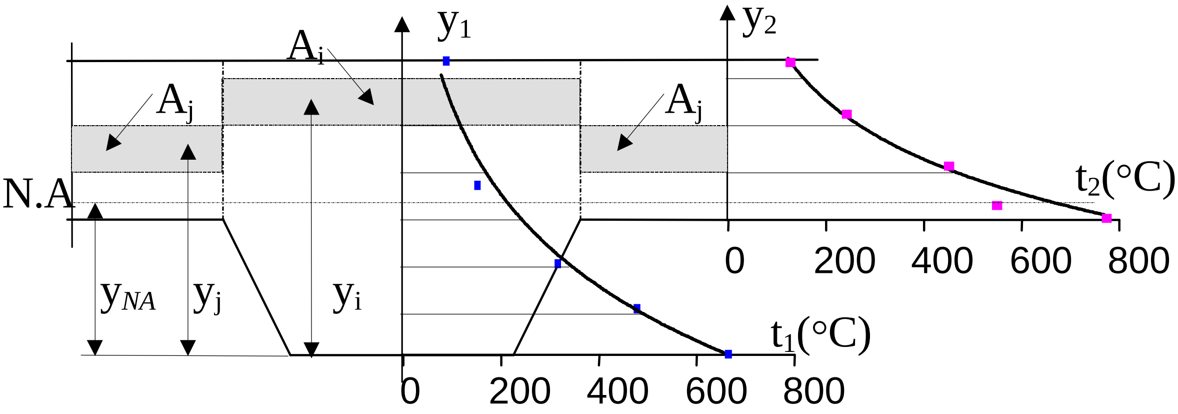
5.1. Concrete cross section

The concrete modelling is based on the global behaviour of the concrete section, taking into consideration the above factors. In each direction, the beam elements, have a pre-defined force-strain and moment-curvature relationship. These relationships are calculated based on the geometry and the material properties of the section in each direction and taking into account the temperature distribution over the cross section and the corresponding material properties are as follows.



Cross section of the composite slab in the lateral direction

Figure 1



Temperature distribution over the slab cross section at end of fire

Figure 2

5.2. Axial force-strain

This direction represents the axis of the slab ribs, running perpendicular to the secondary joists. At ambient temperature, the maximum compression force to be carried by the section is based on the concrete reaching it's crushing strain. At this condition the section resistance limit is calculated by adding the crushing strength of the concrete to the compression force in the steel for the same level of strain. The ultimate section force capacity is considered when the mesh reaches the yielding limit, at this point the total section force is the sum of the maximum forces in the steel combined with the compression force developed in the concrete at the steel yield strain. In the numerical model the behaviour of the reinforced concrete section in compression is approximated by a bi-linear relationship between the axial force and the corresponding axial strain to facilitate the convergence of the numerical solution.

At ambient temperature the section compression force (F) is defined by:

$$F = \sigma_C \; A_C + \sigma_{SD} \, A_{SD} + \sigma_{SM} \, A_{SM} \qquad [1]$$

where σ_C : is the compression stress in the concrete .

