Modern Philosophy of Structural Brickwork Design (and a Change of Outlook for the Brick Industry)

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SYNOPSIS

Forget the wall. A wall is a 'plate' section and a single unconnected plate is not an efficient structural section. The paper briefly outlines some methods of massively improving the strength of brickwork and thus making it a highly competitive structural material and not merely attractive, waterproof 'wall-paper'. The paper urges the industry to appreciate more fully the structural potential of its product - and to co-operate more with experienced practising engineers.

1.0 INTRODUCTION

To exploit the structural potential of any material it is essential to understand its strengths and weaknesses.

Brickwork is strong in compression, weak in tension and is brittle.

To use the material with structural efficiency and economy, engineers must exploit its strength and overcome its weakness.

The common structural form, up to the recent past, had been of massive heavy walls utilising brickwork's compressive strength. But a wall is basically only a plate section. A single unconnected plate is a very inefficient structural element and is rarely used in other structural materials.

When walls were subject to significant bending moments the stock answer was to thicken the wall, thus increasing its section modulus and decreasing the bending tensile stress. When walls were subject to significant compressive load again the stock answer was to thicken the wall, thus increasing its radius of gyration (and cross-sectional area) and the design compressive stress. The stock answer is:-

(a) structurally inefficient

(b) wasteful in material

(c) uneconomic - and prices brickwork out of the structural market.

The brick research 'industry' in the U.K. (and probably elsewhere), in general, has with an almost myopic concentration investigated the compressive strength of walls and recently (meekly accepting brickwork's role as mere cladding) looked at the cladding wall's resistance to wind pressure.

This lack of adequate engineering thought has resulted in such a savage decline in the structural use of brickwork that it is now relegated almost entirely to housing, cladding and other non-structural applications - a situation which the bulk of the industry appears to accept with an almost fatalistic equanimity. (In the last decade, or so, the use of concrete blocks has grown so rapidly that in Britain more walling is now built in concrete blockwork than in clay brickwork. So having practically lost the structural market the brick industry would now appear to be in danger of losing much of the non-structural market).

2.0 Change of Philosophy

Instead of merely thickening the wall it is more effective to devote fundamental thought to developing structural forms and techniques which would exploit brickwork's compressive strength and overcome its tensile weakness. (This has been done for many years with concrete which, too, is strong in compression but weak in tension - but to consider reinforced brickwork as an all-embracing panacea borders on the infantile).

Having accepted the fact that the brick wall, as a plate, is structurally inefficient then to make brickwork efficient it must be appreciated that it needs to be shaped, stiffened, prestressed, interconnected with other plates etc. Engineers rarely use thick plates in other structural materials - they use concrete Tee beams, steel I sections, plywood box-beams etc.

The fundamental thought to bring about this improvement in structural efficiency is simple and elementary - the results are dramatic. The change of philosophy makes brickwork:-

(a) highly economically competitive with other structural materials.

(b) rapidly increases its share of the building, structural and civil engineering market - and far less dependant on housing and cladding.

(c) a 'new' and exciting material - particularly for young ecology-conscious engineers.

3.0 Basic Structural Formulae

Going back to first principles and considering the basic structural formulae:-

(1) direct stress, $f_d = {}^{W}/A$

(2) bending stress, $fb = \pm M/Z$

(3) combined stress, $fc = {}^{W}/A \pm M/Z$

where W = load A = cross-sectional area
M = bending moment Z = section modulus

If A is kept constant then by altering the other factors it can be shown that brickwork can be made much stronger (for little increse in cost):-

(i) in the direct stress equation the design compressive stress is dependant on the slenderness ratio, $\frac{\text{effective height}}{\text{radius of gyration}}$

(The radius of gyration, r, $= \sqrt{\frac{I}{A}}$, where I = second moment of area).

The greater the slenderness ratio of the wall then the weaker it is in compression. It is obvious that a reduction in the slenderness ratio would be beneficial - but, to emphasise again, merely to thicken the wall to achieve this could be uneconomic. It is more efficient to increase the I value (and thus the r value) and/or decrease the effective height.

(ii) In the bending stress equation an increase in Z (without increasing A) and/or a decrease in M would reduce the bending tensile stress - and brickwork has low resistance to such stress.

(iii) in the combined equation the:-

(a) compressive stress $\frac{W}{A} + \frac{M}{Z}$, will be reduced by increasing Z and decreasing M - and the design compressive stress increased by increasing r.

