THE THERMAL BOWING OF BRICK WALLS EXPOSED TO FIRE ON ONE SIDE

Gordon M E Cooke, Fire Research Station, Building Research Establishment, Garston, UK and K S Virdi and N Jeyarupalingam, Structures Research Centre, City University, London, UK

SUMMARY

This paper provides new experimental and analytical data on the unrestrained thermal bowing of non loaded cantilevered clay brick walls exposed to fire on one side. Two specimen walls, 950 mm wide and 3000 mm high, were tested. They were 215 mm (9 in) and 323 mm (13 in) thick and were simultaneously exposed to the heating conditions of BS 476 : Part 20 (ISO 834) for a period of 1½ hours. Experimental data show that the horizontal deflection at the top of the specimens were nominally 110 mm and 120 mm for the 215 mm and 323 mm thick walls respectively after the 1½ hour exposure. A simple equation based on geometry can be used to predict deflections for walls which are higher than, but otherwise identical to, the tested wall, and a worked example is given. Analyses using the SOSMEF program show that such deflections can be predicted with reasonable accuracy but that there is a need for more data on the elevated temperature properties of brick. The data are of practical importance in the design of tall brick fire walls, where thermal bowing can lead to structural instability.

INTRODUCTION

In a fire, separating elements such as walls and floors are exposed to heat on one side. This gives rise to temperature differences across the thickness of the element which, if unrestrained, induces thermal bowing due, in the case of brick and concrete for example, to expansion of the hot face material.

Knowledge of these phenomena is not new. What is new, however, is the discovery that there are sparse data on the magnitude of thermal bowing of building constrictions subjected to the elevated temperatures, eg 1,200°C, likely to be reached in fires in buildings. This seems strange on first sight because very many standard fire resistance tests have been carried out on walls.

In a wall furnace test the nominally 3 m high loaded specimen is usually horizontally position fixed at the top and bottom, and horizontal thermal bowing deflections are very rarely measured because there is no requirement to do so. In some designs brick walls are not position fixed at the top so they are free to bow as a cantilever and perhaps topple over. In single storey storage buildings fire separating walls can be very high, in some cases more than 25 m high, and thermal bowing can then become an important stability criterion[1] even when position fixed at the top.

EXPERIMENTS

The Fire Research Station (FRS) has carried out a number of tests at elevated temperatures to assess thermal bowing deflections of members made of steel and reinforced concrete[2,3]. To obtain the thermal bowing data reported here two specimen brick walls were built into the standard fire resistance furnace wall test frame at the Warrington Fire Research Centre. The walls, which were solid and constructed using clay bricks, acted as vertical cantilevers so they were free to move vertically and horizontally when exposed to heat in one side. One wall was 225 mm (9 in) thick and the other was 337 mm (13 in) thick. Both were nominally 950 mm wide by 3000 mm high and were exposed side by side in a standard wall furnace using the BS476: Part 20 (ISO 834) temperature-time curve for a period of 3 hours.

Temperature profiles within each wall were obtained using 3 mm Inconel sheathed mineral insulated thermocouples placed in blind holes drilled from the unexposed face. The thermocouples were placed at mid height and at 1 m above and below. Horizontal deflections were measured at mid height and at the top and bottom of the walls using linear displacement transducers mounted on water-cooled hollow steel stands. Hence both the horizontal deflection at the top and curvature could be obtained.

Figure 1 shows the variation with time of the horizontal deflection at the top of both walls. The deflections are surprisingly large: 70 mm for the thinner wall and 55 mm for the other after 30 minutes exposure. Figures 2a and 2b shows the measured average temperature profiles at different times of exposure for the two walls.

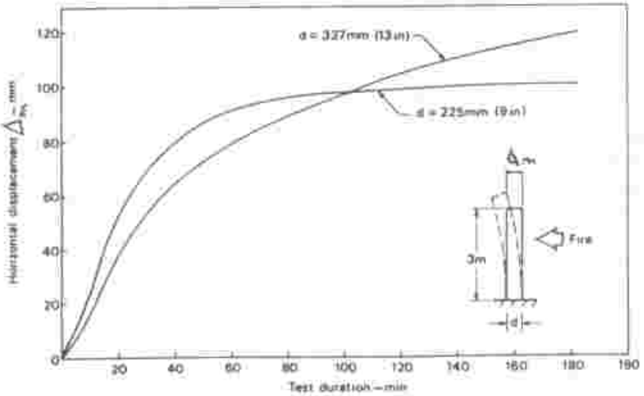
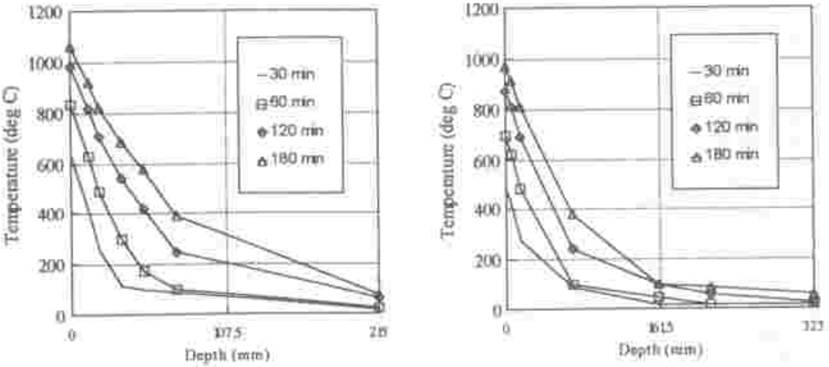


Figure 1. Thermal bowing of solid masonry walls



(a) 215 mm Wall

(b) 323 mm Wall

Figure 2. Temperature distribution in the test specimens at different times

THEORY

Simple theory

A simple theory of thermal bowing can be used to extrapolate from test data to obtain the bowing deflections of walls which are higher than, but otherwise identical to, those for which thermal bowing test data are available. For a non-loaded and unrestrained vertical cantilever member heated uniformly over its fire exposed face which is assumed to bow into a circular arc it can be shown[2] that the horizontal deflection Δ at the top normal to the wall is given by:

$$\Delta = \alpha H^2 T/2d \qquad (1)$$

Where α = coefficient of linear thermal expansion, H = height of wall, T = difference of temperature between the exposed and unexposed faces, and d = thickness of the wall.