A_C , A_{SD} , A_{SM} : area of concrete, steel deck and the mesh respectively

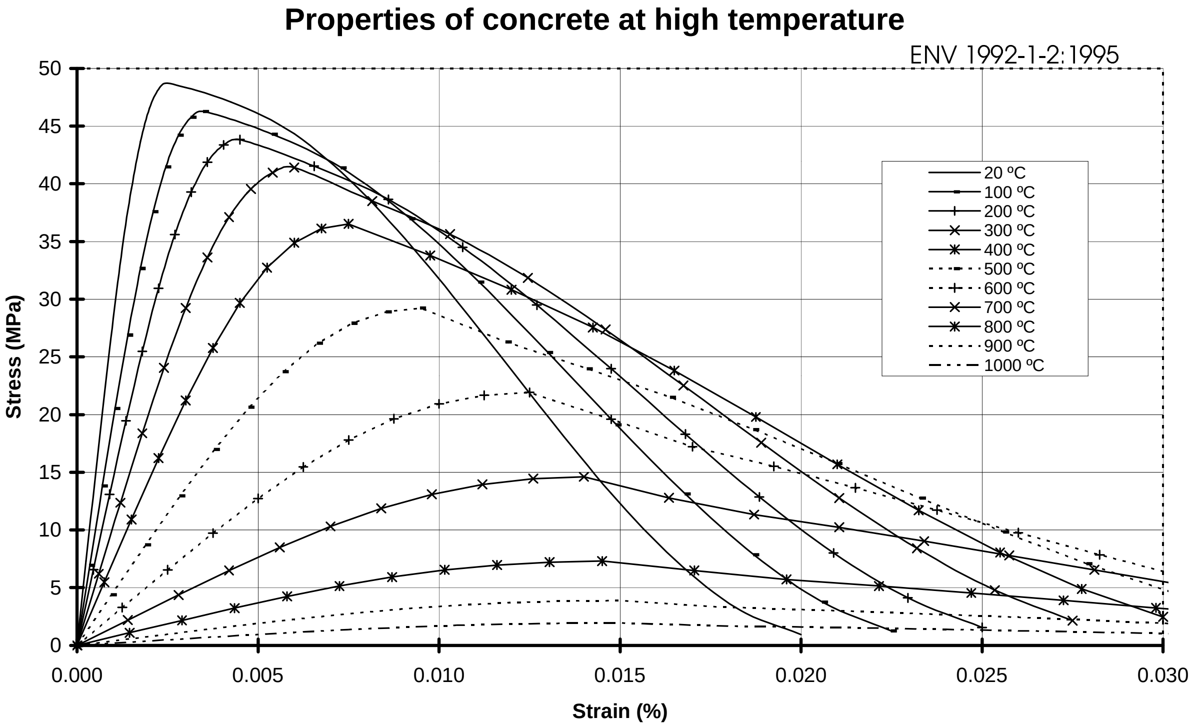
σ_{SD} , σ_{SM} : the corresponding stress in the steel deck and the mesh

At higher temperatures, the material degradation of the steel and the concrete reduces the section axial force capacity. A typical temperature distribution over the cross section of the slab at end of the fire regime is shown in Figure . is temperature is measured at 10 points located at 2 vertical lines, one across the thick depth of the slab (130mm) and the other line across the thin depth (70mm). The temperature distribution over the slab can be approximated in both cases by a third degree polynomial relationship between the height *(y)* above the reference level (the interface level between the slab and the joists) and the corresponding temperature *t(y)*. In this case, the section compression force F_C^t can be defined by :

$$F^t = \int_0^{130} \sigma_C^t(y) \, b(y) \; dy + \sigma_{SD}^t \, A_{SD} + \sigma_{SM}^t \; A_{SM} \qquad [2]$$

