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Thermal bowing in fire and how it affects building design

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During a fire, heat can affect one side of a wall or floor causing thermal bowing resulting from the differential thermal expansion. Data from experimental and theoretical work can be used in the design of buildings to reduce the detrimental effect of thermal bowing in, for example, tall walls.

This guidance will be of importance to architects and designers as well as building control officers and fire authorities.

INTRODUCTION

In most fires, walls and floors are subject to heat on one side which gives rise to temperature differences across the thickness of the element. In the case of steel and concrete, expansion of the hot face will result in bowing towards the heated area relative to the ends of the element unless the element is restrained. With timber elements, bowing is in the opposite direction due to loss of moisture causing shrinkage in the hot face material. Restraint may reduce the magnitude of bowing. This is not a new phenomenon but what is new is the discovery of just how little data are available on the magnitude of thermal bowing in a building on fire, where temperatures of 1200°C may be reached. This is despite the wealth of information from fire resistance tests where the elements of construction are usually carrying their maximum load and the deflection due to thermal bowing alone is unknown.

The total deflection in a fire test on a steel floor may comprise

- a thermal bowing deflection
- an elastic deflection due to the application of the imposed load
- reduction in the elastic modulus of the steel with increase in temperature
- a plastic deflection.

If thermal bowing is a large portion of the total deflection attempts to reduce the total deflection by

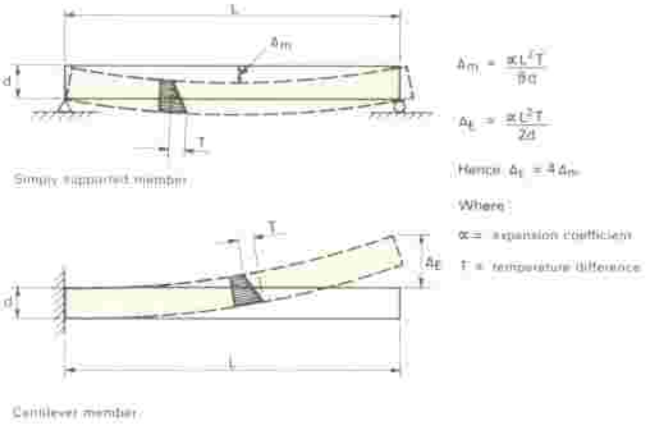

Figure 1 Thermal bowing relationships

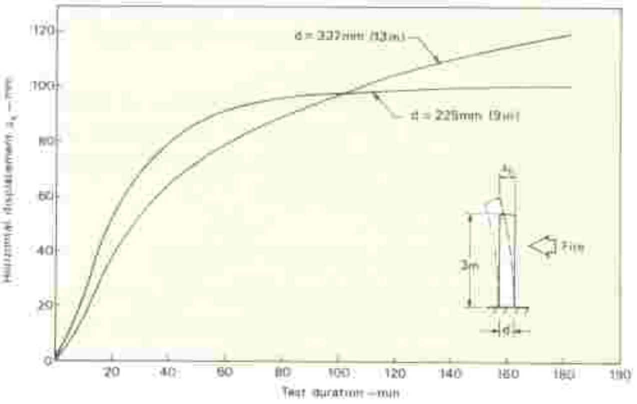

Figure 2 Thermal bowing of solid masonry walls

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reducing the imposed load will have a negligible effect.

In a standard wall furnace test, the specimen (maximum size 3m x 3m) is fixed in position both at the top and bottom. The horizontal thermal bowing deflection at mid-height is very rarely measured as there is no requirement to do so in the British Standard[1].

During a fire any wall may collapse if a floor burns through and leaves the wall unsupported. Indeed a collapsing floor could have a levering effect on a wall.

In practice some tall walls are not fixed at the top and are therefore free to bow in a fire and can topple over.

THERMAL BOWING THEORY

Cooke[2] has developed a simple theory of unrestrained thermal bowing which has been validated for metallic elements at elevated temperatures. Information on prediction of thermal movements and stresses is also given in BRE Digest 229[3].

