FULL-SCALE TESTING OF VERTICALLY RESTRAINED MASONRY CLADDING

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SUMMARY

The paper describes a series of full-scale tests to investigate the time-dependent behaviour of clay brick masonry cladding panels subject to vertical restraint from a reinforced concrete frame. Stresses and strains recorded in a number of panels are compared with those predicted by composite modelling of data obtained from complementary tests on small-scale brickwork and concrete specimens. The potential benefits of vertically restrained masonry cladding over more complicated systems involving shelf angle support brackets are described. Details of a design methodology for vertically restrained masonry are provided.

KEYWORDS: Masonry; restraint; stress; strain; composite model

NOTATION

A = cross-sectional area (mm^2)
E = modulus of elasticity (kN/mm^2)
α = coefficient of linear thermal expansion (strain x 10^{-6}/°C)
t = temperature (°C)
F = force (kN)
σ_0 = stress at time t_0 (N/mm^2)
$\sigma(t)$ = stress at time t (N/mm^2)
C_s = specific creep i.e. creep per unit stress (strain x$10^{-6}/N/mm^2$)
S = shrinkage (+ve), or moisture expansion (-ve) (strain x10^{-6})
χ = aging coefficient
$\Phi(t,t_0)$ = creep coefficient (ratio of creep at time t to elastic strain at time t_0)
Δ = change

Subscripts b and c refer to brickwork and concrete, respectively.

INTRODUCTION

Clay brick masonry is often used as a solid infill on concrete frame buildings, particularly in regions of the world that are subject to seismic activity such as the Mediterranean. Numerous failures of this type of cladding have, however, been reported in the UK during the past thirty

or so years. These have been attributed to incompatibility between the vertical movement of the clay brickwork, which undergoes a long-term irreversible moisture expansion, and drying shrinkage and creep of the concrete in the columns of a frame (Beard et al. 1983). This was thought to have led to excessive levels of stress being set up in the brickwork, typically causing it to crack or crush and bulge outwards. The exact cause of these failures is, however, disputed. Sutherland, in particular, attributes them to a weak architectural detail, namely, a boot lintel which induced eccentric loading in the brickwork (Sutherland 1988). In the case of concentrically restrained brickwork, Sutherland maintains that no such problems occur, as the levels of stress are greatly reduced due to the relieving effect of creep action within the brickwork and concrete.

To provide a better understanding in this area, a series of tests were carried out in which full-scale masonry panels were subject to vertical restraint from a seven-storey high concrete frame. As part of this programme, a composite model was also developed to predict the elastic and time-dependent stress/strain behaviour of brickwork panels under conditions of vertical restraint from a concrete frame. The model utilised data from a complementary series of creep and free moisture movement tests that were carried out on small-scale brickwork panels and concrete prisms. The performance of the composite model was then evaluated in relation to the full-scale results, with a view to developing a design methodology for vertically restrained clay brickwork masonry cladding on concrete frame buildings generally.

A brief description of the test programme is provided in this paper, full details having already been published elsewhere (Bingel et al. 2004). The composite model equations are then presented and selected results from the full-scale tests are compared with composite model predictions. The potential advantages of vertically restrained brick masonry over more complicated systems of cladding involving stainless steel support brackets are outlined. Finally, details of a proposed design methodology for this form of restrained masonry are given.

TEST PROGRAMME

Testing was carried out on the seven-storey high concrete test frame at the Building Research Establishment (BRE) Hangar at Cardington, near Bedford in the UK. This cast-in-situ frame was built primarily to study the concreting and construction processes involved with frame construction and incorporated a number of high strength concrete mixes (Figure 1).