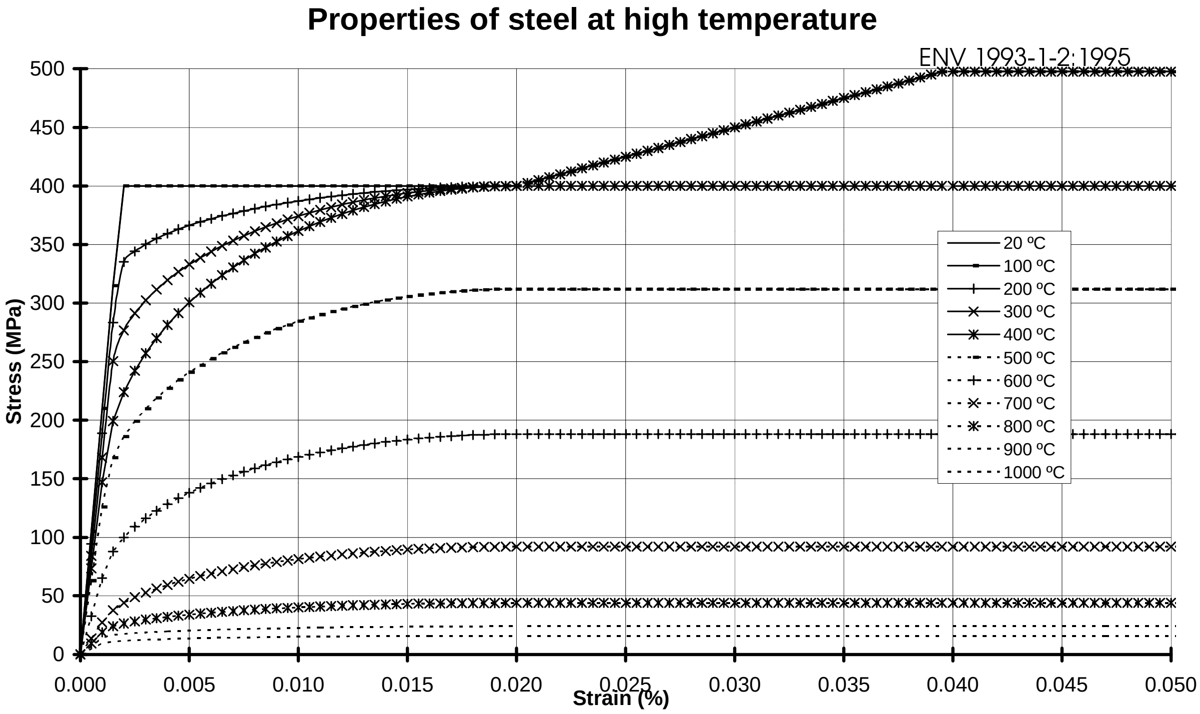
b(y) : is the width of the concrete section at height *y*

To solve the above equation, the slab thickness is divided into a number of horizontal layers and we assume a mean temperature over each layer obtained from the temperature



Concrete stress-strain relationship at high temperature

Figure 2



Steel stress-strain relationship at high temperature

Figure 3

distribution over the section. This approach is applied for both the thick and the thin part of the slab. At time (t) of the fire, the above integral can be reduced to :

$$F^t = \sum_{i=1}^{np1} \sigma_{Ci}^t A_i + \sum_{j=1}^{np2} \sigma_{Cj}^t A_j + \sigma_{SD}^t A_{SD} + \sigma_{SM}^t A_{SM} \qquad [3]$$

np1 , *np2* : are the number of layers for the thick and thin part of the section

A_i area of the concrete layer (i) in the thick part of the slab

A_j area of the concrete layer (j) in the thin part of the slab

For a constant axial strain over the section (ε^t), the stress acting over each strip can easily be calculated, knowing its temperature and using the stress-strain relationships of Figure 2 obtained from the Eurocode2 (1995)^2. Similarly the stress in the steel can be obtained from the stress-strain relationships of Figure 3 obtained from the Eurocode3 (1995)^3. For any intermediate values of temperature, a linear interpolation can be used between the two corresponding curves. In this case the section force is calculated by:

$$F^t = \varepsilon^t \left(\sum_{i=1}^{np1} E_{Ci}^t A_i + \sum_{j=1}^{np2} E_{Cj}^t A_j + E_{SD}^t A_{SD} + E_{SM}^t A_{SM} \right) \qquad [4]$$

E_{Ci}^t , E_{Cj}^t : are the secant elastic modulus for the concrete over each layer of the thick and thin part of the slab respectively.

E_{SD}^{Et} , E_{SM}^{Et} : is the secant elastic modulus for the steel deck and the mesh at same time.

In the above equation all secant elastic modulus are functions of temperature and strain level (ε^t). To define the bi-linear relationship for the numerical model, the section resistance force is calculated based on the strain level equal to the crushing strain of the upper coldest layer and the section ultimate strength is calculated based on the mesh at yielding limit.

