Bridging and Restraint Effects of Localised Fires in Composite Frame Structures

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Summary

Software developed at the University of Sheffield was used to model one of a series of fire tests on the full-scale composite test frame at Cardington, in which a single beam was heated. The effect of local buckling, which occurred in the test, on the beam's overall behaviour was investigated using the software. Both analyses and test showed that the cool adjacent structure has a beneficial effect on the behaviour of the heated beam, permitting redistribution of load by bridging to the adjacent structure. This is seen to diminish as the fire compartment is increased to a more realistic size.

1. Introduction

Structural fire engineering is a relatively new philosophical approach to the design of structures against collapse in a fire. For steel structures recent limit state fire engineering design codes include BS5950 Part 8[1] and EC3 Part 1.2[2], as well as EC4 part 1.2[3] which covers the fire resistant design of composite structures. These codes, which classify fire as an accidental limit state, are based on load levels which are statistically likely during a fire, material stress-strain relationships at elevated temperatures and non-uniform heating where applicable. This concept, which provides a new range of fire resistance options, is slowly beginning to replace the traditional approach of retrospectively prescribing a thickness of protective coating to steelwork.

In the UK it has recently been estimated that fire protection contributes 23% of the overall cost of typical commercial frames. Also, the hidden costs involved in actually fixing the protection and consequent programme delays need to be considered.The use of fire engineering principles can result in considerable cost savings compared with the traditional approach, since standard protection thicknesses are specified from manufacturers' tables which are implicitly based on limiting the maximum temperature of the steel to 550°C. This is the temperature at which, in simplistic terms, it has been assumed that the yield strength of steel is reduced to the extent that an ultimate strength design loses its safety margin. However, this assumption is based on the steel being uniformly heated and fully stressed at ambient temperature, and also ignores the fact that stress-strain curves become highly non-linear at elevated temperatures.

Although the new design codes have provided a more scientific approach to assessing the response of steel-framed buildings in fire they are limited by being based on isolated member design, developed from standard furnace tests. The failure criteria for isolated members in standard fire tests are defined in terms of displacement, and are set at values which prevent damage to the furnace during testing. However, the validity of basing full-structure predictions on the behaviour of isolated members is highly questionable, and recent research has increasingly been focused on the full structural behaviour of buildings in fire. In the UK this has included a series of fire tests conducted during 1995 and 1996 on a full-scale composite test frame, constructed by the Building Research Establishment at its Cardington Laboratory. The main aim of the tests was to provide extensive experimental data as a validation for computer software which can predict the structural response of the building during a fire.

Because of the very high cost and limited validity of fire tests, reliable computer software is required to allow different structural and fire scenarios to be studied economically. At the University of Sheffield a purpose-written computer program[4] has been developed which can sensibly be used on a standard Personal Computer. Previous predictive model analyses using this software, as well as observations from the tests, have shown that the surrounding cold structure, in particular the continuous flooring system, has a significant beneficial effect on the behaviour of the heated zone. However, the area of the heated zone in these cases has been very limited, and it is predictable that the support provided by the surrounding structure might diminish in a more realistic scenario in which the fire compartment is more extensive. To investigate the effect of increasing the fire compartment size the model was validated against the first fire test on the Cardington frame, and then the compartment size increased to a more realistic size.

The computer software is capable of predicting the structural response of steel-framed buildings subject to any specified fire scenario. The steel beam-column members are represented by two-noded one-dimensional finite elements which are capable of modelling three-dimensional response including warping, and incorporate a high degree of both material and geometrical nonlinearity at ambient and elevated temperatures. Arbitrary temperature distributions can be specified through the cross-section and also along the length of a steel member. Semi-rigid connection behaviour can be modelled using spring elements with any specified moment-rotation-temperature relationship. The floor slab is represented by four-noded shell elements which can be connected to the one-dimensional beam elements at a common nodal point, thus modelling full composite action between the steel framing and the supported floor. Thermal strains due to heating the concrete are also included. An extremely simple cracking model has been used to represent the behaviour of the concrete floor based on limiting the bending stress in the shell elements.

