VERTICALLY RESTRAINED CLAY BRICKWORK CLADDING

BACKGROUND

At present, differential vertical movement between brickwork cladding and a structural frame is accommodated by appropriate detailing or by limiting the uninterrupted height of the brickwork. This second method involves supporting the brickwork on metalwork brackets attached to the frame at regular intervals.

Following an extensive programme of research, including full-scale testing of 7-storey high brickwork panels on a reinforced concrete frame, a third option is now available, namely **'VERTICALLY RESTRAINED CLAY BRICKWORK'.**

Here, differential vertical movement is prevented by 'locking' together the brickwork and the structural frame. This is achieved by building in the brickwork solidly between floors or, for off-the frame brickwork, by the use of an extended roof slab.

The main advantages of this form of construction are

- Simpler brickwork detailing and construction, leading to more robust and durable buildings
- Elimination of costly and complicated metalwork support systems for brickwork cladding
- Improved appearance of brickwork through a wider choice of bonding patterns, deeper reveals at openings and the elimination of horizontal movement joints
- Reductions in maintenance, leading to savings in whole life costs of buildings

ECONOMICS OF VERTICALLY RESTRAINED BRICKWORK

Vertically restrained clay brickwork cladding is cost-effective when compared with alternative forms of brickwork cladding construction. For example, Figure 1 shows a 'typical' six-storey steel/reinforced concrete frame building clad with clay brickwork masonry. The internal floor area is 20m x12m, each storey being 3m high. Using published building price indices, three alternative forms of cladding construction were costed. The total price of each scheme was as follows

		Total Cost
Scheme 1:	215mm thick full height 'off the frame' restrained brickwork cladding & non-structural inner leaf	= £95,332
Scheme 2:	102.5mm brickwork outer leaf supported on stainless steel brackets & structural studding inner leaf	= £94,875[#]
Scheme 3:	102.5mm brickwork outer leaf supported on stainless steel brackets & 100mm blockwork inner leaf	= £94,869[#]

An additional whole life cost of resealing/replacing horizontal movement joints should be added to these figures. This varies from £6,810[1] to £49,724[2] and is based on the joints being replaced at 15year intervals, and the building lasting 60 years.

[1] - based on no price increases over the 60 year period
[2] - based on 6%p.a. increase in prices over the 60 year design life

Whilst the initial cost of vertically restrained, off-the-frame brickwork is within 1% of the other forms of cladding, savings in the whole life cost of the building are achieved as horizontal movement joints are eliminated.