In tension, the concrete is not considered to support any tension, and the total section elastic and ultimate limit are calculated based on both the deck steel and the mesh reaching their elastic and yielding limit respectively. Figure 4 shows the force-strain relationship for the slab in the transverse direction.

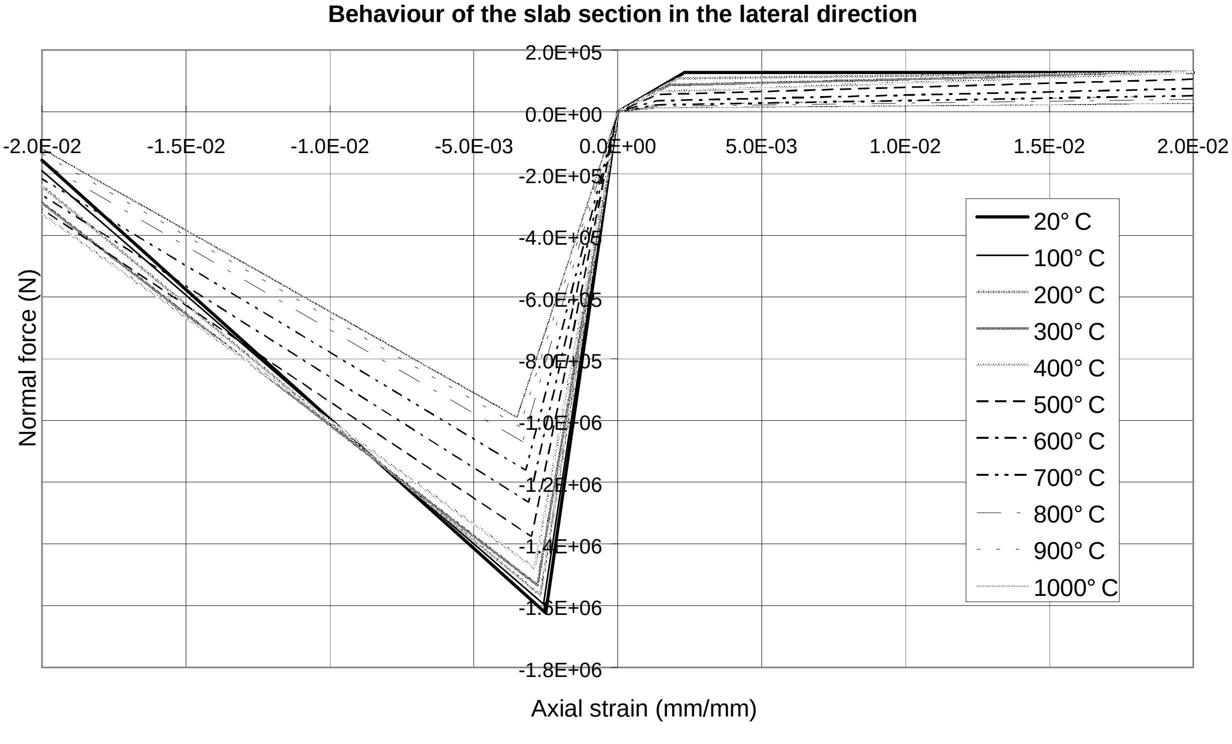
5.3. Moment-curvature

At ambient temperature, the reinforcement is provided by the steel mesh and the steel decking. The contribution of the steel decking increases considerably the section moment capacity in the sagging region. The general equation used to calculate the moment (*M*) is :

$$M = \int_0^{130} \sigma_C(y)\, b(y)\, (y - y_{NA})\, dy + \sigma_{SD}\, A_{SD}(Y_{SD} - y_{NA}) + \sigma_{SM}\, A_{SM}(Y_{SM} - y_{NA}) \quad [5]$$

