PIT Project

Behaviour of steel framed structures under fire conditions

STUDIES USING NUMERICAL MODELS : EFFECT OF SLAB TEMPERATURE VARIATION IN BRITISH STEEL TEST1

Research Report

Report R00-SM4

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February, 2000

ABSTRACT

Modelling the British Steel Fire Tests has led to new understanding of the behaviour of structures under fire conditions. Much of this understanding has come from parametric analysis of the models. The structural phenomena observed in highly redundant, composite structures, during a compartment fire are due to the huge impact of restrained thermal expansion. The large deflections experienced in the structural elements in the region of the fire are almost solely due to restrained thermal expansion. Thermal gradients play a supporting role but material degradation and loading are secondary influences. A clear understanding of the response of the structure to temperature and temperature gradients is essential. This paper discusses the response of the grillage model of test 1 to changes in the mean temperature and temperature gradient applied to the slab.

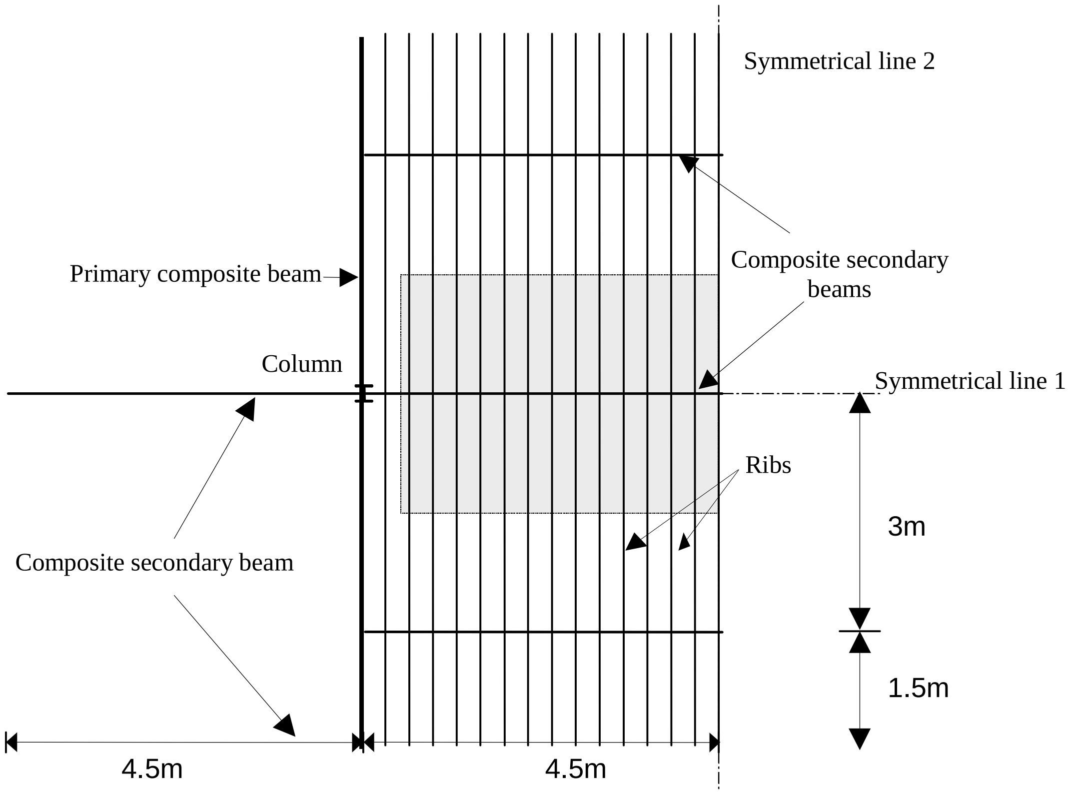
INTRODUCTION

Restrained thermal expansion is a major influence on all the structural phenomena experienced in the Cardington Frame Fire tests. Therefore, the effect of temperature and temperature gradient must be clearly understood. The finite element models, using the commercial package ABAQUS[1], developed to simulate the behaviour of the structure in Cardington fire tests (Sanad 1999)[6,7] reproduce all the phenomena occurring during a fire and have the advantage of providing a description of the complex behaviour in a relatively simplified context by virtue of representing the slab using a *grillage* type model. The report sets the context and provides brief details of the model used before presenting the results and their interpretation for the case of applying different thermal regimes to the concrete slab.

THE FINITE ELEMENT MODEL

The study of the effect of temperature on the structural behaviour is carried out using a finite element model which was developed by the authors and validated against the test results in a previous paper (Sanad & al. 1999)[8]. A brief description of the model is given below. The model was developed to illustrate the structural behaviour in BS Test1 in a relatively simple manner. Exploiting symmetry, only half the compartment was modelled and the effect of the surrounding floor was also represented by symmetry boundary conditions (Figure 1). In the model, the slab was represented by a grillage of cross beams running in the two orthogonal directions, parallel to the secondary beams (longitudinal direction) and parallel to the primary beam (transverse direction). The model is fully geometrically and materially non-linear including temperature dependent material properties.

In the transverse direction, each rib of the slab is represented by a discrete beam connected to the secondary beams. In the longitudinal direction, the composite slab is represented by a concrete beam rigidly connected to the secondary steel joist below it. The effective width of the composite slab and the material properties used for concrete were deduced from Eurocode[2, 4]. Each secondary steel joist is connected to either a column or a primary beam according to the arrangement in the real building. The primary joist also has a slab rigidly connected to it to model the composite behaviour. The temperature regime applied to the slab was represented by a mean temperature acting at the geometric centroid and a mean gradient acting through its depth as illustrated in Figure 2 for the ribs, and in Figure 3 for the composite longitudinal slab.