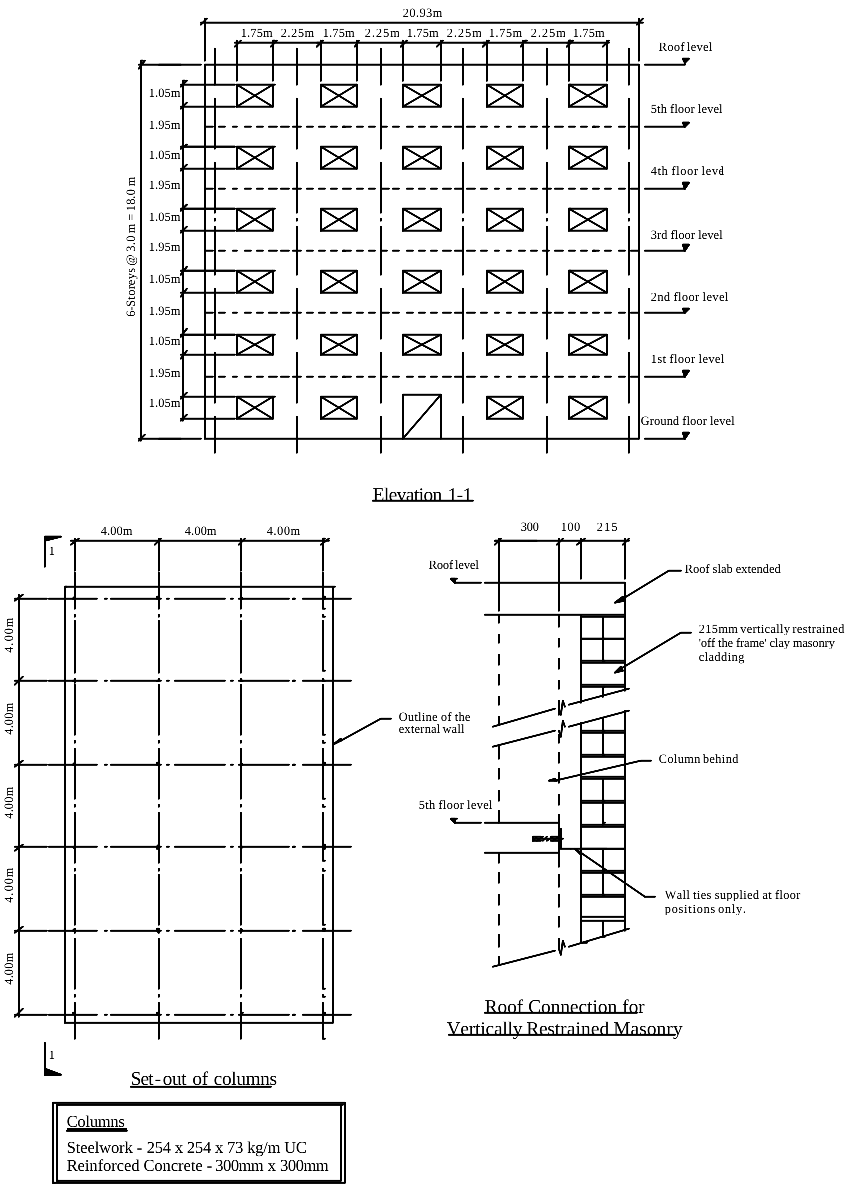

Figure 1 – 'Typical' six-storey framed building

DESIGN OF VERTICALLY RESTRAINED OFF-THE-FRAME CLAY BRICKWORK

Using the results from the full-scale testing of brickwork panels, a design methodology has been developed to predict the stresses that occur in off-the-frame restrained brickwork panels (Appendix A). These can then be compared with the design resistance of the panels in accordance with BS 5628.

LOAD COMBINATIONS AND PARTIAL FACTORS OF SAFETY FOR DESIGN OF RESTRAINED BRICKWORK CLADDING

The following load combinations and partial factors of safety for ultimate limit state design are suggested:

LOADING	Load combinations	
	1	**2**
Dead	1.4	1.2
Imposed	1.6	1.2
Wind	-	1.2
Restraint of moisture movements (reversible and irreversible)	1.4	1.2
Thermal	-	1.2

DESIGN EXAMPLES

Two examples of the design of vertically restrained off-the-frame brickwork cladding are given for the building shown in Figure 1 above. The first assumes a steel-frame whilst the second is for a reinforced concrete frame. Both examples are based on BS 5628: Parts 1 & 2.

LOADINGS

DEAD LOAD

GENERAL

150 mm thick reinforced concrete floor slab = 3.54 kN/m^2
Ceiling = 0.10 kN/m^2
Services = 0.15 kN/m^2

REINFORCED CONCRETE DESIGN EXAMPLE ONLY

Self-weight of reinforced concrete columns	= 6.05 kN/floor

<u>IMPOSED LOAD</u> (BS 6399 : Part 1 : 1996)

Roof level only, assuming no access	= 0.75 kN/m^2
General office load	= 2.50 kN/m^2
Partitions	= 1.00 kN/m^2

<u>WIND LOADING</u> (CP3 : Chapter V : Part 2 : 1972)

Wind speed, V		= 46 m/s
S_1 and S_3		= 1
S_2 Ground roughness		= 3
Building size		= Class B
Maximum external pressure coefficient, C_{pe}		= + 0.7
Internal pressure coefficient, C_{pi}		= - 0.3
Force due to wind loading, F	3m	= 0.47 kN/m^2
	5m	= 0.55 kN/m^2
	10m	= 0.71 kN/m^2
	15m	= 0.90 kN/m^2
	20m	= 1.05 kN/m^2