To obtain an absolute measure of Δ requires that α and T are known. However this is unnecessary if test data are available. Assume that at a given time of fire exposure the measured horizontal deflection at the top of a cantilever of height H_m is Δ_m. A predicted deflection Δ_p is needed for a height of H_p. From Equation (1):

$$\Delta_m = (\alpha_m T_m / 2d_m)\ H_m^2$$

$$\Delta_p = (\alpha_p T_p) / 2d_p)\ H_p^2$$

Since in this case $\alpha_m = \alpha_p$, $T_m = T_p$ and $d_m = d_p$ it follows that

$$\Delta_p = \Delta_m \ \frac{H_p^2}{H_m^2} \qquad (2)$$

It can be seen that the deflection varies as the square of the height.

Worked example

What is the horizontal deflection at the top of an unrestrained 10 m high cantilevered solid clay brick wall 323 mm thick when exposed to the heating conditions of ISO 834 for 30 min? From Figure 1 Δ_m = 55 mm. From Eqn (2):

$$\Delta_p = 55\ (\frac{10^2}{3^2}) = 610 \text{ mm}$$

In making predictions of this kind two points should be kept in mind. First the height-to-thickness ratio of a wall may be limited by room temperature design codes so that very high and thin walls (the worst combination for giving large thermal bowing deflections) may not be permitted. Secondly the predictions take no account of out-of-plumb dead loads which can increase the deflections according to the PΔ effect.

Numerical simulation

The computer program SOSMEF[4], developed at City University, was used to numerically simulate the structural response of both the walls. SOSMEF is capable of calculating the structural response of beams and columns subjected to nonlinear variation of temperature in all three directions and any combination of axial and lateral loads. The method of analysis used is finite difference based, which ensures equilibrium at a number of points along the length of the member. More detailed description of the numerical method is given elsewhere[5]. In the present paper, the walls were modelled as columns. The method has been validated by experiments on steel columns and other columns[3,4].

The self weight of the specimens was approximately modelled as an axial force. As there are little data available in the literature on the material properties of bricks at elevated temperatures, it is assumed that the material properties are independent of the temperature. The following values were used for different parameters of the material model.

Maximum compressive strength	14.0	N/mm^2
Maximum tensile strength (flexural)	2.0	N/mm^2
Young's modulus	10	kN/mm^2
Coefficient of thermal expansion	6.0×10^{-6} / °C	
Strain at the peak compressive stress	0.0028	

The compressive part of the stress-strain relationship is assumed to be a parabola with the peak value as the maximum compressive strength. The tensile part is assumed to be linear up to the maximum tensile stress and then linearly decreasing to zero, at five times the peak strain.

A comparison of computed and experimental horizontal deflections at the top for both the specimens are given in the following Table.

Time (minutes)	Maximum deflection (mm)			
	215 mm Wall		323 mm Wall	
	Test	Computer	Test	Computed
30	77.16	67.57	55.46	22.61
60	98.49	97.33	79.72	49.89
90	103.20	107.18	93.52	59.70
120	105.00	112.06	105.10	64.76
150	106.20	115.59	114.10	68.37
180	107.50	118.34	120.30	71.53

Computed deflections for the 215 mm wall are very close to the test values. For the 323 mm wall, computed deflections are somewhat lower than the test values. This may be attributed to the assumption that material properties are independent of the temperature. Maximum strength and the Young's modulus of the brick can be expected to be lower at elevated temperatures. These results also show the need to obtain more data on the material properties of the brick at elevated temperatures.

CONCLUSIONS

Tests have shown that elevated temperature thermal bowing of brick fire walls is large. A simple theory has been developed which facilitates the prediction of thermal bowing deflections of walls taller than those tested but otherwise identical. The computer program SOSMEF, which has proved capable of satisfactorily predicting thermal bowing deflections of steel and composite steel/concrete members, cannot yet be fully utilised for brick walls because of lack of elevated temperature material properties.

REFERENCES

1. Cooke G M E, *Fire engineering of tall fire separating walls*. Fire Surveyor, Parts 1 & 2, June & August, p13-29 and p19-29 respectively, 1987, London.

2. Cooke G M E, *The structural response of steel I-section members subjected to elevated temperature gradients across the section*, PhD thesis, The City University, London, September 1987.

3. Cooke G M E and Morgan P B E, *Thermal bowing in fire and how it affects building design*, BRE Information Paper 21/88, Building Research Establishment, December 1988.

4. Jeyarupalingam N, *SOSMEF Version 3.0 User Manual*, Structures Research Centre, Department of Civil Engineering, City University, 1992, London.

5. Jeyarupalingam N, *Steel, composite and reinforced concrete beams and columns exposed to fire*, PhD Thesis, Department of Civil Engineering, City University, 1966, London.

6. Jeyarupalingam N and Virdi K S, *Steel beams and columns exposed to fire hazard*, Structural design for Hazardous Loads - The role of physical testing, Edited by J L Clarke, F K Garas and G S T Armer, E&FN Spon, 1992, London.