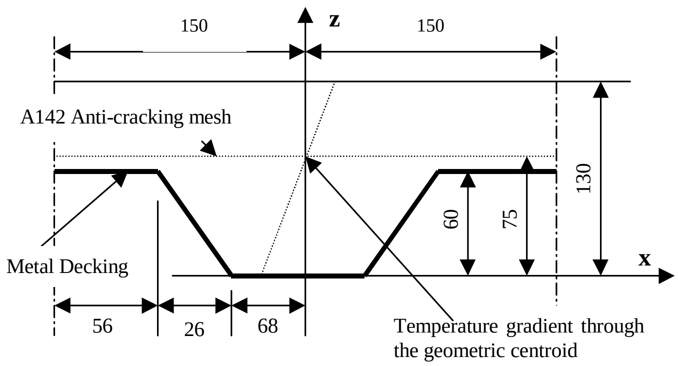


Layout of the Cardington Fire tests
Figure 1

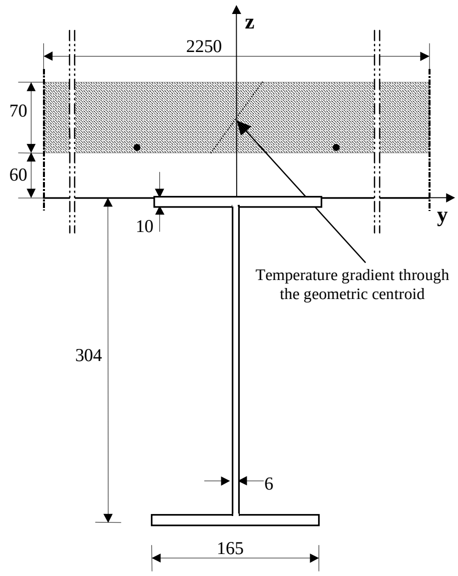
The temperature applied to each member was increased linearly from ambient to the maximum temperature. The gradient in the slab and the joist was also increased linearly from zero to the final value. The actual variation of temperature and gradient in the tests was not linear, however this idealisation of linear evolution allows an easier interpretation of the structural behaviour. This is because in a detailed examination of model results the events related to structural phenomena are separated from variations caused by changes in the thermal regime. The temperatures and gradients over the structural elements were applied separately for the steel joists, the longitudinal composite slab and the transverse ribs. Table 1 gives the values used in the reference calculation for the test.

Structural member	**Reference final temperature**	**Reference final gradient**
Heated Joist	800°C	0.26°C/mm
Composite slab	265°C	4°C/mm
Ribs	360°C	5°C/mm

Reference thermal loading on the structure
Table 1



Cross section of one rib showing the location of the geometric centroid and the temperature gradient through its depth
Figure 2



Cross section of the composite beam showing the location of the slab geometric centroid and the temperature gradient through it
Figure 3

PARAMETRIC STUDY

This parametric study looks at the effect of changing the mean temperature applied at the geometric centroid of the slab and the temperature gradient through it. Table 2 lists the four parts to the parametric analysis. In each case only the mean temperature or gradient in the slab was changed and only in one direction, in the longitudinal direction parallel to the joist or in the transverse direction perpendicular to the joist. All other values remained constant.

Part	Parameter Investigated	Location in the Model
1	Mean centroidal temperature	Transverse direction
2	Mean centroidal temperature	Longitudinal direction
3	Temperature Gradient	Transverse direction
4	Temperature Gradient	Longitudinal direction

Four Parts to the parametric analysis
Table 2

Increasing the temperature applied at the geometric centroid of the slab will increase the axial thrusts induced by the coupled effect of thermal expansion and restraint provided by the rest of the cold slab. Similarly reducing the temperature applied will decrease the axial thrusts experienced. Temperature differentials between the top and bottom surface of the slab lead to thermal bowing and tensile strains, which can increase deflections. Some of the increase in length caused by thermal expansion will be absorbed by the action of thermal bowing.

RESULTS/OBSERVATIONS

Changing the temperature at the geometric centroid of the transverse slab

Increasing the temperature of the ribs in the model leads to an increase in the restrained thermal expansion experienced in this direction.

Response of the composite joist

As the temperature applied is increased from the reference case (measured test 1 temperatures) the deflection at mid-span increases. 1.5 x temperature produces 25mm greater deflection throughout the test compared with the reference case (1.0 x temperature), see figure 4. All the figures showing the results of the parametric analysis are plotted against the joists lower flange temperature.