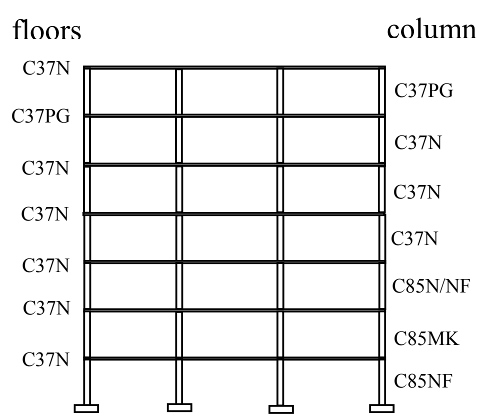

Figure 1. Cardington Test Frame - Concrete Mixes

In total, four full-size panels were solidly built in to the frame, each representing a different form of masonry cladding (Table 1 and Figure 2). Two types of brick were used. Panels A, B & C were locked in to the frame at roof level by steelwork frames bolted directly on to the roof slab. Figure 3 shows panels A and D on the frame. Complementary small-scale tests were also carried out on separate brickwork panels and concrete prisms to determine the elastic and time-dependent properties of the brickwork and concrete used.

Table 1. Panel Details

Panel	Form of Construction	Brick
A	Free-standing 215mm off-the-frame brickwork	Kempston Melford Yellow
B	Half-brick thick brick/brick cavity wall, outer leaf free-standing, inner leaf supported on frame at each floor	Ibstock Harewood Russet Orange
C	Half-brick thick brick/block cavity wall, outer leaf free-standing, inner leaf supported on frame at each floor	Ibstock Harewood Russet Orange & Hemelite aggregate block
D	215mm brick infill panels solidly built-in at each floor	Kempston Melford Yellow

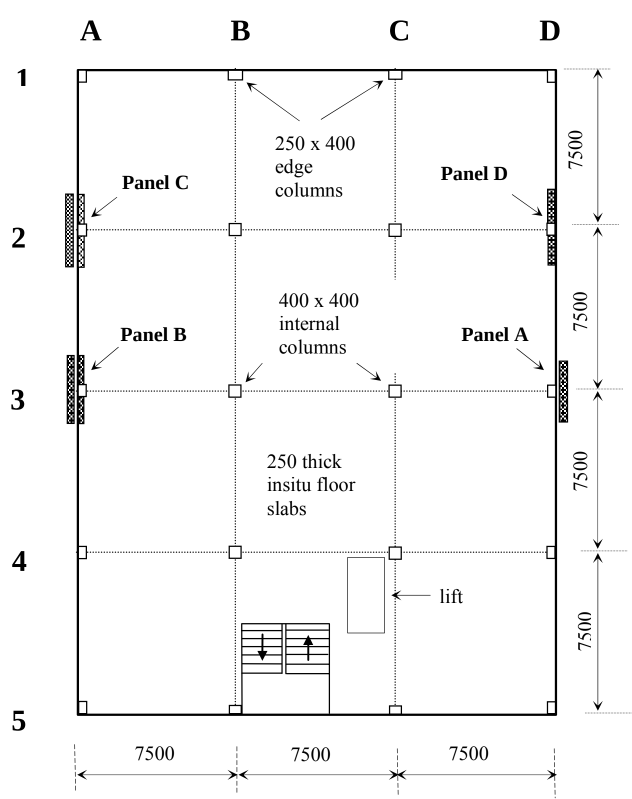

Figure 2. Floor Plan Showing Location of Test Panels

Figure 3. Panels A & D (© The Building Research Establishment)

INSTRUMENTATION

Load cells were incorporated at selected locations to monitor the stresses (loads) that developed in the brickwork panels. Typically this was at the ground, third floor and roof level, according to panel construction. Strains in the panels and columns of the concrete frame were measured at each floor using a 750mm Demec gauge.

TIMESCALE

Bricklaying began approximately four months after completion of the test frame, the four panels being 'locked-in' approximately six weeks later. As such, early age shrinkage of the concrete had already occurred before the brickwork was locked-in. The panels were monitored for approximately twenty seven months, during which time a number of other tests took place on the frame. One of these involved placing sand bags on each floor. The sand bags on lower floors were subsequently relocated to the upper floors so as to purposely overload the top of the building. Stresses (loads) and strains in the panels and columns were, consequently, affected by this particular test. No control of the environmental conditions within the hangar was possible due to its very large size, the air temperature ranging between 2°C and 26°C during the monitoring period. Similarly, no control over the relative humidity was possible.