(b) tension stress, $\frac{W}{A} - \frac{M}{Z}$, will also be reduced by increasing Z + decreasing M.

M can be reduced in a number of ways by competent engineers. For example simply by propping a free cantilever reduces the maximum bending moment by 75%, fixing a simply supported beam halves it etc.

Similarly the effective height can be reduced in a variety of applications. Using a stiffened base of a suspended ceiling to prop the wall leads to an impressive reduction in effective height. Since, too, the slenderness ratio of a wall depends on the lesser of its effective height or length then very tall walls of short effective length would have low slenderness ratios.

Summing up - without increasing the cross-sectional area of the brickwork but increasing Z, I, r and W and by decreasing M and the effective height, brickwork can be used more effectively, economically, exploit its strength and overcome its weakness.

All the above is both simple and obvious (and is comparable to using a heavy pile-driver to crack an egg) - yet would appear to have escaped the attention of many brick researchers, ignored by the engineers and unappreciated by the brick industry.

It is not possible in a short paper to show all the developments and alternatives to the defeatist (and uneconomic) 'solution' of thickening the plate wall.

A few of the simplest are shown for engineers to:-

(a) stimulate and interest them to create their own forms and designs,

(b) apply the developments in other structural materials to brickwork,

(c) devise new and improved construction techniques.

4.0 Applications of Change of Philosophy

4.1 Diaphragm Walls

The diaphragm wall (ref 1 and 2) is the most simple development by the author's, of the 'new philosophy'. It is basically a wide cavity wall with the two leaves bonded together by brick cross-ribs to form a series of connected box sections, see Fig.1

For a minimal increase in cross-sectional area, A, there is signifi-

cant increase in I, Z and r with a corresponding massive increase in both vertical and lateral loading.

4.2 Fin Walls

Another of the author's simpler developments to increase a wall's structural efficiency is to add deep, slender piers or 'fins'(ref.3). This converts the wall into a series of connected Tee sections, see Fig.2.

Again, as with the diaphragm, for a small increase in A there is a significant increase in I,Z and r, see Table 1

TABLE 1

Wall	Area, Am^2	Section modulus $Z \times 10^{-3}m^3$	2nd Moment of area $I \times 10^{-4}mm^2$	$\frac{Z}{A}$	r
260mm cavity	0.205	3.50	1.795	0.017	0.0296
Dia-phragm	0.245	52.49 26.39	177.16	0.214 0.086	0.269
Fin	0.307	48.67	171.57	0.158	0.236

		Proportional increase in:-			
Wall	A	Z	I	Z/A	r
Cavity	1	1	1	1	1
Dia-phragm	1.2	15	98.7	12.6	9.1
Fin	1.5	7.5 13.9	95.6	5.1 9.3	8

(Note. Values relate to the equivalent 1m length of each wall type,Z value of effective fin only is used. Fin centres assumed at 3m).

It will be seen from the table that:-

(i) for a mere 20% increase in area a diaphragm wall has a 1500% increase in bending resistance!

(ii) If the slenderness ratio is limited to 27 then the maximum height of a 260 mm cavity wall is about 4m - and at that height its load-bearing capacity is reduced by over a half. There is little problem in building a diaphragm wall three times that height with double the load-bearing capacity.

Economic single-storey structures, using these techniques, have been built 10m high with a 40m clear span!, and we can now go higher and wider.

4.3 Post-tensioned Brickwork

Even with an increased Z the tensile stress may still exceed the tensile strength of the brickwork. The engineer can either reinforce the brickwork to carry the tensile stresses or post-tension it to eliminate them. The authors' long practical experience has shown that prestressed brickwork has many obvious advantages over reinforced. Whilst they continue to reinforce concrete-block masonry, which is nearly always cost competitive with brickwork (and likely to erode further the brickwork market) they almost always prestress brickwork.

One of the early uses, by the authors' practice,wasfor low-height cavity walls (ref 4). The technique is simplicity itself. Vertical high-tensile steel rods are anchored in a concrete floor slab, brick cavity walls are built round them and capped. The rods are then tensioned by a torque spanner. With increased experience taller and taller walls and piers were constructed and found to be highly competitive with steel and concrete frames. There is a limit to the height of such post-tensioned walls and the magnitude of the post-tension compressive force because of the wall's relatively low radius of gyration.