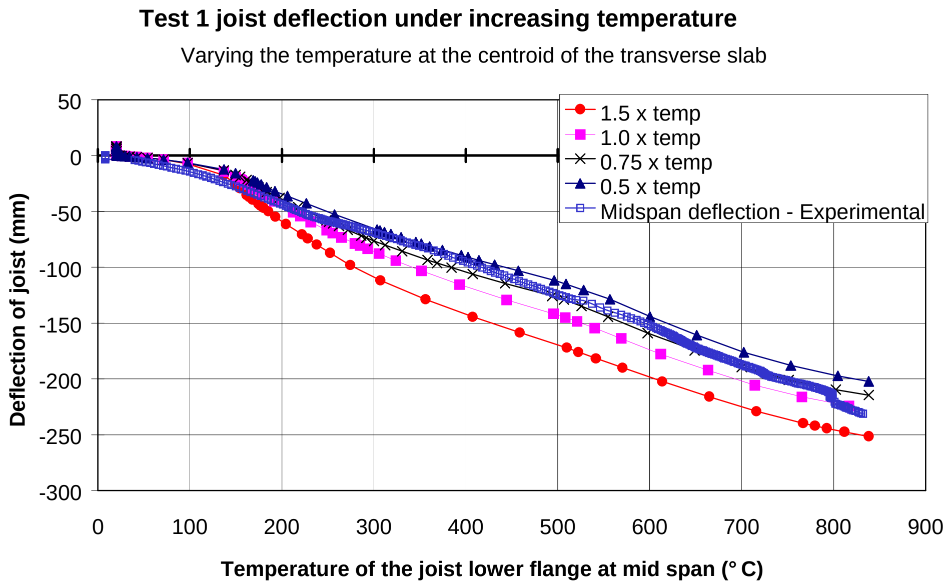


Figure 4: Test 1, Joist deflection: Varying the temperature at the centroid of the transverse slab

In general the axial force in the composite beam and concrete section decreases as the temperature applied to the ribs is increased. Looking at axial forces in the concrete and the joist separately, along the length of the joist at x/l=0.0 (column/furnace wall) the joist is insensitive to changes in the applied temperature because it has reached its first yield limit in compression (figure 5). At x/l=0.5 (mid-span) the concrete axial force is much greater than the joist axial force because the loads have been redistributed from the joist to the concrete slab. This can be seen clearly in figure

6. However, the compressive axial force in the concrete is decreasing with an increase in the temperature applied in the transverse direction.

In terms of moment, overall the moment differences increase as the temperature applied increases (figure 7). However, the *P*-• moment (moment due to axial force (*P*) and deflection (•)) decreases because although the deflection is increasing with temperature the axial force is decreasing. The joist increases in hogging at the support (x/l=0.0) and sagging at mid-span (x/l=0.5) as the temperature applied increases (figure 8). Figure 8 shows only the moment in the joist because the moment in the concrete is insignificant in comparison. The joist moment is of the order 5 x 10^7 Nmm and the concrete moment 1 x 10^6 Nmm.

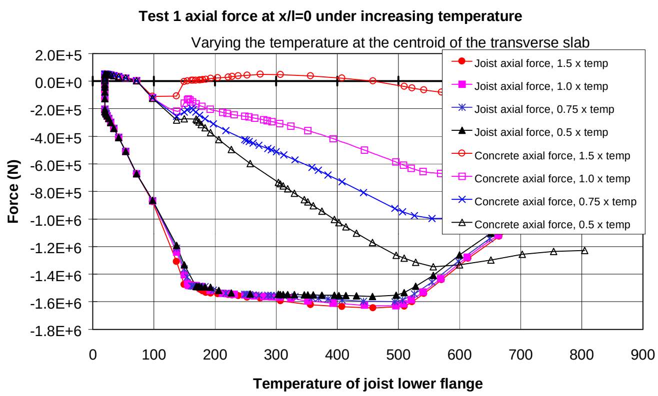


Figure 5: Test 1, Axial force at x/l=0.0: Varying the temperature at the centroid of the transverse slab

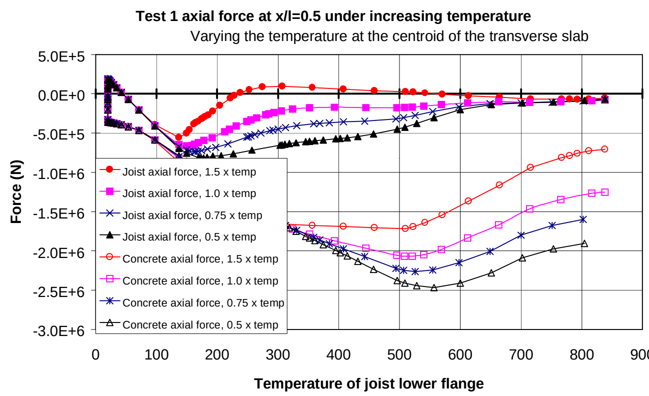


Figure 6: Test 1, Axial force at x/l=0.5: Varying the temperature at the centroid of the transverse slab

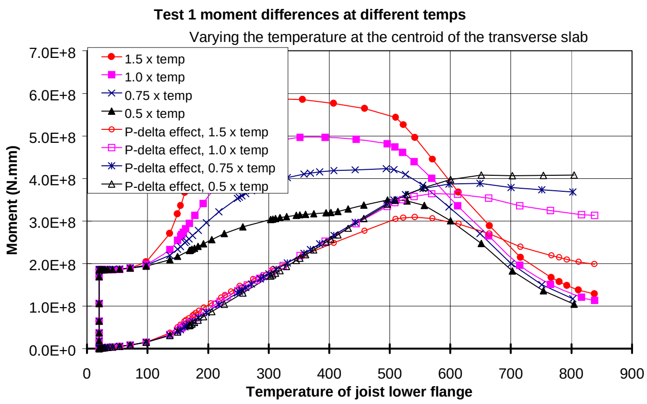


Figure 7: Test 1, Moment Differences: Varying the temperature at the centroid of the transverse slab