Measurements from the small-scale tests indicated that, at the end of the 27 month monitoring phase, the Kempston brickwork had undergone a free vertical moisture expansion of approximately 150×10^{-6}. Free moisture movement of the Ibstock brickwork on the other hand was variable, with two of the small test panels recording an expansion of 100×10^{-6} and a third undergoing a contraction of 50×10^{6}. Shrinkage of the C37 and C85 concrete mixes over this period typically ranged from 50 to 100×10^{-6}. Full details of the elastic and time-dependent properties of the brickwork and concrete are given elsewhere (Bingel et al. 2006).

COMPOSITE MODEL

As already noted, a composite model was developed to predict elastic and time-dependent changes in stress and strain in a brickwork panel under conditions of vertical restraint from a concrete column and subject to a superimposed floor loading of W (Figure 4).

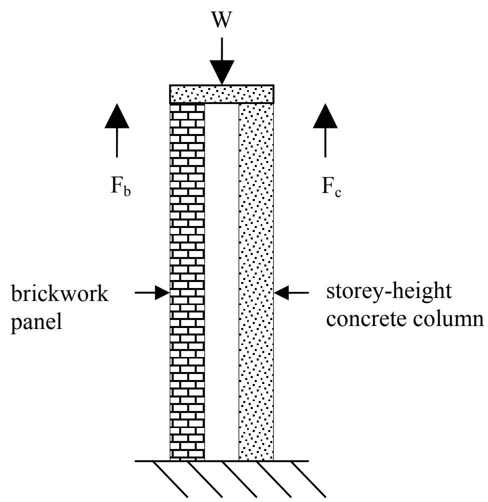

Figure 4. Composite Model

Table 2 gives the relevant equations for brickwork stress, these being derived from consideration of load and strain compatibility in the concrete/brickwork composite system. In these equations, time-dependent changes in stress were evaluated using an age-adjusted effective modulus approach (Neville et al. 1983). The full derivation of the equations, together with additional equations for prediction of time-dependent changes in brickwork strain, is provided elsewhere (Bingel et al. 2006).

Table 2. Composite Model Equations

Loading Condition	Equation
1. Short-term (elastic) stress, σ_{bo}, due to Imposed load, W	$\sigma_{b0} = \dfrac{W}{A_b + \dfrac{E_c A_c}{E_b}}$ (1)
2. Time-dependent change in stress, $\Delta\sigma_b(t)$ due to imposed load W	$\Delta\sigma_b(t) = \dfrac{\dfrac{W\phi_c(t,t_0)}{A_c E_c} - \sigma_{b0}\left[\dfrac{\phi_b(t,t_0)}{E_b} + \dfrac{A_b}{A_c E_c}\phi_c(t,t_0)\right]}{\dfrac{1}{E_b}\left[1+\chi\phi_b(t,t_0)\right] + \dfrac{A_b}{A_c E_c}\left[1+\chi\phi_c(t,t_0)\right]}$ (2)
3. Time-dependent change in stress, $\Delta\sigma_b(t)$, due to dead load from an upper floor	$\Delta\sigma_b(t) = \dfrac{\sigma_{c_{dl}} C_{sc}(t,t_0) - \sigma_{b_{dl}} C_{sb}(t,t_0)}{\dfrac{1}{E_b}\left[1+\chi\phi_b(t,t_0)\right] + \dfrac{A_b}{A_c E_c}\left[1+\chi\phi_c(t,t_0)\right]}$ (3)
4. Time-dependent change in stress, $\Delta\sigma_b(t)$, due to restraint of moisture movement(s)	$\Delta\sigma_b(t) = \dfrac{S_c - S_b}{\dfrac{1}{E_b}\left[1+\chi\phi_b(t,t_0)\right] + \dfrac{A_b}{A_c E_c}\left[1+\chi\phi_c(t,t_0)\right]}$ (4)

PERFORMANCE OF COMPOSITE MODEL

Figure 5 compares the stresses measured in a number of full-scale panels with those predicted by the model from the data obtained in the complementary small-scale tests on brickwork and concrete specimens (equations (1)-(4) in Table 2). To eliminate the effect of short-term changes in ambient temperature within the Cardington Hangar, all stresses in Figure 5 have been normalised with respect to the temperature at the time the panels were initially locked-in.