4.4. Post-Tensioned Diaphragms, Fins and Box sections

Because of the increased radius of gyration and Z/A ratio of diaphragms and fins (see Table 1) they are obviously ideal sections for prestressing and no engineer would consider a solid rectangular section!).A number of projects have been successfully completed using relatively low levels of prestress. It was appreciated, of course, that high levels of prestress could be applied but unfortunately (for the brick industry) access to the necessary research facilities and funding were not available to the authors' until recently. (whilst much of the authors' development work has been achieved with some brickwork built by friendly contractors, loaded vertically with plastic dust-bins filled with water, laterally loaded by bulldozers and measurements taken with a couple of proving rings and a few dial gauges there is a limit to what can be achieved with such unsophisticated equipment). The recent work at UMIST by the first author and Dr.Phipps (ref 5) partly funded by the Brick Development Association, has more than confirmed the authors' expectations. As a direct result of this research a major post-tensioned diaphragm wall project is under construction, some are on the 'drawing board' and more are in the pipe-line. It is highly likely that post-tensioned masonry could replace reinforced concrete in many retaining structures (ref.6)

Recapitulating the combined (tensile) stress equation $f = \frac{W}{A} + \frac{M}{Z}$;-

whilst A and M have remained constant the increase in both W and Z will reduce or eliminate the tensile stress and will more fully exploit brickwork's conpressive strength.

For example the compressive strength of brickwork is often 20 times its tensile strength. Prestressing to half the compressive strength gives a ten-fold increase in resistance to bending Since M = fZ, then post-tensioning the diaphragm wall, see Table 1, can give a resistance of 10 x 15 = <u>150 times that of a cavity wall</u>! The example has been simplified, for the sake of brevity (and in practice there are complications, qualifications etc.) but does not distort the fact that enormous increases in strength are possible.

The research shows too that the brittleness of brickwork, subject to bending, is reduced. A normal wall, temporarily and slightly over-loaded will be permanently cracked and weakened but on removal of such load from a prestressed wall the crack would close up and the wall would be as good as 'new'.

4.5 Multi-Storey Structures

The application of the philosophy to multi-storey buildings is dealt with in more detail elsewhere (ref 7, 8 and 9) and is outlined only briefly here.

Interconnected plates (as in wine cartons, bee hives, cardboard packets etc). can form stiff, strong 'structures'. Similarly when brick walls are interconnected in the vertical plane and stiffened by floors and roofs, acting as 'plates' in the horizontal plane they too can form strong and economic structures. Many tall cellular blocks of flats have been built in a number of countries using this principle. The technique is common and obvious - and does not appear to have been developed. The technique transfers the wind forces from walls perpendicular to the force, by plate action of the floors and roof, to walls parallel to the wind force (known as shear walls) - and walls have a much higher resistance to in-plane lateral forces than perpendicular lateral forces. There is such an enormous increase in section modulus in the wall's longitudinal axis, compared to its lateral, that the bending tensile stress becomes insignificant. For example a 210mm shear wall only 5m long has a Z of over 20 times a panel wall so the design is then based on the wall's resistance to principal tensile stress and shear strength. The spacing of the shear walls is mainly limited by the economic span of the floor acting as a plate, and not by the brickwork properties of the shear walls(which could be of high-strength brickwork thickened, shaped, prestressed etc.

Too often structural designers determine a steel or concrete frame layout and then add walls to clad and sub-divide the structure. In a wide variety of structures if the necessary walls are carefully designed and positioned there is no need for a structural frame of columns and beams - with a consequent and patently obvious saving in construction cost and time. It is still a common fallacy to think that brick structures are only appropriate to residential buildings with a large number of small rooms. This fallacy probably grew out of the closely spaced walls in the early cellular blocks and cross-wall structures. But a quarter of a century ago the first author was constructing cross-wall structures with the walls at 7 to 8m centres. Such structures are ideal for hospital wards, school classroom blocks, some types of offices etc. The scope for the closely spaced cross-wall structures can also be increased by the use of 'podium' construction. This technique has been used where the ground floor planning requirements dictate large open spaces (eg reception areas for hotel's ground floor to a bedroom-block over or shops and offices on the ground floor of a student hall of residence). The conflict of structural form between the ground floor and the floors above can be resolved by the use of the podium, see Fig.3.

For more open-plan structures, such as some office blocks and other types of multi-storey buildings, requiring greater freedom of space the use of 'spine-wall' construction is appropriate, see Fig.4. Where even more open-plan is required say for departmental stores, warehouses and the like brick column structures can be used (and the cruciform section is obviously more efficient than 'square' sections. If, on the rare occasions, no internal restrictions at all are permitted then consideration should be given to multi-storey post-tensioned

fin wall construction.