<u>MATERIAL PROPERTIES</u>

<u>BRICKWORK</u>

Compressive strength of masonry unit	= 50 N/mm^2
Mortar designation – 1:1:6	= class (iii)
Assumed characteristic compressive strength of masonry, f_k (BS 5628 : Part 1 : 1992)	= 10.6 N/mm^2
Density of masonry, g_b	= 21.6 kN/m^3
Area of brickwork adjacent to steelwork column, A_b	= 483,750 mm^2
Elastic section modulus of brickwork, Z_b	= 17,334,375 mm^3
Coefficient of linear thermal expansion, a_b	= 7 x 10^{-6} / $^{\circ}$C
Modulus of elasticity of brickwork, E_b	= 4.77 kN/mm^2
Note, $E_b = 450\ f_k$ – (Appendix A)	
Creep coefficient of brickwork, $f_b(t,t_o)$, (BS 5628 : Part 2 : 1985)	= 1.5
Specific creep strain of brickwork, C_{sb}	= 314 x 10^{-6}
Irreversible vertical moisture movement of brickwork, S_b (BS 5628 : Part 2 : 1985)	= -500 x10^{-6} (0.5mm/metre) (-ve = Expansion)
Age-adjustment factor for creep of brickwork, *?*	= 0.8

<u>STEELWORK</u>

Area of steelwork, A_s - 254 x 254 x 73 kg/m UC	= 9,290 mm^2 / column
Modulus of elasticity of steelwork, E_s	= 205 kN/mm^2

CONCRETE

Characteristic strength of concrete, f_{cu}	= 40 N/mm^2
Density of reinforced concrete, g_c	= 23.6 kN/m^3
Area of concrete, A_c (ignoring reinforcement)	= 90,000 mm^2 / column
Characteristic strength of reinforcement, f_y	= 460 N/mm^2
Area of reinforcement, A_s, main reinforcement in columns - 4 No. 25mm diameter bars	= 1,963 mm^2
Modulus of elasticity of concrete, E_c (BS 8110 : Part 2 : 1985)	= 28 kN/mm^2
Assumed time taken to build frame	= 4 months
Assumed age at which masonry is locked into frame	= 2 months after completion of frame
Assumed final (30-year) creep coefficient of concrete, $f_c(t,t_o)$ (BS 8110 : Part 2 : 1985)	= 2.0
Specific creep strain of concrete, C_{sc}	= 71 x 10^{-6}
Ultimate drying shrinkage, S_c, adjusted for the effect of the reinforcement in the column (BS 8110:Part 2:1985)	= 350 x 10^{-6}
Assumed average relative humidity of concrete	= 60 %

DESIGN EXAMPLE 1 - STEEL FRAME BUILDING

DEAD LOADING

Self-weight of brickwork (Total) = (0.215 m x 60.975 m^2) x 21.6 kN/m^3
= 283.17 kN

Stress due to dead load (Average), $s_{bsw(av)}$ = + 0.29 N/mm^2 (S.L.S.)

IMPOSED LOADING

Total imposed load

(2m x 4m) x (0.75 kN/m^2 + 5(2.50 kN/m^2 + 1.00 kN/m^2)) = 146 kN

Average imposed load, W = 73 kN

Change in stress due to imposed load, ? s_{bll} = + 0.08 N/mm^2 (S.L.S.) [Eq. 1]

WIND LOADING

Moment due to wind loading = 0.107 x 0.47 kN/m^2 x 3.15m x (3m)^2
= 1.425 kNm (S.L.S.)

Maximum compressive stress due to wind load,
? s_{bwl} = 1,425,000 Nmm / 17,334,375 mm^3 = + 0.08 N/mm^2 (S.L.S.)

TIME-DEPENDENT INTERACTION

The long-term change in the stress in the brickwork, ? $s_b(t)$
= + 0.74 N/mm^2 (U.L.S. - load combination 1) [Eq. 2]
= + 0.64 N/mm^2 (U.L.S. - load combination 2) [Eq. 2]

THERMAL EFFECTS

Allowing for a maximum 22.5°C difference in temperature between the steelwork frame and the brickwork cladding, i.e. ? t_b = 22.5°C.