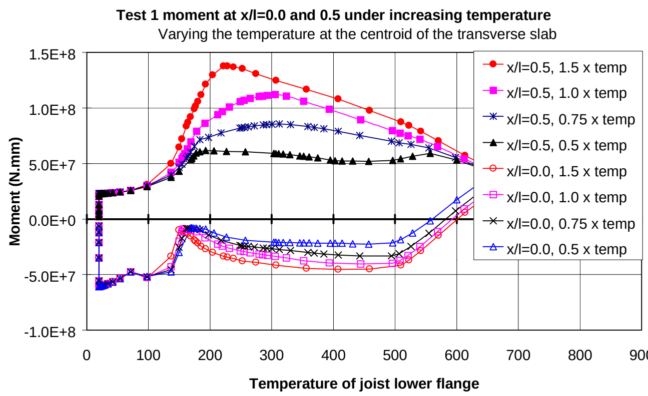


Figure 8: Test 1, Joist Moment at x/l=0.0 and 0.5: Varying the temperature at the centroid of the transverse slab

Response of the Ribs

Figures 9 and 10 highlight the response of the ribs at x/l=0.0 and 0.5. The axial force in the ribs increases significantly with increasing temperature. This is expected because as the temperature in the ribs increases they will expand and the effect of restrained thermal expansion will be greater.
The ribs moment over the joist is relatively unaffected by the change in temperature of the ribs until x/l=0.3, 0.4, 0.5 when the moment increases in sagging bending as the temperature increases. The

ribs moment over the joist only shows significant changes after a joist lower flange temperature of 200°C.

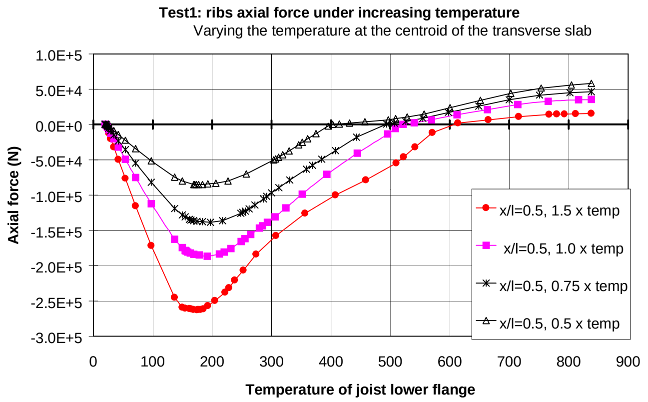


Figure 9: Test 1, Ribs Axial force at x/l=0.0 and 0.5: Varying the temperature at the centroid of the transverse slab

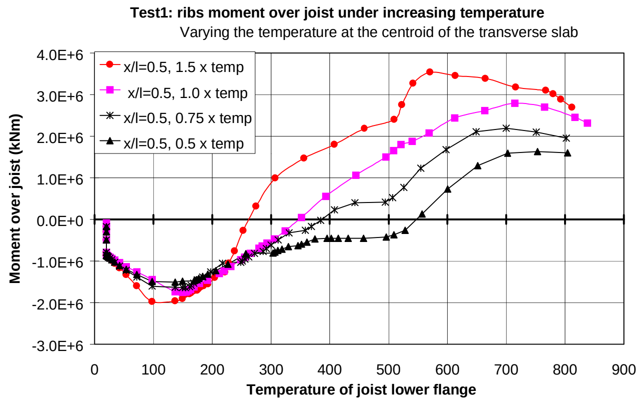


Figure 10: Test 1, Ribs moment over the joist at x/l=0.0 and 0.5: Varying the temperature at the centroid of the transverse slab

Changing the temperature at the geometric centroid of the longitudinal slab

This situation enhances the effect of restrained thermal expansion in the concrete in the direction of the tested joist. In this case the slab temperature is varied in the direction perpendicular to the ribs in the thinner part of the slab. Moreover, the heated slab is longer in this direction leading to a greater change in length in this direction and larger *P*-• moments.

Response of the Joist

As the temperature applied is increased the mid-span deflection gradually increases until at the end of the test the deflection calculated for 1.5 x temperature and 2.0 x temperature is 50mm greater and 100mm greater respectively than the reference case. See figure 11.

The composite axial force increases significantly as the temperature applied is increased. This is mainly due to the axial force in the slab (-4200kN at 2.0 x temp compared with -2000kN at 1.0 x temp) see figure 13. As before a x/l=0.0 the joist s insensitive to changes in the temperature applied and at x/l=0.5 the axial force in the joist is insignificant compared with the huge compressive axial forces in the concrete. The large increase in axial force with temperature causes the moment due to *P*-• to grow enormously. Figure 4 illustrates this.

At x/l=0.0 hogging moment increases if the temperature applied is reduced but only until a lower flange temperature of 150°C is achieved. Beyond this, the moment at x/l=0.0 is insensitive to the applied temperature until nearer the end of the test when the joist moves into sagging bending and an increase in applied temperature increases the moment response. Sagging moment in the joist at mid-span increases with an increase in temperature applied to the concrete in the direction of the joist. This is illustrated in figure 15.

