REPORT AM02

Analysis of Results from BS/TEST1 models
Part B: Half floor models

INTRODUCTION

This report discusses the results of modeling of the British Steel restrained beam test (Test no. 1). The test was a gas heated test on a 305X165x40 UB secondary beam on gridline 2 between the columns on gridlines D and E (see Figure 1).

The models were developed using three variations of FE models namely, grillage/shell, shell/shell and grillage/beam representations of the fire loaded area and included simplified temperature profiles based on the Cardington tests applied to the heated beam and slab in the models so that a comparison between model and test could be made. The results comparison highlights the sensitivity of each modelling methodology along with the observed behaviour.

The results showed the overall behaviour was highly complex and affected by such phenomena as; temperature profile through the member, degree of thermal restraint offered by the surrounding structure, degradation in material properties with increasing temperature and development of alternative load carrying paths. Various results are plotted showing the change in member behaviour throughout the application of fire loading and reveal the development of alternative complex load paths which enable the structure to retain its structural integrity.

Observations from the test showed that extensive local buckling of flanges and webs in the heated secondary steel beams took place. This would not be captured using beam elements so a rigorous model of the heated beam was generated. This rigorous model discretisation included a shell representation of heated beam. The grillage/shell model used beam elements to represent the concrete slab, beam elements to represent the unheated primary and secondary beams and a shell representation of the heated secondary beam. Such models fail to include in-plane shear transfer across the slab but offer reasonable accuracy when the primary mode of failure is by flexure. To account for shear transfer the second model type included a shell representation of the slab. The final model looked at the effect of replacing the rigorous representation of the beam behaviour with a beam element. This model had a grillage representation of the slab. Figure 2 outlines the various models used.

DEVELOPMENT OF MODELS

The modelling procedures used in the analyses are outlined in the relevant reports(MD04,MD05,MD06). Overall, it is important in any modelling procedure that the key structural behaviour is captured in the developed model. This was achieved in this project by developing models of varying complexity to examine the differences in various modelling assumptions on overall structural behaviour. This process is not only necessary in the development of robust models but is an essential part in developing understanding of structural behaviour. For completeness the major differences in the modeling procedures are outlined below

Grillage/Shell Model
It is still uncertain how representative a grillage approach is, but due to its simpler slab representation, it offered a means of explaining the complex 3D effects of structural restraint and load transfer paths. The slab spanning in the primary beam direction was modelled using beam elements representing as a series of 500 mm wide strips. These included the properties of the downstand in an overall representation of slab behaviour consisting of temperature varying moment-curvature and axial-strain relationships to represent decoupled bending and membrane stiffness in this direction.

The shell representation of the beam also included partial depth endplate to column web connection behaviour. The connections were included with the use of gap contact and spring elements. The gap contact elements modelled the effect of the beam bottom flange closing against the column web as the beam expanded upon heating.

Shell/Shell Model
A shell/shell model, consisting of a shell representation of the floor, was developed to further understand the 3D effects such as tensile membrane action in the slab and, in particular, the contribution of in-plane shear within the highly deflected regions of the slab. This model used shell elements for the top 70 mm of the slab and trapezoidal beam elements in the slab spanning direction to represent the downstand beams. The heated beam was modelled as above.

Grillage/Beam model
Finally, the shell representation of the heated beam was replaced with a beam element to understand the importance of including local buckling on overall structural behaviour. The grillage representation of the slab was used in this model.

DISCUSSION OF RESULTS
A level of confidence was generated in the models by comparing slab vertical deflections, column lateral displacements and column strains to test results (reports MD04,MD05,MD06). The more rigorous the model, the better the agreement and hence confidence in structural behaviour to a real scenario. Understanding the structural behaviour was based on examination of member forces to reveal load redistribution paths. For this purpose all the models were extensively post processed.

The important point is to match model behaviour to observed behaviour. Observed behaviour is discussed first and then the models are compared to this behaviour to assess the success of the various modeling approaches in capturing observed behaviour.

Observed Structural Behaviour
The behaviour of the floor system in test 1 followed a distinct pattern. The restrained beam element was heated at a different rate than the floor slab due to differing thermal inertia. This heating gave rise to thermal expansions and as this expansion was significantly restrained then a large increase in forces in the beam took place. The test floor was effectively restrained on the boundaries of the test compartment by the colder

structure, in this case the rest of the floor slab. Additionally, the unprotected steel beam were heated at a much greater rate than the concrete slab giving rise to a differential temperature gradient through the floor system.. The cooler concrete slab also effectively restrained the steel beam from expanding, giving rise to forces within both the steel and slab elements. The connections between the steel beams and the columns could initially be regarded as rigid due to composite action in the connection area. However, after the onset of local buckling in the connection areas would act more like pinned connections.