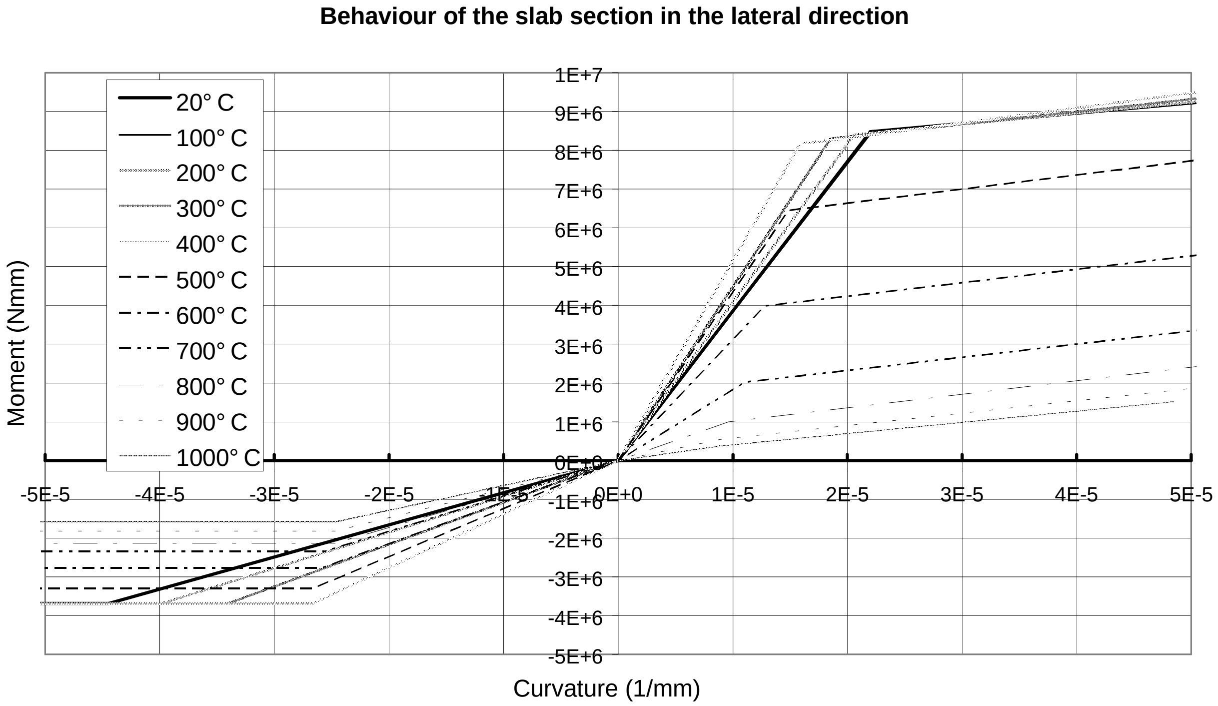
Y_{SD} , Y_{SM} are the heights from the reference level to the steel deck and the mesh respectively. The height of the neutral axis (y_{NA}) is calculated using equilibrium condition between the steel in tension and the concrete in compression and considering linear strain variation across the section.

In sagging, the section elastic moment capacity, is calculated based on the deck steel at yielding, and the section ultimate moment based on the mesh at yielding.



Axial Force- Axial Strain relationship at high temperature in the lateral direction

Figure 4



Moment-Curvature relationship at high temperature in the lateral direction

Figure 5

In hogging a similar approach is followed considering the mesh and the upper part of the steel deck in tension with a balanced force provided by the lower part of the concrete in compression. The section elastic hogging moment is calculated when the mesh reaches its elastic limit. The section ultimate hogging moment is calculated when the mesh reaches its yielding stress. In the numerical model, the moment-curvature relationship, in both zones, is approximated by a bi-linear relation defined by the elastic and the ultimate moment capacity.