4.6 Sub-Structures

The brick industry has, in many countries, practically ignored the civil engineering field. The philosophy and techniques outlined above are obviously applicable to such structures as settling tanks, water and earth retaining structures, shafts, bridge abutments, inspection chambers etc. etc. (And in a brief paper it is impossible to discuss arches, vaults, tubes etc).

5.0 Conclusions

It is hoped that in this very brief and simple outline, showing only a few developments, that it is possible to increase the bending resistance, load-bearing capacity and height of brickwork so economically that it can become an even more highly competitive structural material.

For too long has the engineer practically ignored brickwork. Mainly because the subject is not taught at most universities. The subject is not taught because there are few text books - there are few text books because the subject is not taught. This vicious circle is now being broken in a number of countries. To further compound the failure - most engineers are not aware of the economy and speed of construction of brick structures, and when engineers do discover these (and other) advantages there has been - until recently an almost complete lack of up-to-date design manuals for them to study. (look in an engineering department library at the row upon row of books on steel and concrete design - then try and find books on brickwork design).

For too long has the brick industry practically ignored engineers.

For example the number and seniority of experienced structural engineers in the brick research industry, in some countries, compares very unfavourably with that in concrete and steel research. Whilst there will always be a place and a continuing need for the physicist ceramicist, applied mathematician/engineer etc. for fundamental research the time has surely come for the introduction of more experienced,practising structural and civil engineers to carry out more applied research. (None of the examples of some of the authors' developments mentioned above owe anything to the brick research industry - apart from some guidance on design stresses and further developments are seriously delayed or halted due to lack of funds, resources and co-operation). If the brick industry continues to regard its product as a 'pretty wall-paper' that stops the rain coming in to and letting the heat out of a house then it will continue to decline in the structural field - to its own detriment and society's loss in the built environment.

Of course structural brickwork has its limitations. It is highly unlikely to replace steel for long span suspension bridges, prestressed concrete for heavily loaded wide-span suspended floor slabs etc. But its appropriate structural use has been under-valued, under-developed and under-researched.

The author's suggest that creative and adventurous engineers could do much to redress the balance, revive structural brickwork as a competitive structural material, ensure that not just the survival of the brick industry but its rapid growth and bring back to modern building a human face. And they would and could do it quicker with the fuller and more wholehearted cooperation of the brick industry - the investment would not be cheap but would be insignificant compared

to the return.

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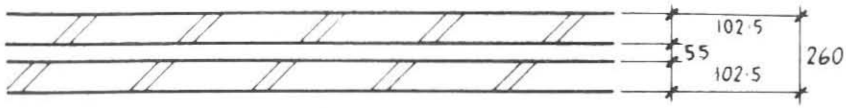

FIG. 1. 260 THICK CAVITY WALL.

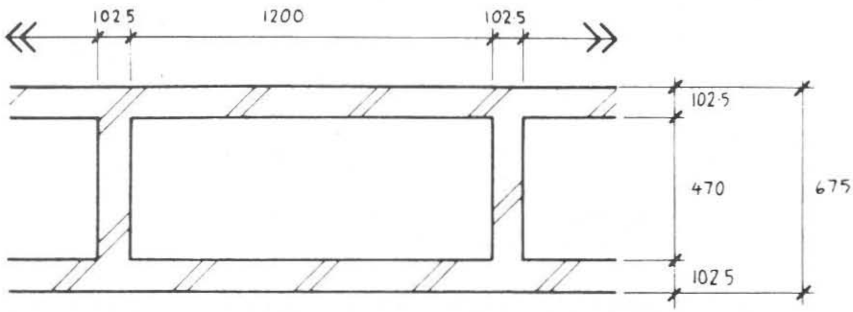

FIG. 2. 675 THICK DIAPHRAGM WALL.