Theoretical studies outlined in reports SM1-5 demonstrate that encastre (rotationally and axially) elastic beams, supporting a uniform load, subjected to such a thermal regime result in an increase in the axial force in the composite member with little corresponding increase in vertical deflection. Eventually, the beam will reach its thermal buckling capacity and the rate of vertical deflection increases in a stable post-buckling mode. In this case, the rise in deflections is beneficial as it limits the force transferred to the rest of the structure and helps to localise damage to the heated compartment. In contrast, rotationally pinned but axially restrained beams subjected to a predominantly large temperature gradient result in an increase in tensile force due to membrane effects associated with the larger corresponding increase in vertical deflection (normally termed thermal bowing).

In the fire test, the true restrained state and the actual thermal regime was somewhere between the two theoretical extremes explained above. The strain gauge readings from the beam outside the test 1 compartment on gridline 2 between C and D demonstrate the behaviour, Figure 3. The readings clearly show an initial increase in axial compressive strain as a reaction to the axial force generated in the heated beam in the test compartment. The rate of increase in deflections is low at this point. The force then decreases around 140 ^{0}C , this is due to the failure of the web of the steel beam at the partial depth endplate connection. This effectively reduces the end connection stiffness from near rigid to the near pinned condition. Therefore, the compressive force is seen to reduce and deflections increase at a greater rate. At 240 ^{0}C, compressive forces start to pick up again and this is due to the gap between the bottom flange of the beam and the column (due to the partial depth endplate connection) closing up and the beam again acting more like a rigid connection. At 400^{0}C, the beam reaches its thermal buckling capacity and the force levels off. At 560^{0}C , the force starts to reduce as the steel properties degrade to a level where the steel element reaches its plastic limit in axial compression. The force continues to reduce until the end of the test at approximately 830^{0}C.

Model Comparisons

All models underestimate vertical deflections (Figure 4). This is due to the simplified temperature profiles applied to the models in comparison with the actual test temperatures (see reports MD04, MD05, MD06). However, the grillage models underestimate the deflection more than the elastic shell representation. This would seem to indicate that in-plane shear effects in the slab are important. Additionally, the model with the beam representation of the heated beam does not deflect as much as the shell representation. This could be due to the inability to pick up local buckling.

All models give reasonable values of lateral deflection in comparison with the test results. An example of such agreement is given in Figure 5. The models with the shell representations of the heated beam are better in terms of predicting the timing of certain structural events in that they show similar deviations in behaviour in time as the test. However, it is the grillage model which gives best agreement with the actual magnitude of the deflections in the test. However, the magnitude of the deflections needs to be borne in mind when making this judgement – maximum deflections are of the order of 1.5 mm.

The ability of each of the models to pick up the observed structural behaviour is perhaps best indicated by the comparison of beam strain behaviour in the unheated beam adjacent to the test beam (Figure 6). The shell representations of the beam can be seen to picking up all the observed behaviour. This is because these representations include realistic representations of the partial depth endplate and gap behaviour at the end of the beams. Also the magnitude of the strains is in very good agreement. The beam representation of the heated beam fails to pick up the early local buckling effects, as expected but does pick up the major structural event which is the peaking of the axial force in the beam due to material degradation starting to kick in. Two important points can be made from this. The first is that the global response of the structure will not be greatly affected by neglecting local buckling under axial loading due to restrained thermal expansion as beam elements can pick up the main structural event. The second is that the effect of the local buckling is to reduce the magnitude of the level of strain achieved under a given thermal regime. That is the effect is beneficial as it reduces the amount of mechanical strain in the main structural elements.

CONCLUSIONS

An understanding of the structural behaviour under fire attack has been developed through the development of rigorous models. The main conclusions deduced are:

- A high level of confidence in the development of rigorous models has been generated due to the extensive calibration against test results.
- The composite behaviour is initially dominated by the underlying steel beam, which drives the slab down, until the steel temperature reaches approximately 500^{o}C where material degradation occurs. The slab temperatures at this stage start to rapidly increase and subsequently the slab dominates the overall response of the structure.
- Modelling of the steel beam element using both shell and beam elements indicate that whilst the shell representation gives better overall correlation in deflections and force distributions, the beam element picks up the main global steel beam mechanism.