At high temperature, the material degradation of the steel and the concrete reduces the section moment capacity. From the temperature distribution over the slab (Figure), we notice that a high thermal gradient exists across the section, the top zone of the slab remains at relatively low temperature, near 100°C, while the deck steel reaches nearly 700°C at end of fire. At this temperature steel, looses most of its strength, which reduces considerably the sagging moment capacity of the section. In hogging, the section capacity reduces due to the reduction of the yield stress in the mesh and the reduction of the concrete ultimate compression due to the high temperatures affecting the bottom of the slab acting in compression. In both cases the section moment is calculated by :

$$M^t = \sum_{i=1}^{np1} \sigma^t_{Ci} A_i (y_i - y_{NA}) + \sigma \sum_{j=1}^{np2} \sigma^t_{Cj} A_j (y_j - y_{NA}) + \sigma^t_{SD} A_{SD} (Y_{SD} - y_{NA}) + \sigma^t_{SM} A_{SM} (Y_{SM} - y_{NA}) \qquad [6]$$

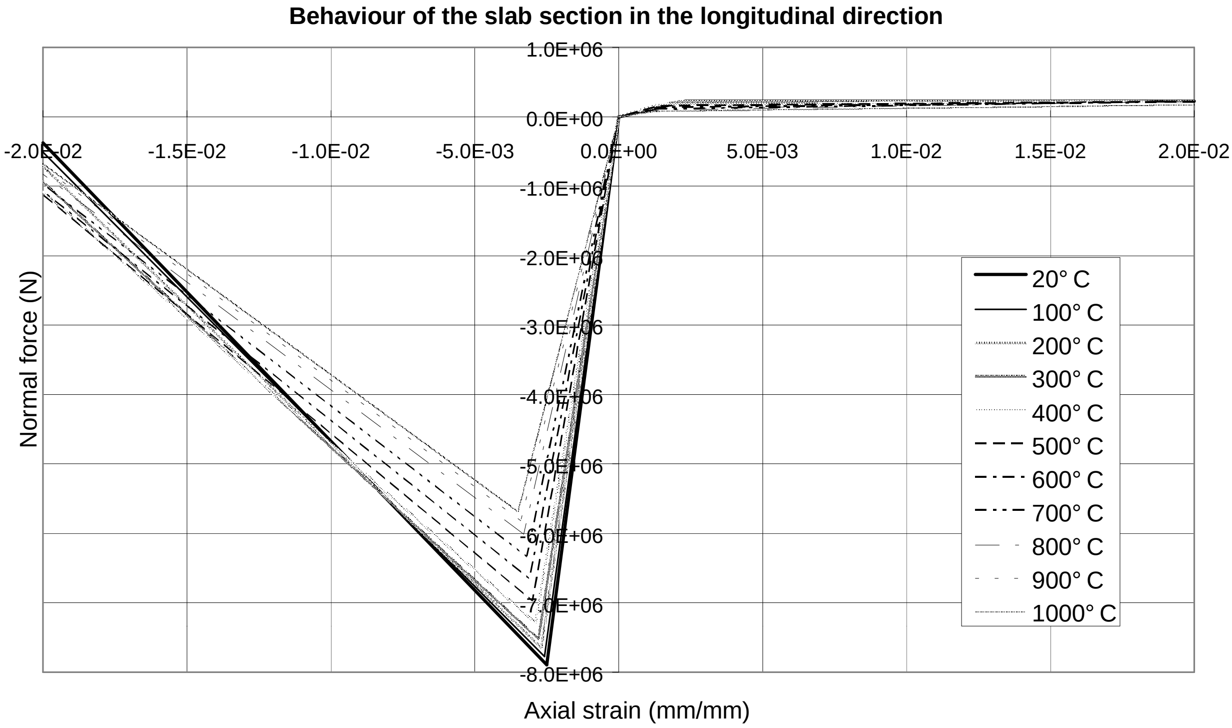
In the above equation the stresses are calculated using the strain and temperature distributions across the section in a similar way as in [4]. Figure 5 shows the moment-curvature relationship at different temperature (hogging moment have negative sign).