2. Comparison with a Cardington Fire Test

On 19 January 1995, the first of a series of fire tests was carried out by British Steel. The test building consisted of an eight-storey steel frame acting compositely with the supported floor slabs via shear studs. The building footprint was 21m x 45m, with the general structural layout shown in Fig. 1. The floor was of typical UK composite construction, consisting of 0.9mm thick steel deck (PMF CF70) with lightweight concrete and A142 anti-crack mesh. The overall specified depth of the slab was 130mm. The fire test involved heating a secondary beam on the 7th floor, over the central 8.0m of its 9.0m length, as shown in Fig. 1.

Previous computer simulations[5] have been conducted of this test, in which the beam was modelled as an isolated composite section (Fig. 2) and as a sub-frame which included a large area of cold structure including the continuous floor slab, as shown in Fig. 1. The comparison between the test results and computer simulations is shown in Fig.2, with the local deflected shape shown in Fig. 3 at a steel beam flange temperature close to the maximum measured during the test.

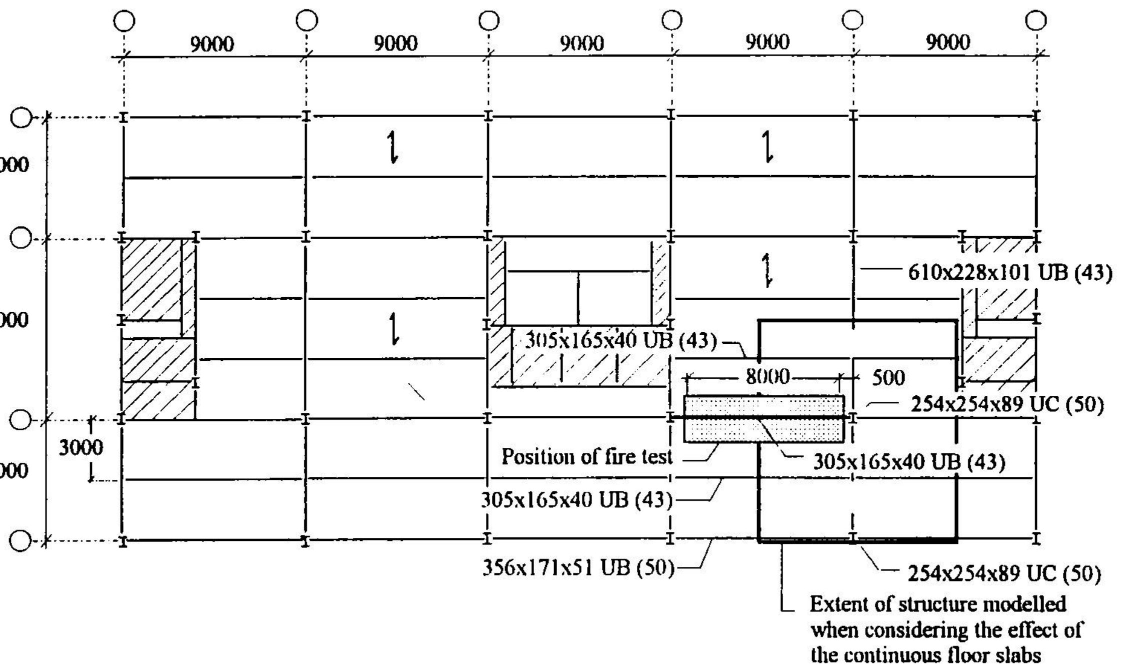

Fig. 1 General layout of test frame and position of first fire test.