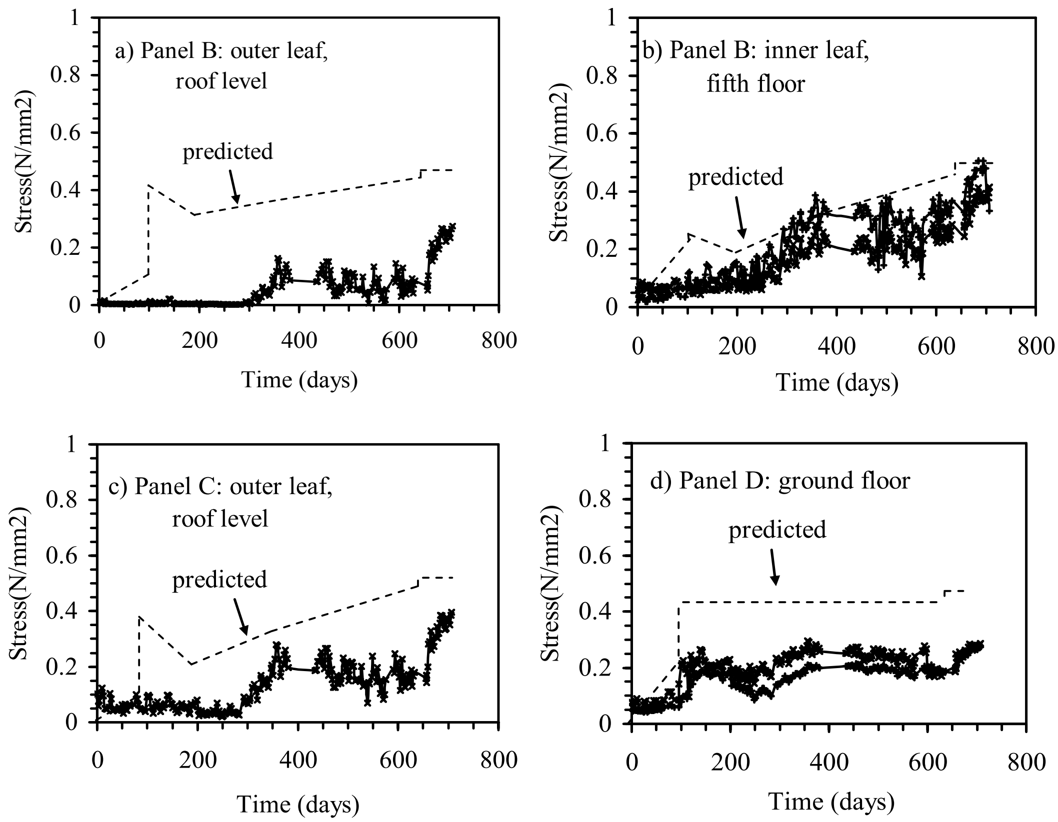

Figure 5. Predicted and Measured Stresses in Brickwork

It can be seen that, in general, the stresses predicted by the model were higher than those measured in the full-scale panels. It should be noted, however, that the stresses that developed in the full-scale panels were affected by the presence of the load cells, the axial stiffness of which was less than that of the brickwork they replaced. The effect of this was to reduce the levels of stress in the brickwork. In addition, in the full-scale tests slight 'lack-of-fit' between the load cells and the adjacent brickwork or concrete frame may have occurred, although this could not be verified. This would, nevertheless, also have led to lower stresses being developed in the full-scale panels. In this respect, 'lack-of-fit' is a recognised practical problem for tests involving restraint generally (Neville et al. 1983).