REFERENCES

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2 Rotter, J.M, Sanad, A.M., Usmani, A.S., Gillie, M., Structural Performance of Redundant Structures under Local Fires, *Proceedings of Interflam ‘99*, pp1069-1080, Edinburgh, Scotland, June-July, 1999.

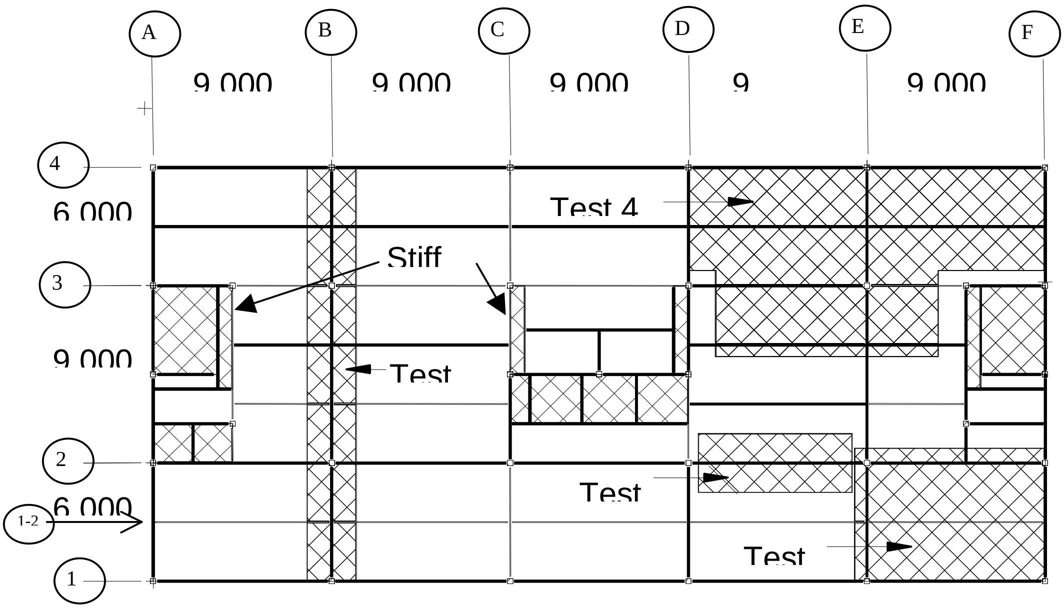
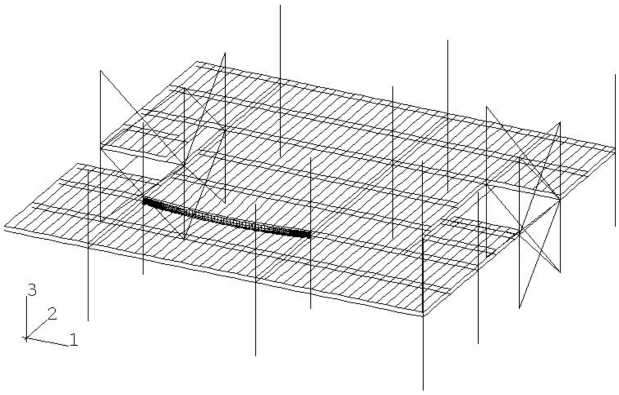
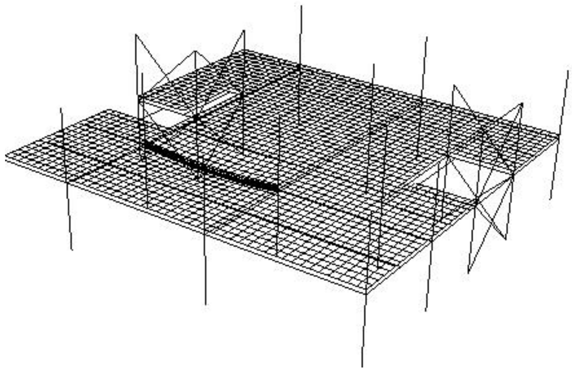
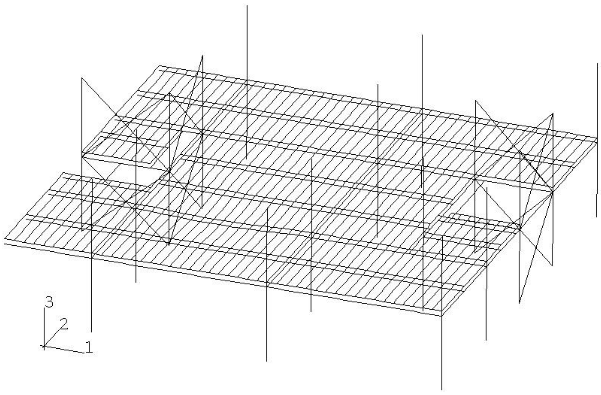