An unloaded and unrestrained member of length L and thickness d having a coefficient of linear expansion α will bow into a circular arc when it experiences a temperature difference T across its thickness. Equations for the mid span deflection of a simply supported member and the deflection of the free end of a cantilever member are given in Figure 1.

The equations assume that the temperature variation across the thickness is linear and that α remains roughly constant with the change in temperature.

THERMAL BOWING OF METALLIC STRUCTURES

Although the temperature distribution across a section is actually curvilinear (and not linear as assumed in theory), the shape of the temperature profile across a section has been shown by experimental work at FRS not to be important. It has also been shown that design loaded, pin ended I-section model steel columns first bow towards the heat source, straighten out and fail by bowing in the reverse direction[2].

In thermal bowing analyses the coefficient of linear expansion α is 14×10^{-6} per degree Centigrade for structural steel and 24×10^{-6} per degree Centigrade for structural aluminium alloy.

THERMAL BOWING OF BRICKWORK

Materials such as concrete and brickwork have a lower thermal conductivity than metals and so the temperature distribution across the section is markedly curvilinear. The temperature gradient is steep near the heated face, hence the choice of the heated face temperature to be used in the calculation of thermal bowing is difficult to make.

To gain thermal bowing data two specimen brick walls were built into the standard furnace wall test frame. The walls acted as vertical cantilevers so they were free to move vertically and horizontally when exposed to heat on one side. One wall was 225mm (9 in) thick and the other was 337mm (13 in) thick; both were nominally 1m wide by 3m high.

The specimens were heated as per British Standard procedure[1] and Figure 2 shows that the horizontal deflections (Δ_{R}) at the top of the specimen are surprisingly large. Deflections of 70mm for the thinner wall and 55mm for the other after 30 minute exposure were recorded. Normally these deflections would be partially suppressed in a standard loaded wall test.

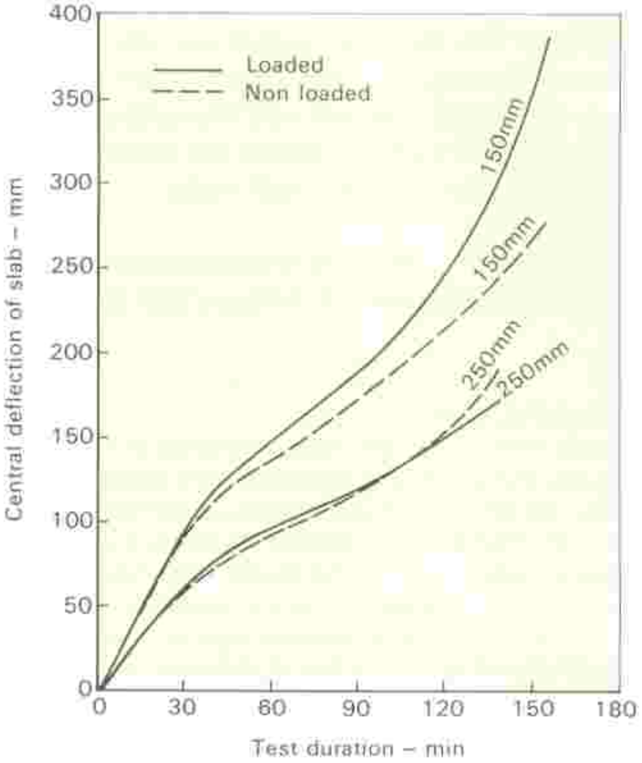

Figure 3 Deflections of reinforced concrete floor slabs showing effect of thermal bowing