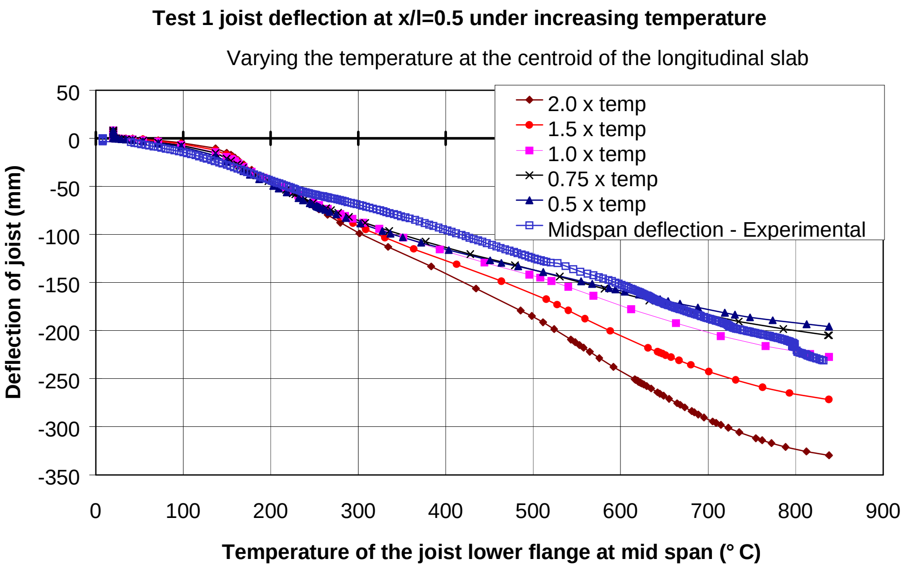


Figure 11: Test 1, Joist Deflection: Varying the temperature at the centroid of the longitudinal slab

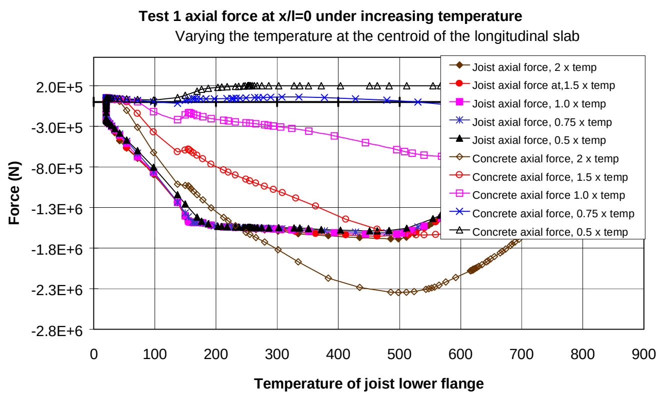


Figure 12: Test 1, Axial force at x/l=0.0: Varying the temperature at the centroid of the longitudinal slab

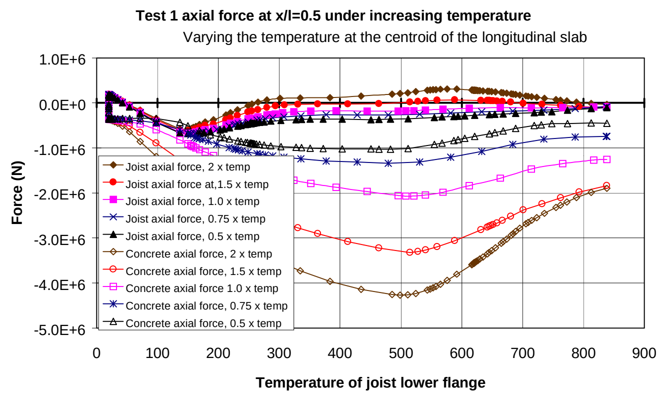


Figure 13: Test 1, Axial force at x/l=0.5: Varying the temperature at the centroid of the longitudinal slab

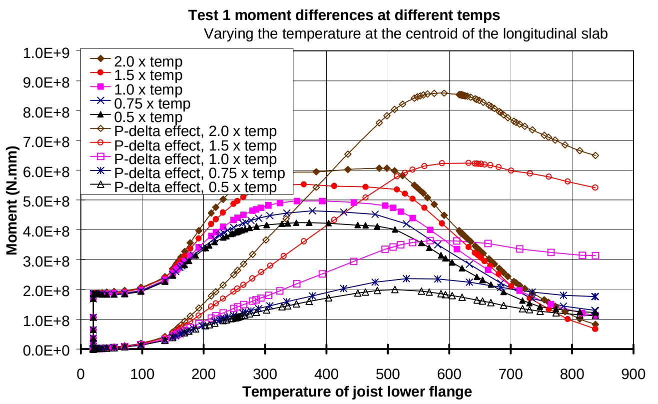


Figure 14: Test 1, Moment Differences: Varying the temperature at the centroid of the longitudinal slab

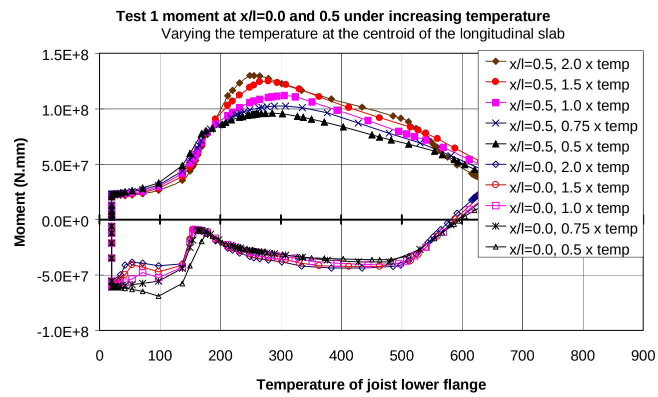


Figure 15: Test 1, Joist Moment at x/l=0.0 and 0.5: Varying the temperature at the centroid of the longitudinal slab

Response of the Ribs

The ribs compressive axial force starts to decrease a third of the way into the test at x/l=0.3,0.4,0.5. Figure 16 shows the axial force at x/l=0.0 and 0.5. The compressive strains in the ribs are absorbed as the slab and joist pull the ribs down. Again, nearer the mid-span of the ribs over the joist as the temperature increases the moment increases by a vast amount in sagging. See figure 17. The moment achieved is 6 x 10^6 Nmm when the temperature applied is raised by 50% at the centroid of the longitudinal slab compared with 3.5 x10^6 Nmm for the same case in the transverse slab. Compare figures 10 and 17.