6. SECTION BEHAVIOUR FOR COMPOSITE SLAB IN THE LONGITUDINAL DIRECTION

The slab running in the longitudinal direction, parallel to the secondary beams, acts in a composite manner with the joists. The composite action is developed by means of a large number of shear connectors transmitting the shear between the slab and the steel member and provides a composite section moment capacity, known to be far larger than the moment capacity of the joist and concrete members separately. To be able to represent the joist and the longitudinal slab by beam elements, the composite slab behaviour is described as following.

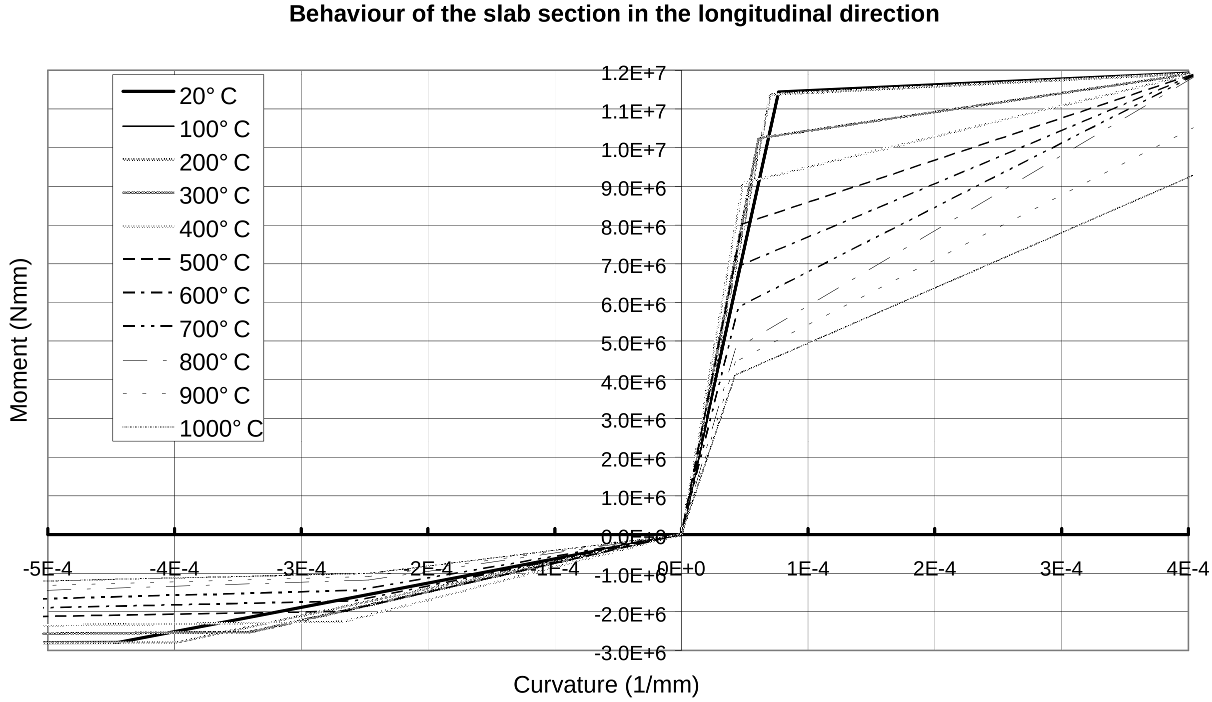
6.1. Axial force-strain

In the longitudinal direction, the section behaviour is pre-defined in a similar manner as for the lateral direction. The effective width of the slab acting together with the beam is defined according to the Eurocode4 (1994)[5] and equal to 2250mm with a depth of 70mm. For the calculation of the section force and moment, only the steel of the mesh is considered for the section design as the deck steel is not continuous along the slab axis.



Axial Force- Axial Strain relationship at high temperature in the longitudinal direction

Figure 6



Moment-Curvature relationship at high temperature in the longitudinal direction

Figure 7

Moment-curvature

Taking into consideration the rectangular shape of the section and the temperature distribution along its depth, the maximum and ultimate compression force can be calculated from equation 3 and 4 respectively. Figure 6 represents the axial force-strain relationship of the composite slab section in the longitudinal direction in both compression and tension regions.