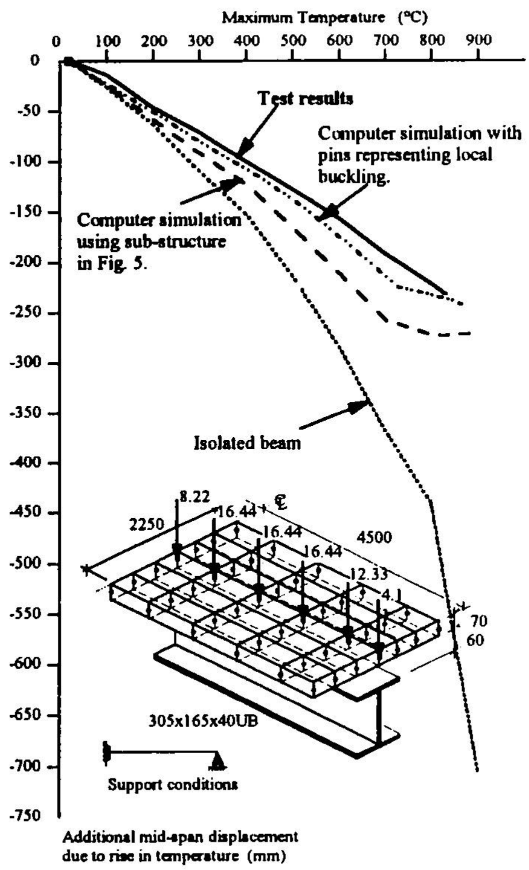

Fig. 2 Comparison between computer predictions and test results.

Inclusion of the behaviour of the continuous floor slab in the computer simulation clearly has a significant influence on the behaviour, compared to the equivalent isolated beam. Comparison with the test results shows that using the sub-frame model reasonable predictions are obtained, showing clearly the beneficial effect of the "bridging" action by the slab across the heated beam, an action which transfers load to the surrounding cold structure. This form of load transfer away from the heated member could not be achieved without the continuity in the slab which is inherent in this form of composite construction.

On removal of the furnace following the test it was found that local buckling had taken place in the exposed flange of the steel beam at a position just inside the furnace. It can be surmised that this was caused by the high axial forces due to restraint of thermal expansion, together with the negative moment occurring at this position during the rise in temperature. This type of buckling had previously been seen during the investigation following the Broadgate Fire[6] in the UK. Since one-dimensional finite elements are used to represent the steel members local distortional buckling cannot be modelled. However, to investigate the influence of local buckling the previous computer simulation was re-run with spring elements of zero rotational rigidity inserted at the positions of local buckling. Due to numerical problems removal of axial stiffness in the buckled areas was not possible, although this was not considered to be significant since in composite construction of this type the axial force would in practice be redirected through the slab. Inserting these pins from the start of the computer simulation of the test is over-conservative, but nethertheless it provides an indication of the significance of local buckling. The predictions from this simulation are shown in Fig. 2, in which it can be seen that the local buckling does not have a major effect on the behaviour of the beam, but causes slightly lower displacements. The reason for lower predicted displacements is mainly due to the failure of the concrete in the hogging zones. This can be explained by considering a fixed-ended beam for which the position of the points of contraflexure is at 0.21 of the beam span from its ends. If this is compared with the present case where the position of the points of contraflexure is set at the local buckling position, 0.06 of the span from its ends, it can be seen that less of the beam's length is in hogging, resulting in less concrete cracking and thus a stiffer beam.

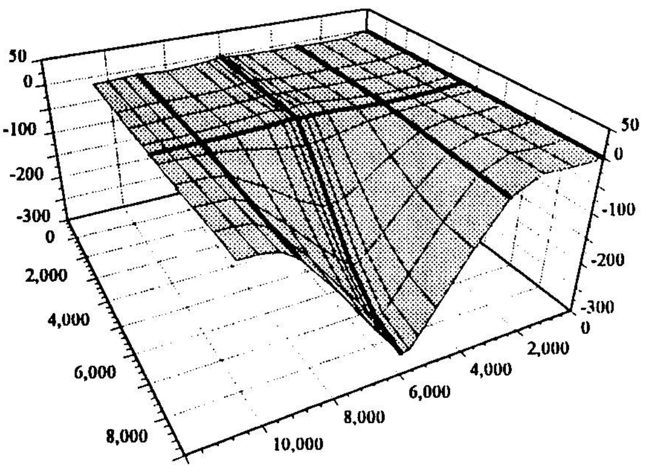

Fig.3 Deflections of the local area at 800°C.

Inserting a pin at each position of local buckling is conservative, since it assumes that local buckling is present from the start of the test whereas in reality it would occur at a reasonably late stage during heating. Therefore the two curves representing the behaviour with and without pins can be classed as upper and lower bounds, with the actual behaviour changing from the one to the other as heating progresses.