Figure 1: Plan of Cardington showing Cores and Test Compartments



a)Grillage/shell model





b)Shell/Shell model c)Grillage/beam model

Figure 2: Discretisation of half a Cardingtion floor for modelling test 1

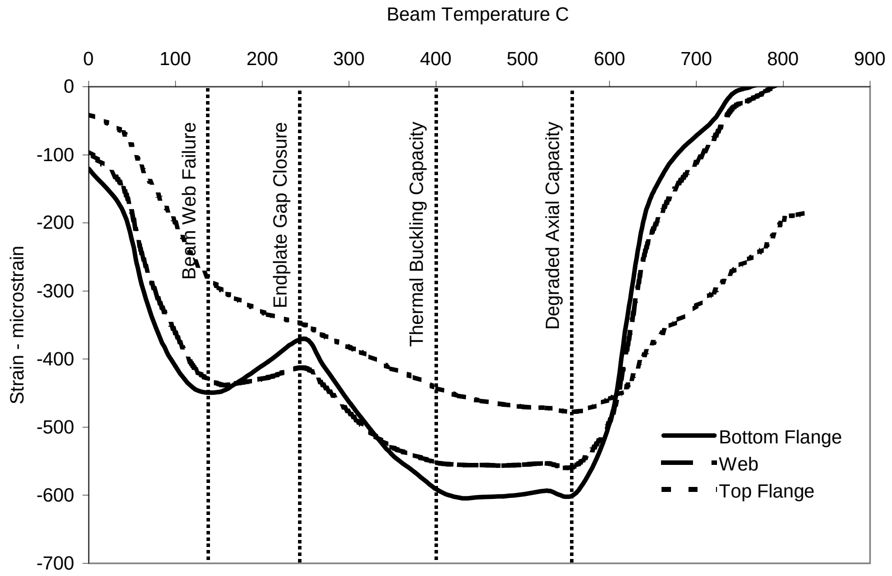


Figure 3: Typical Strain Response of Unheated Steel Beams adjacent to Heated Steel Beams