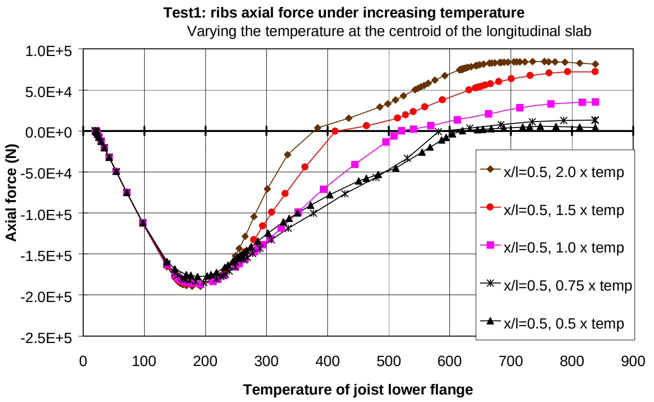


Figure 16: Test 1, Ribs axial force at x/l=0.0 and 0.5: Varying the temperature at the centroid of the longitudinal slab

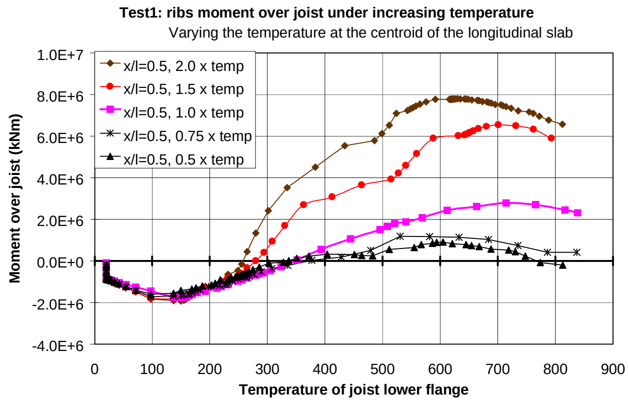


Figure 17: Test 1, Ribs Moment over the joist at x/l=0.0 and 0.5: Varying the temperature at the centroid of the longitudinal slab

Changing the gradient in the transverse slab

In theory an increase in gradient in the transverse slab will increase the thermal bowing effect in that direction thereby increasing the tensile strains or absorbing the compressive strains in the concrete in the direction of the ribs.

Response of the Joist

Decreasing the gradient applied to the model by 25% and 50% caused convergence problems beyond a lower flange temperature of 300°C (one third of the way through the test). Therefore, a full set of results for a 20% decrease in gradient applied is also reported. Changing the gradient in the transverse slab has a small effect on the deflection at mid-span but the deflection at the end of the test remains unchanged. A decrease in the gradient applied causes a slight increase in deflection (See figure 18).

In general the composite axial force increases slightly when the gradient is increased and the moment differences decrease as the gradient is doubled. At x/l=0.0 and 0.5 (figures 19 and 20} the compressive force in the concrete increases with an increase in the gradient applied to the ribs but still doubling the gradient has only a small effect compared with doubling the temperature applied at the geometric centroid of the slab. The moment due to P-delta is more or less constant with changing gradient due to the small changes in deflection and axial force.

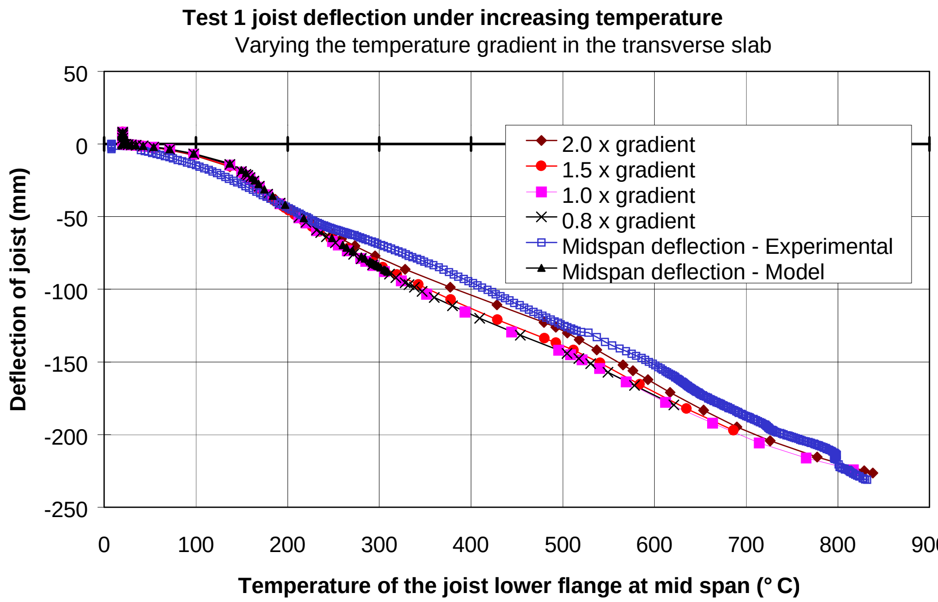


Figure 18: Test 1, Joist Deflection: Varying the temperature gradient in the transverse slab