Intuitively it might be expected that local buckling in the steel beam, caused by the restraint of the surrounding structure, would be detrimental to the fire resistance of the beam, rather than beneficial as is shown in the simulation. However, the position at which local buckling occurred in this particular test was governed by the location of the furnace. In a naturally occurring fire the whole beam would normally be affected, with the ends possibly being slightly cooler. Therefore it would be expected that if local buckling did occur then it would be at positions very close to the connections, as observed in the aftermath of the Broadgate Fire. This can be viewed as the beam transforming from a semi-rigid to a simply supported member, resulting in larger displacements. In order to simulate local buckling in detail the beam cross-section would need to be modelled using shell elements rather than the existing line elements. This would increase the computer runtime very considerably, probably reduce the area of structure which can practically be modelled and almost certainly result in a need to transfer the analysis away from the PC platform. Alternatively a conservative approach might be to treat all steel-to-steel connections as pinned, to allow for any possible detrimental effect that could occur due to local buckling.

3. Extension of the Fire-Affected Area

Both the fire test and computer simulations have shown clearly the beneficial effect of bridging action and the detrimental effect of local buckling in composite-framed buildings. However the

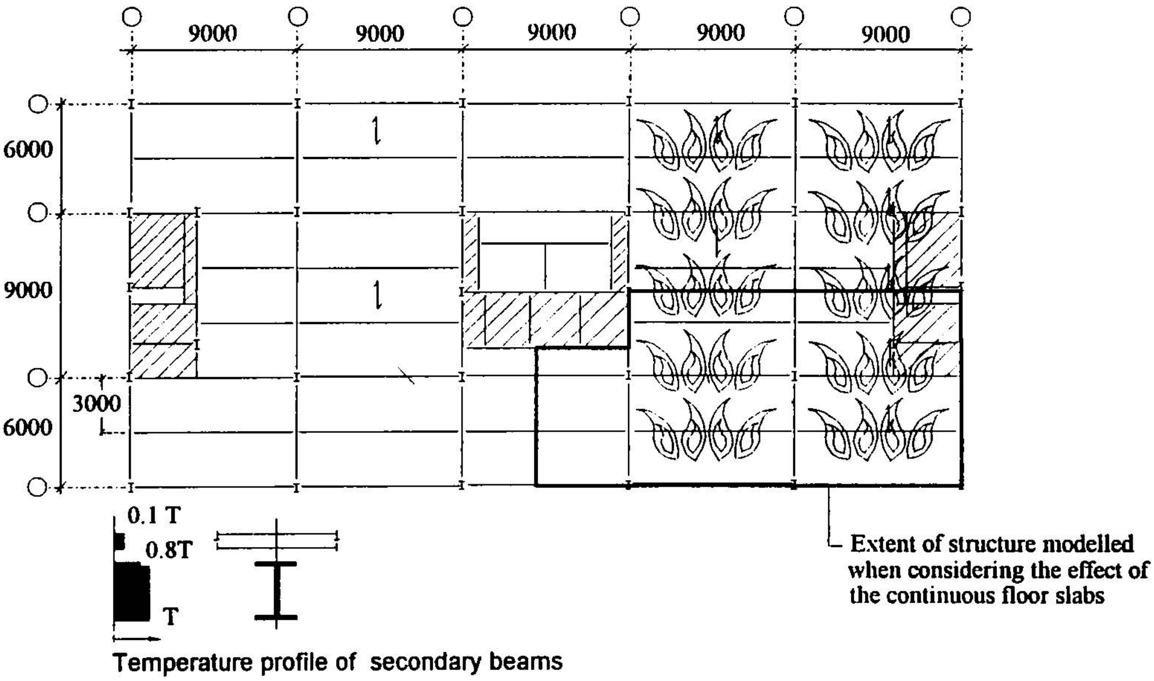

Fig. 4 Large compartment fire.