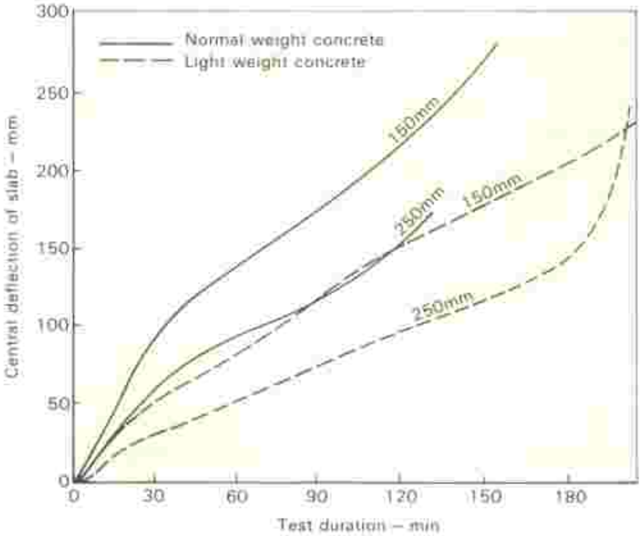

Figure 4 Deflections of reinforced concrete floor slabs showing effect of type of concrete

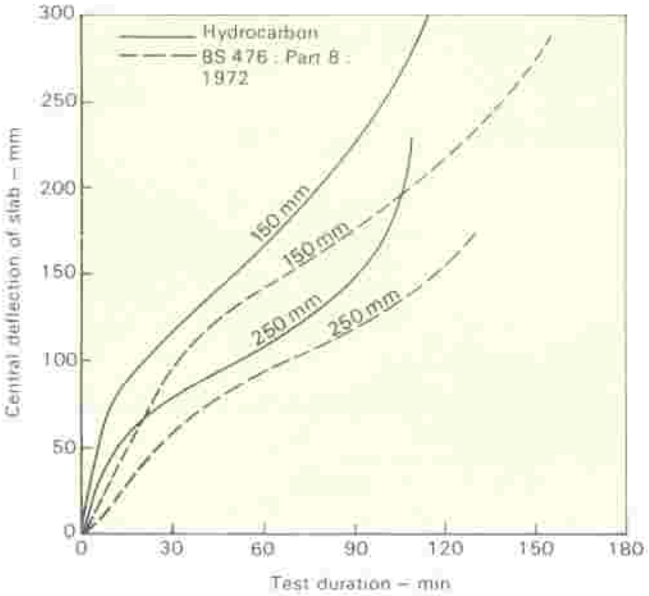

Figure 5 Deflections of reinforced concrete floor slabs showing effect of different heating exposures

For walls having a length/thickness ratio not less than 60, the maximum height/thickness ratio is 15 for walls restrained at both ends but not at the top (see Clause 18.5 of BS5628:Part 3:1985[4]. If the specimen walls had been built to the maximum height/thickness ratio of 15, the horizontal deflections at the top of the 225 and 337 mm thick walls, would have been 1.27 and 2.84 times greater respectively than the 3m high specimens tested. Hence for a 30 minute exposure to heating on one side, the deflections would have been 89mm for the 225mm wall and 156mm for the 337mm wall: assuming they had not already fallen over.

THERMAL BOWING OF CONCRETE

In another test simply-supported reinforced concrete floor slabs of 4.5m span were used to measure mid-span and longitudinal deflections caused by thermal bowing. The slabs were of 150mm and 250mm thickness and of normal weight concrete (NWC) and lightweight concrete (LWC) using a river gravel aggregate and a pulverised fuel ash aggregate respectively; both concretes had a characteristic cube strength of 30 N/mm^2.

To examine the effect of concrete type, slab thickness, heating exposure, loading, density of reinforcing steel and ceiling the following conditions were imposed

loading — by their own weight
— 1.5 kN/m^2 (this corresponds to the floor loading for residential buildings)[5]

slab design — based on the ultimate load condition[6]

concrete cover to reinforcing steel — chosen for 1.5 hour fire resistance: 25mm for NWC and 20mm for LWC

heating exposure — either to BS476:Parts 20 – 23[1] or to the more severe hydrocarbon fire test[7].

Some results are given in Figures 3 to 5. In Figure 3 one can see that the imposed load only causes a small part of the total deflection — less than 10% — and that the ratio of thermal bowing deflection for the two thicknesses of concrete is roughly as predicted by theory.