When brickwork was entirely built-in between floors i.e. without load cells being present, better agreement was obtained between the full-scale results and composite model predictions for brickwork strain (and hence, indirectly, brickwork stress) (Figure 6). Further discussion of the factors influencing the prediction of brickwork stress and strain and the composite model performance are available elsewhere (Bingel et al. 2006).

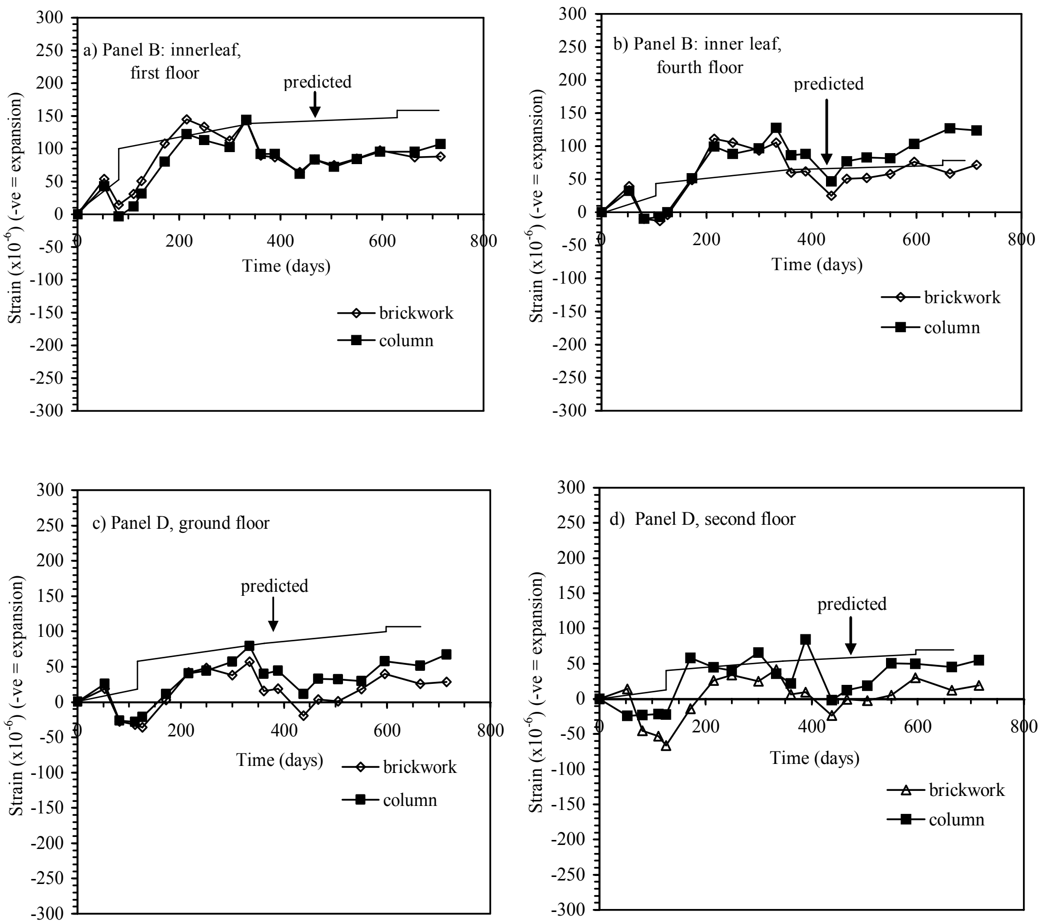

Figure 6. Predicted and Measured Strains in Brickwork

CONCLUSIONS FROM COMPOSITE MODELLING

A composite model was developed to predict the short-term and time-dependent stress and strain behaviour of brickwork panels subject to vertical restraint within a concrete frame. When compared with the results from full-scale tests on vertically restrained panels it was found that

1. Stresses predicted by the model were generally higher than those measured in the full-scale tests. In the full-scale tests, however, the presence of load cells together with slight 'lack-of-fit' between the load cells and the adjacent brickwork or concrete frame reduced the levels of stress that developed in the restrained brickwork panels.