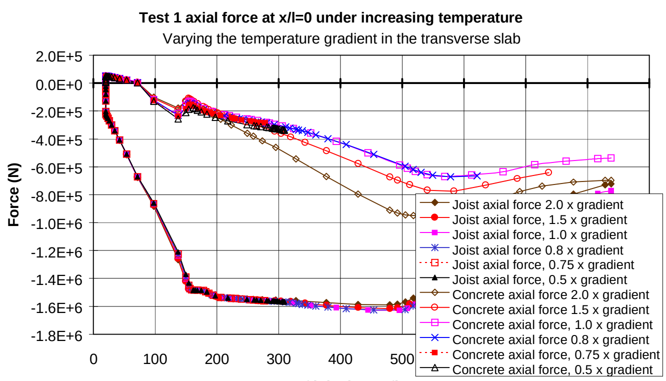


Figure 19: Test 1, Axial force at x/l=0.0: Varying the temperature gradient in the transverse slab

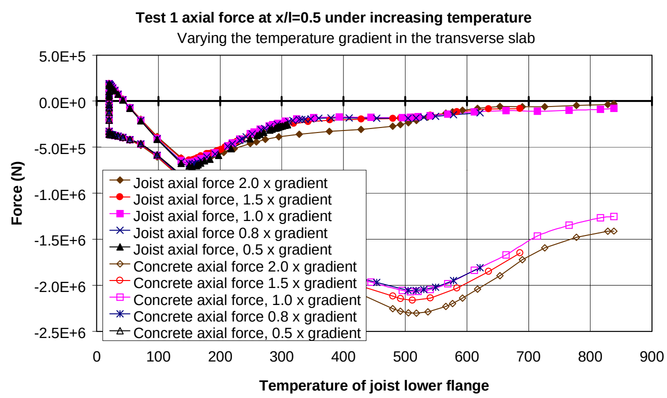


Figure 20: Test 1, Axial force at x/l=0.5: Varying the temperature gradient in the transverse slab

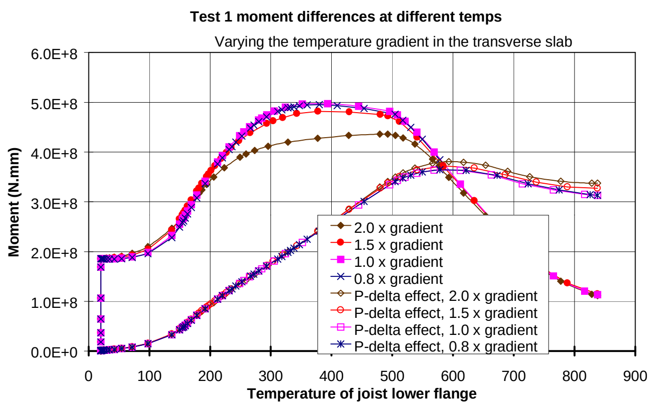


Figure 21: Test 1, Moment Differences: Varying the temperature gradient in the transverse slab

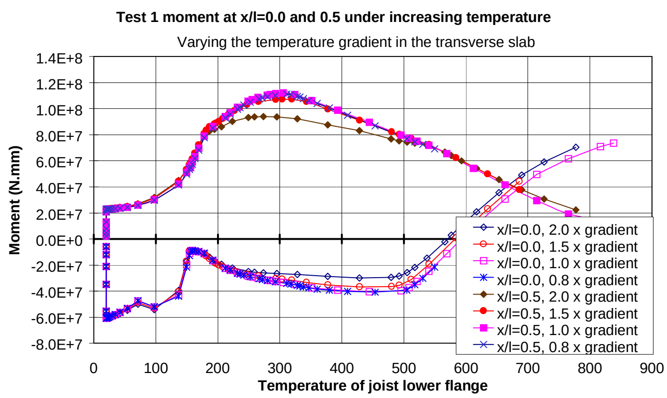


Figure 22: Test 1, Joist Moment at x/l=0.0 and 0.5: Varying the temperature gradient in the transverse slab

Response of the Ribs

The ribs axial force is reduced by increasing the gradient applied. This is due to some of the compressive strain caused by restrained thermal expansion being absorbed by thermal bowing induced deflections. This can be seen clearly in figure23. Figure 24 shows at high gradients the moments are relatively low and negative at low gradients the moments are large and positive.

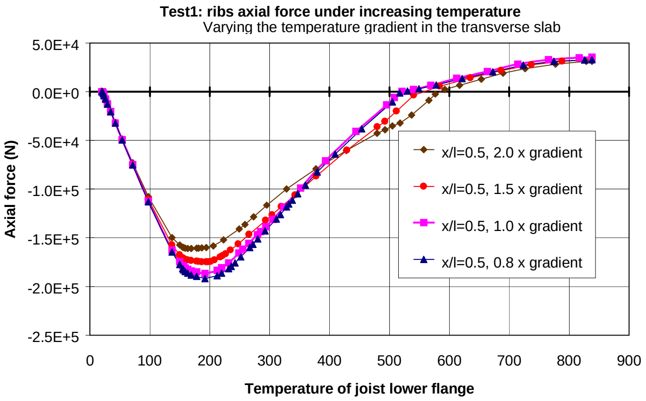


Figure 23: Test 1, Ribs Axial force: Varying the temperature gradient in the transverse slab