6.2. Moment-curvature

In sagging region, the design of the section is based on a cracked section for the concrete, the tension force is produced by the mesh. The section elastic moment capacity is calculated when the steel reaches its proportional limit defined from the stress-strain relation (Figure 3) at the corresponding temperature. For the ultimate moment capacity the steel is considered at yielding state. The same method is used to define the elastic and ultimate moment in hogging regions, taking into consideration the reduction of the tension force in the mesh at high temperatures and the reduction of concrete strength in compression at the bottom of the section. Figure 7 shows the moment-curvature relationship for the concrete section, in the longitudinal direction, under different temperatures.

7. CONCLUSION

In this report we described a new approach used to model the reinforced slab behaviour in a composite structures under fire. First a generalised stress strain relationship was developed to describe the slab behaviour in each direction, the direction parallel to the joist and in the direction of the ribs (transverse direction). The generalised relationship is based on the global behaviour of the slab section in each direction where the temperature distributions and the reduction of material properties is taken into consideration by dividing the section area to horizontal strips and considering the strain compatibility over the section. The results of this analytical formulation produced an uncoupled force-strain and moment-curvature relationships which can then used in the finite element “grillage” models developed to predict the behaviour of the composite framed structures during the fire tests carried on Cardington slab.

8. REFERENCES

Abaqus (1994), “Abaqus theory manual and users manual, version 5.4, Hibbit, Karlsson and Sorensen Inc., Pawtucket, Rhode Island, USA"

P.N.R. Bravery (1995), “Cardington large building test facility, Construction details for the first building, internal report British Steel plc.”

D.J. O’Connor and al. (1995), “Determination of the fire endurance of model concrete Long. slabs using a plastic analysis methodology, The Structural Engineer, Volume 73, No 19/3.” (1995)

Eurocode 2 (1995), “Design of concrete structures Part1 2 : General rules Structural fire design, ENV 1992 1 2.”

Eurocode 3 (1995), “Design of steel structures Part1 2 : Fire resistance, ENV1993 1 2.”

Eurocode 4 (1994), “Design of composite steel and concrete structures Part1 1 : General rules and rules for buildings, ENV 1994 1 1”

B.R. Kirby (1995): Behaviour of a multi storey steel framed building subject to natural fires: Test1 restrained beam, deflection measurements, Document ref; S423/1/Part D1, British Steel plc.

Rotter, J.M., Sanad, A.M., Usmani, A.S. and Gillie, M. (1999) "Structural performance of redundant structures under local fires", Proc., Interflam ’99, 8th International Fire Science and Engineering Conference, Edinburgh, 29 June - 1 July, Vol. 2, pp 1069 - 1080.

Sanad, A.M., Rotter, J.M., Usmani, A.S. and O'Connor, M.A. (1999) "Finite element modelling of fire tests on the Cardington composite building", Proc., Interflam ’99, 8th International Fire Science and Engineering Conference, Edinburgh, 29 June - 1 July, Vol. 2, pp 1045 - 1056.

Sanad A.M. (1999) “British Steel Fire Test1: Reference ABAQUS model using grillage representation for slab” Research report R99-MD1, University of Edinburgh, Department of Civil and Environmental Engineering.

Sanad, A.M., Lamont, S., Usmani, A.S. And Rotter, J.M. (2000) " structural behaviour in fire compartment under different heating regimes – part 1 (Slab thermal gradients)" to submit Fire Safety Journal.

Sanad, A.M., Lamont, S., Usmani, A.S. And Rotter, J.M. (2000) " structural behaviour in fire compartment under different heating regimes – part 2 (Slab temperatures)" to submit Fire Safety Journal.

Sanad A.M., Rotter J.M., Usmani A.S. and O'Connor M.A. (2000), "Behaviour of beams in composite building under fire", to submit Fire Safety Journal.