The maximum stress in the brickwork due to the temperature, s_t,

= + 0.34 N/mm^2 (S.L.S.) [Eq. 4]

Summary

	S.L.S. loading (N/mm^2)	U.L.S. loading Combination 1 (N/mm^2)	U.L.S. loading Combination 2 (N/mm^2)
Maximum stress due to dead load, $s_{bsw(max)}$	+ 0.58	+ 0.82	+ 0.70
Change in stress due to imposed load, ? s_{bll}	+ 0.08	+ 0.13	+ 0.10
Change in stress due to wind load, ? s_{bwl}	+ 0.08	-	+ 0.10
Long-term change in the stress in the brickwork, ? s_b(t**)**	-	+ 0.74	+ 0.64
Maximum stress in the brickwork due to the temperature, s_t,	+ 0.34	-	+ 0.41
		S= 1.69 N/mm^2	**S = 1.95 N/mm^2**

DESIGN STRESS RESISTANCE OF PANEL

From clause 32.2.1 of BS 5628: Part 1, design stress resistance of panel = *ß* x f_k / $?_m$

The effective height of the wall, h_{ef} = 1.0 h = 3,000 mm
(Clause 28.3.1.1 of BS 5628 : Part 1 : 1992)
The effective thickness of the wall, t_{ef} = t = 215 mm
(Clause 28.3.1.1 of BS 5628 : Part 1 : 1992)
h_{ef} / t_{ef} = 14

∴ From table 7 of BS 5628 : Part 1 : 1992, *ß* = 0.89

For normal categories of manufacturing and construction controls, $?_m$ = 2.3
(Table 4 of BS 5628 : Part 2 : 1985)

Design stress resistance = 4.10 N/mm^2 > 1.95 N/mm^2 ∴ adequate

<u>DESIGN EXAMPLE 2</u> - REINFORCED CONCRETE FRAMED BUILDING

<u>DEAD LOADING</u>

BRICKWORK, $s_{bsw(av)}$

Self-weight of brickwork (Total) = 283.17 kN

Stress due to dead load (Average), $s_{bsw(av)}$ = + 0.29 N/mm^2 (S.L.S.)

REINFORCED CONCRETE COLUMN, $s_{csw(av)}$

Self-weight (Total),

= 6(((2m x 4m) x (3.54 kN/m^2 + 0.10 kN/m^2+ 0.15 kN/m^2)) + (6.05 kN / floor))
= 218.22 kN

Stress due to dead load (Average), $s_{csw(av)}$ = + 1.21 N/mm^2 (S.L.S.)

<u>IMPOSED LOADING</u>

Change in stress due to imposed load, Δs_{bll} = + 0.07 N/mm^2 (S.L.S.) [Eq. 1]

<u>WIND LOADING</u>

As Design Example 1, the maximum compressive stress due to wind load,
? s_{bwl} = + 0.08 N/mm^2 (S.L.S.)

<u>TIME-DEPENDENT INTERACTION</u>

The long-term changes in the stress in the brickwork, ? s_b(t)
= + 1.25 N/mm^2 (U.L.S. - load combination 1) [Eq. 3]
= + 1.07 N/mm^2 (U.L.S. - load combination 2) [Eq. 3]

<u>THERMAL EFFECTS</u>

Allowing for a maximum 22.5°C difference in temperature between the concrete frame and the 'off the frame' brickwork cladding, i.e. ? t_b = 22.5°C.

The maximum stress in the brickwork due to the temperature, s_t,
= + 0.39 N/mm^2 (S.L.S.) [Eq. 4]

Summary

	S.L.S. loading (N/mm^2)	U.L.S. loading Combination 1 (N/mm^2)	U.L.S. loading Combination 2 (N/mm^2)
Maximum stress due to dead load – brickwork only, $s_{bsw(max)}$	+ 0.58	+ 0.82	+ 0.70
Change in stress due to imposed load, ? s_{bll}	+ 0.07	+ 0.11	+ 0.08
Change in stress due to wind load, ? s_{bwl}	+ 0.08	-	+ 0.10
Long-term change in the stress in the brickwork, ? s_b(t)	-	+ 1.25	+ 1.07
Maximum stress in the brickwork due to the temperature, s_t,	+ 0.39	-	+ 0.47
		S= 2.18 N/mm^2	S = 2.42 N/mm^2

DESIGN STRESS RESISTANCE OF PANEL

As Design Example 1, design stress resistance = 4.10 N/mm^2 > 2.42 N/mm^2 $\therefore$ adequate

NOTE A final check should then be made to ensure that the columns of the frame are capable of resisting the forces that may develop in the restrained masonry.