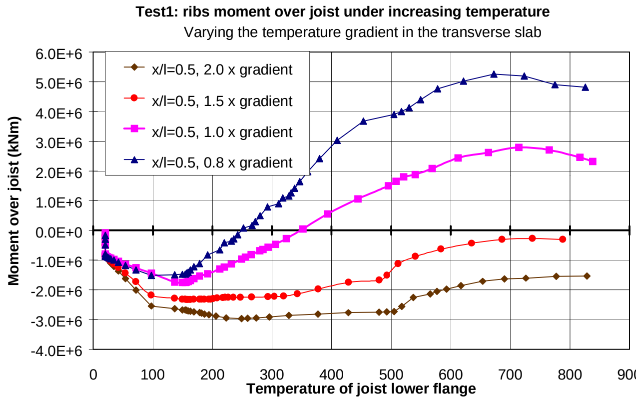


Figure 24: Test 1, Ribs Moment over the joist: Varying the temperature gradient in the transverse slab

CHANGING THE GRADIENT IN THE LONGITUDINAL SLAB

Response of the joist and the Ribs

Altering the temperature gradient in the longitudinal direction has very little or no effect on the response of the structure. This can be seen in figures 25-28.

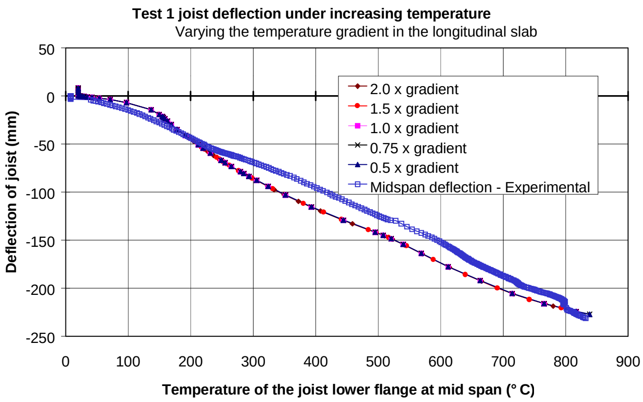


Figure 25: Test 1, Joist deflection: Varying the temperature gradient in the longitudinal slab

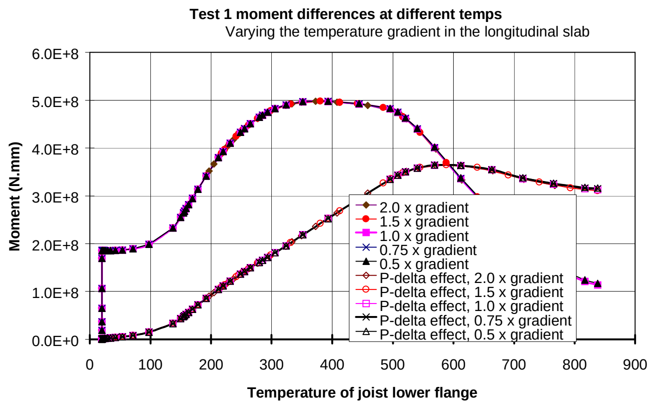


Figure 26: Test 1, Moment Differences: Varying the temperature gradient in the longitudinal slab

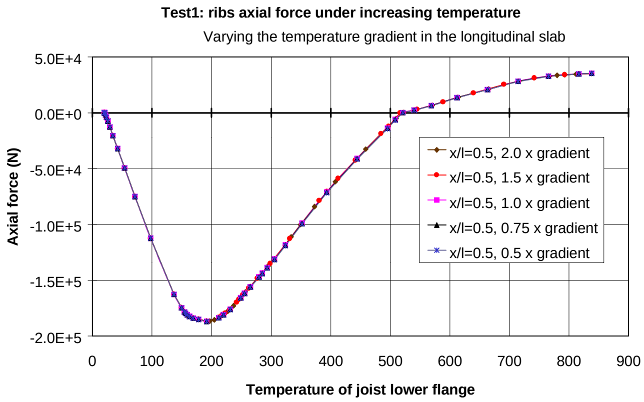


Figure 27: Test 1, Ribs axial force: Varying the temperature gradient in the longitudinal slab

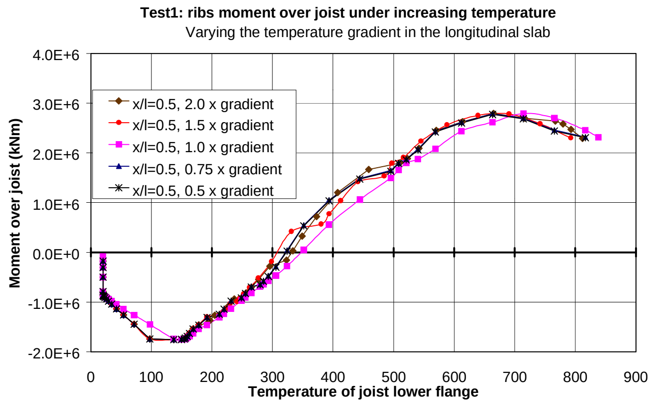


Figure 28: Test 1, Ribs moment over the joist: Varying the temperature gradient in the longitudinal slab

CONCLUSIONS

- An increase in the mean temperature or the temperature gradient applied to the model leads to an increase in the deflection response of the structure.
- However, changing the equivalent mean temperature at the geometric centroid of the slab has a significantly greater effect on the load carrying mechanisms within the structure than changing the temperature gradients applied.
- Changing the temperature gradient applied in the longitudinal direction has an insignificant effect on the structural response.
- Changing the temperature gradient applied to the ribs has a significant effect on the ribs moment over the joist and the axial force in the ribs.
- The thermal bowing action of the ribs due to the increase in thermal gradient absorbs some of the compressive strains caused by restrained thermal expansion.
- More detailed discussion on this topic can be found in Sanad *et al* [9,10] .

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