2. Reasonable agreement was obtained between predicted and measured brickwork strains (and hence, indirectly, brickwork stress) for panels where the brickwork was entirely built-in between the floors of the frame i.e. without the presence of load cells. Some degree of inequality is, of course, to be expected, given the inherent variability in the properties of the brickwork and concrete used.

3. Stresses predicted by the model were considered to provide a safe upper bound to those that would develop in full-scale brickwork panels vertically restrained within a concrete frame.

ADVANTAGES OF VERTICALLY RESTRAINED MASONRY CLADDING

In the UK, clay brickwork cladding is usually supported on stainless steel support brackets bolted to the floors of the structural frame at regular intervals (Figure 7). This form of construction is, however, expensive and requires high levels of workmanship which are often missing on site. In addition, the regular horizontal movement joints associated with this form of construction produce a slab-like appearance in the thin outer skin of brickwork, which can normally only be laid in stretcher bond.

Vertically restrained masonry, on the other hand, is a simpler form of construction that allows the bricklayer to do what he does best i.e. lay bricks. It also offers the possibility of using different types of brickwork bond, as the walls are invariably thicker and more robust than brickwork supported on shelf-angles. In terms of cost, a detailed study has shown that the new build costs of vertically restrained masonry cladding are within 1% of brickwork supported on stainless brackets (www.brick.org.uk). Savings in whole life costs are, however, achieved with vertically restrained masonry as horizontal movement joints, which require regular resealing, are eliminated.

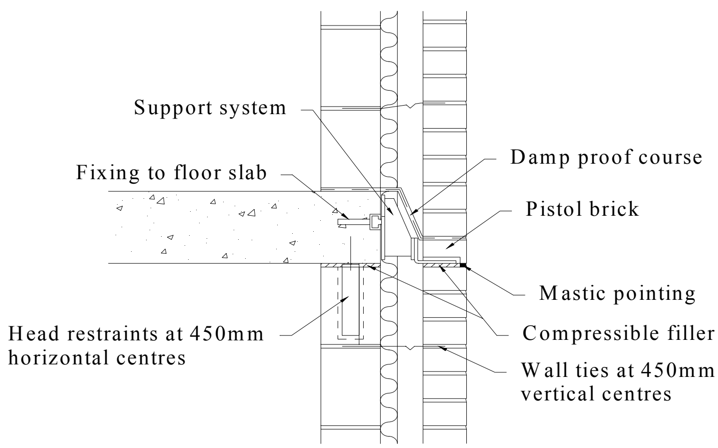

Figure 7. Typical Shelf Angle Support Detail

The use of clay brickwork for the inner leaf of cavity wall construction, as in Panel B, may also prove beneficial as the greater mass of brickwork, combined with increased thermal insulation in the cavity, enable it to act as a more effective ‘heat sink’. Daily temperature variations within a multi-storey building would, therefore, be less pronounced than with, say, a lightweight blockwork inner leaf. In addition the presence of unsightly drying shrinkage cracks commonly found in internal blockwork walls would be eliminated.

Finally, Sutherland considers there are structural benefits to be gained from concentrically building-in brickwork to the structural frame as it increases the overall stiffness of the frame and provides additional load paths (Sutherland 1988). In addition, the lateral load resistance

of solidly built-in brickwork panels may be enhanced due to arching action.

DESIGN METHODOLOGY

Based on the findings from this programme of research, a full methodology for the design of clay brickwork masonry solidly built-in to a concrete frame has been developed, in accordance with BS5628 Pt1 (British Standards Institution 2005). This is available from the UK Brick Development Association website (www.brick.org.uk). The methodology utilises the basic equations shown in Table 4 above and gives worked examples of the design of this form of construction for both a reinforced concrete and a steel frame building. In the latter case, prediction of brickwork stress and strain is simplified as time-dependent vertical movement of the frame is eliminated.

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