Figure 4 illustrates the difference in concrete type — the thermal bowing deflections of the LWC are about half to two-thirds of the NWC slabs and this can be explained by the different coefficients of linear expansion of the aggregates used.

Figure 5 is especially interesting as it confirms and quantifies earlier suspicions that the thermal shock associated with the more stringent hydrocarbon test method would cause larger deflections. Within the first 10 minutes of exposure the deflections were more than double those for the BS476:Part 8 conditions.

GENERAL RECOMMENDATIONS

The following design factors will help alleviate thermal bowing problems:

- choosing a material with a low coefficient of thermal expansion
- reducing the temperature difference and increasing the distance between exposed and unexposed surfaces.
- transforming a member from a cantilever to a simply supported member wherever possible as the mid-span deflection is a quarter of the deflection of a member with a free end (see Figure 1).
- providing edge support to brick walls thereby avoiding cantilever walls. (Guidance for brick walls is given in BS5628:Part 3 Clause 18.5[4].

APPLICATION OF THE DATA TO A DESIGN PROBLEM

Consider a large single-storey warehouse[8] with an extension planned where the architect wished to keep and upgrade an existing steel-framed separating wall. The wall was to be clad with a proprietary lightweight fire-protecting lining system above the 4m level to provide a 2-hour fire resistance. A masonry wall was to be constructed for the lower 4m. Originally it was planned to build a 227mm (9 in) thick brick wall to one side of the steel frame (Figure 6a) until it was pointed out that the thermal bowing of the brickwork could cause problems. If a fire attacked from one side (Figure 6b) a gap of about 150mm could open up along the top allowing the fire to get through; with a fire attacking the other side (Figure 6c) the restrained brickwork could crack and even fall down.

The solution was to build the brickwork directly underneath the existing steel frame, using a compressible flexible fire-stop of mineral wool to close the gap left to cater for vertical expansion of the brickwork in the event of fire. The large horizontal deflection at the top of the brick wall cantilever was eliminated by providing lateral restraint to the top of the brickwork and incorporating a plastic damp proof course at the bottom so that rotation could occur freely. To provide stability, vertical steel plates were embedded in the brickwork at 1.5m intervals (Figure 7).

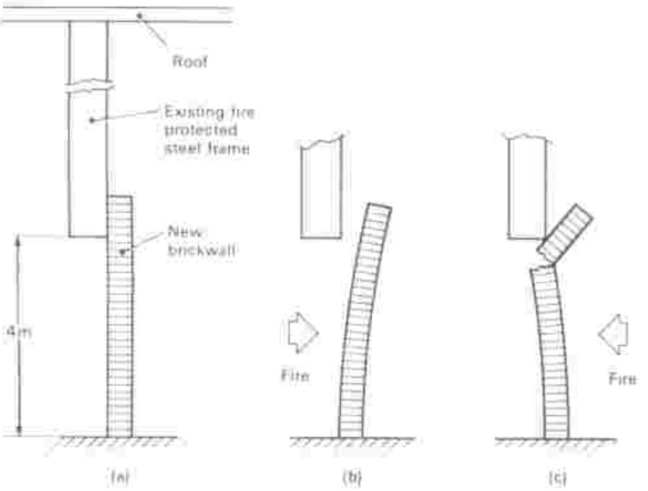

Figure 6 Effect of thermal bowing on free standing brick fire wall
(a) as designed
(b) fire from one side
(c) fire from the other side

Figure 7 Masonry fire wall under construction showing embedded steel plates

CONCLUSIONS

- Large thermal bowing deflections can occur in unrestrained brick walls and concrete floors exposed to the heating conditions of BS476:Parts 20 – 23:1987 fire resistance test. Such deflections are significantly increased, particularly in the first half-hour of exposure, during the hydrocarbon test conditions.
- A simple theory of unrestrained thermal bowing has been validated for metallic elements.
- Designers should allow for, or design against, thermal bowing especially in large elements of construction such as tall walls.

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