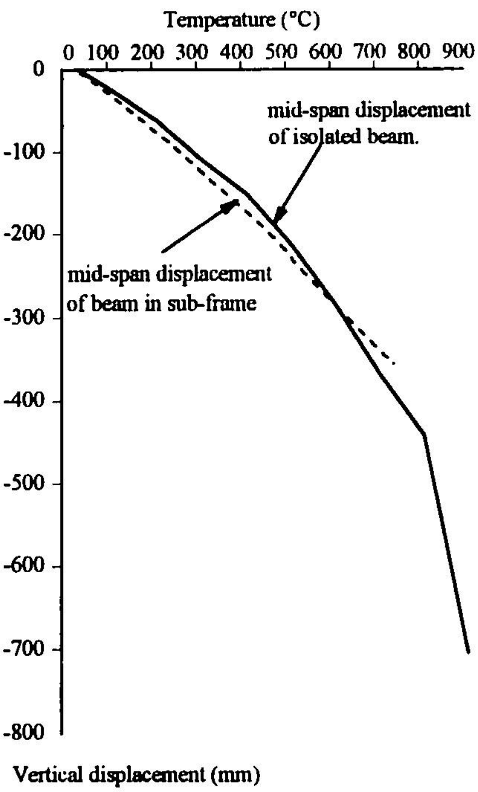

Fig. 5 Computer predictions.

fire-affected area in this test was very small, and in a more usual scenario the fire might affect much more of the structure. This will depend on compartment size and on the compartment walls maintaining their integrity during a fire. The size of a compartment depends largely on the building's use. At one extreme are hotels, nursing homes, etc., where compartments are defined by room sizes, and at the other airports, sports halls, etc, where compartments tend to be defined by the extent of the building plan.

A simulation was performed with the extent of the fire-affected structure increased as shown in Fig. 4, to cover a more realistic area in an office building. All beams were heated at the same rate. The columns were protected and therefore considered to retain their full strength in the analysis. To represent local buckling, all steel-to-steel connections were represented as pinned. The mid-span displacements of the beam from the previous example are shown in Fig 5 for this case. It can be seen that the beam's behaviour is now very close to the prediction for an isolated member, indicating that little beneficial effect is now being obtained from bridging action across the floor slabs. The deflected shape of the slabs and beams in the affected zone at 730°C is shown in Fig. 6.

4. Conclusions

A finite element code capable of predicting the structural response of steel-framed buildings has been developed at the University of Sheffield. This program has shown to give very good predictions of the fire tests conducted on the full scale composite test frame at Cardington. Since one-dimensional finite elements are used to represent the steel members, local buckling, which was found to occur in the first fire test, cannot be predicted. Nevertheless, to investigate the influence of local buckling spring elements were used to represent a pinned connection at the positions of local buckling in the test. Since in reality local buckling occurred at a certain temperature during the test, the insertion of pins from the start of the computer simulation is very conservative.

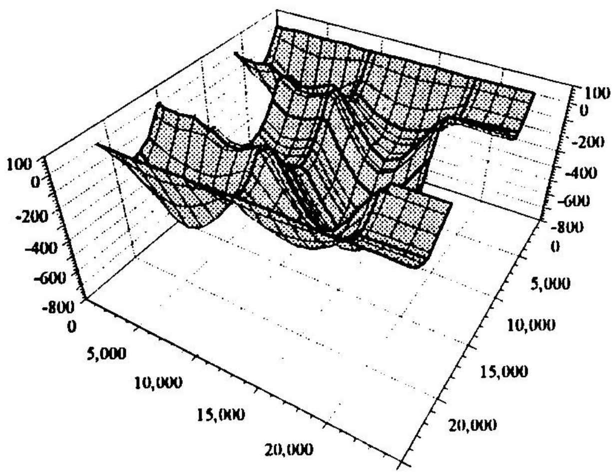

Fig.6. Deflection of large compartment at 730°C.

The results showed that local buckling had little effect on the heated beam's behaviour and in fact the computer simulation indicated that local buckling resulted in lower displacements. This was attributed to the position of the local buckling, determined by the size of the furnace, which influenced the extent of concrete failure. In normal circumstances, if local buckling of beams did occur in a fire it would be in the vicinity of the connections. This would effectively transform the semi-rigid connections to simple connections which would be detrimental to the fire resistance.

It is clear that fire-affected zones of structure can use the adjacent cool structure for re-direction of the local loading paths (the action referred to as bridging), which is advantageous from the viewpoint of fire resistance. However, as the size of the fire compartment increases the support from these areas, as well as their restraint to thermal expansion, diminishes so that the behaviour more closely resembles that of isolated members in furnace testing.

References

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