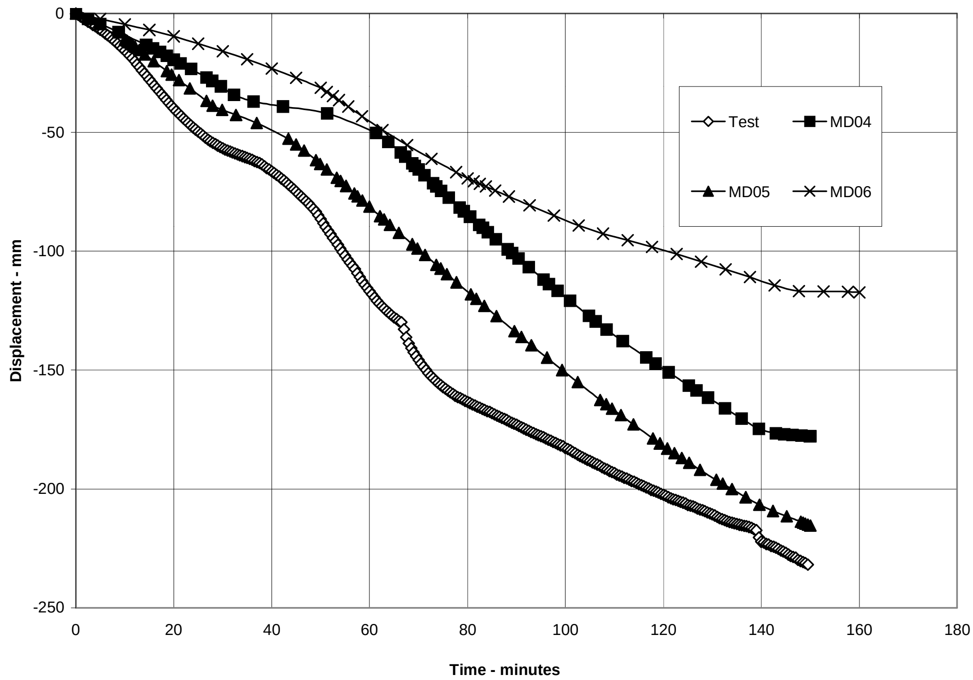


Figure 4: Comparison of Vertical Deflection Response

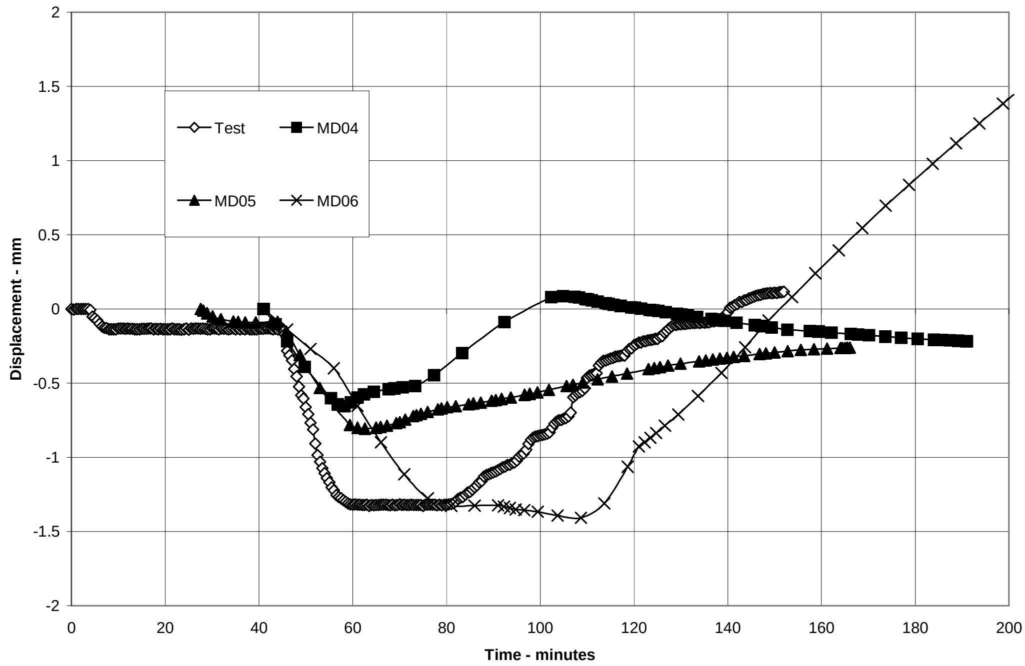


Figure 5: Comparison of Lateral Deflection Response

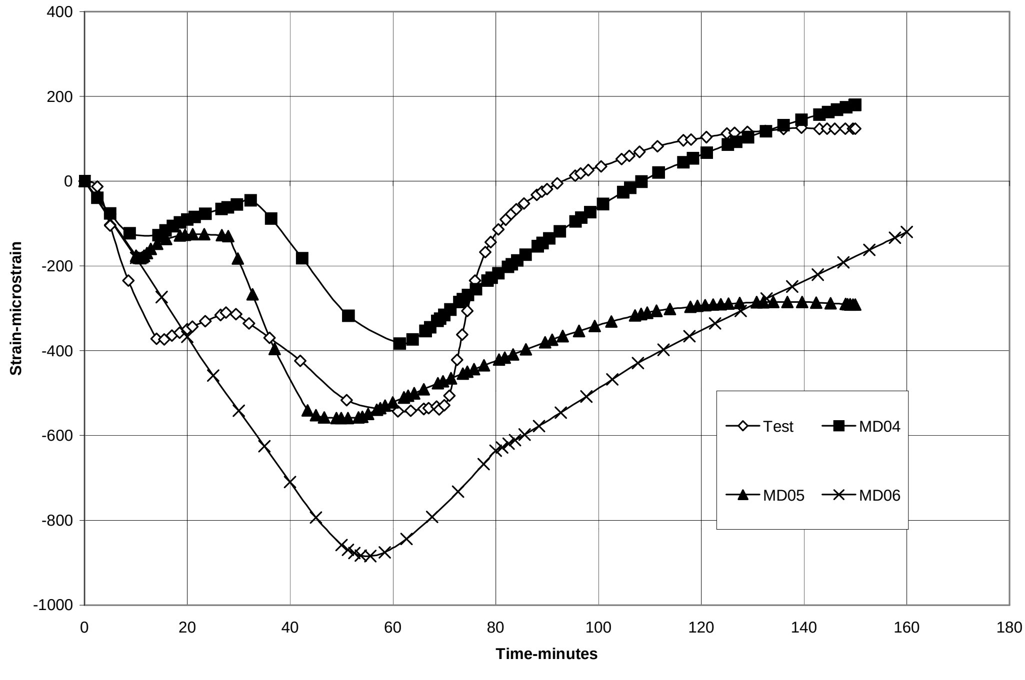


Figure 6: Comparison of Beam Bottom Flange Strain