APPENDIX A: <u>DESIGN METHODOLOGY FOR VERTICALLY RESTRAINED OFF-THE-FRAME BRICKWORK</u>

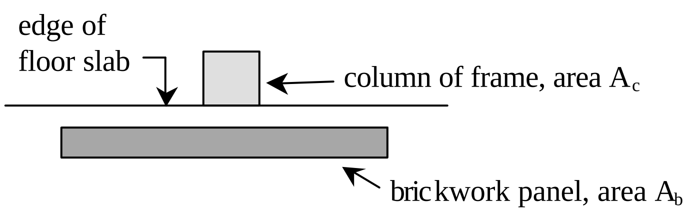

Figure A1. Plan view of brickwork cladding adjacent to a frame

The following equations are recommended for predicting the changes in stress in vertically restrained off-the-frame brickwork cladding (Figure A1).

NB. See Design Examples 1 & 2 for list of symbols used below.

1. Change in stress due to imposed load on frame, ?s_{bll}

For a steel framed building, $$\Delta\sigma_{bll} = \left[\frac{W}{\left(A_b + \frac{E_s}{E_b}A_s\right)}\right] \quad (1)$$

Where W = the average characteristic imposed load acting on the column

Note - for a reinforced concrete framed building substitute A_c and E_c for A_s and E_s

2. Change in stress due to the time -dependent interaction between masonry and a steel frame, ?s_b(t)

$$\Delta s_b(t) = \frac{-\left[\frac{s_{bll} \times f_{b(t,t_0)}}{E_b} + S_b + \left(s_{bsw(av)} \times C_{sb}\right)\right]}{\frac{A_b}{A_s \times E_s} + \left(\frac{1}{E_b} \times (1 + (c\, f_{b(t,t_0)}))\right)} \quad (2)$$

3. Change in stress due to the time -dependent interaction between masonry and a reinforced concrete frame, ?s_b(t)

$$\Delta s_b(t) = \frac{\left[\left(\frac{W f_{c(t,t_0)}}{A_c \times E_c} - s_{bll}\left(\frac{f_{b(t,t_0)}}{E_b} + \frac{A_b}{A_c \times E_c} \times f_{c(t,t_0)}\right)\right) + \left(S_c - S_b\right) + \left(\left(s_{csw(av)} \times C_{sc}\right) - \left(s_{bsw(av)} \times C_{sb}\right)\right)\right]}{\left(\frac{1}{E_b} \times (1 + (c\, f_{b(t,t_0)}))\right) + \left(\frac{A_b}{A_c \times E_c} \times (1 + (c\, f_{c(t,t_0)}))\right)} \quad (3)$$

4. **Change in stress due to thermal effects,** D$\boldsymbol{s}_{\mathbf{t}}$

For a steel framed building, $$\Delta s_t = \frac{a_b \times \Delta t_b}{\left[\frac{1}{E_b} + \frac{A_b}{A_s \times E_s} \right]} \qquad (4)$$

Note - for a reinforced concrete framed building substitute A_c and E_c for A_s and E_s.

It is suggested that ? t_b = 22.5 $^{\circ}$C, where ? t_b is the change in temperature of the brickwork.

5. For ULS design, the design load should be taken as the sum of the products of the component loads multiplied by the appropriate partial factors of safety (See ‘Load Combinations’).

6. Full scale tests have shown that **450 $\boldsymbol{f_k}$** rather than 900 f_k is a more appropriate value for the **Modulus of Elasticity of Clay Brickwork, $\boldsymbol{E_b}$,** under conditions of passive restraint as it allows for the initial bedding-in of the brickwork at low levels of stress and strain.