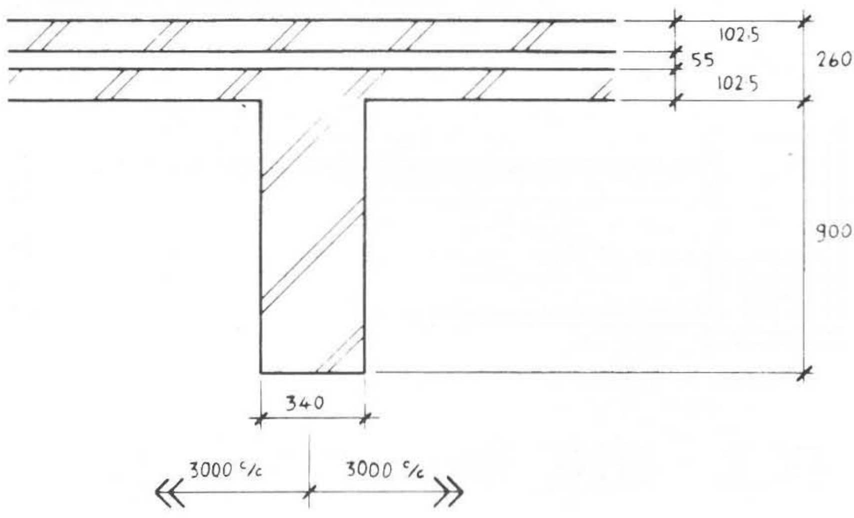

FIG. 3. FIN WALL.

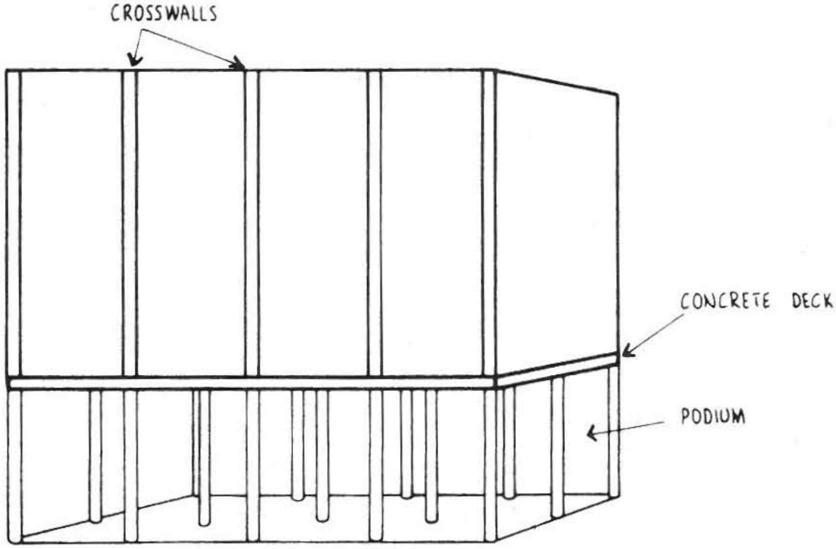

FIG. 4. PODIUM AND CROSSWALL CONSTRUCTION.

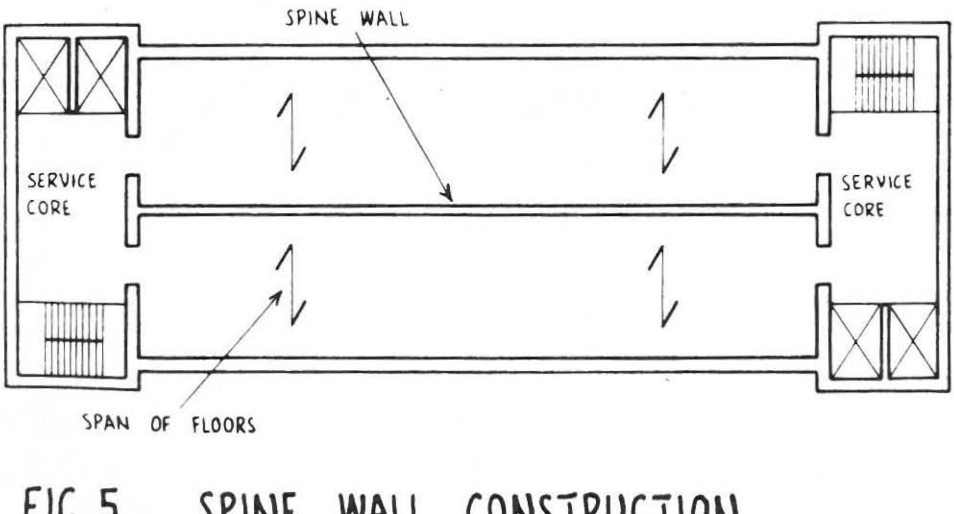

FIG. 5. SPINE WALL CONSTRUCTION.