Post-Tensioned Brickwork

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SYNOPSIS

Post-tensioned brickwork has been found to be highly cost-competitive and will greatly increase the applications of structural brickwork. The paper outlined the advantages and method of prestressing brickwork, its advantages over reinforced brickwork, the authors application of the technique and discusses briefly the theory, design and construction of post-tensioned brickwork.

1.0 INTRODUCTION

Since brickwork is strong in compression but relatively weak in tension (by a ratio of around 20 to 1) its structural application has tended to be confined to such compressive structural elements as compressively loaded walls and columns, arches etc. When, say, walls are subject to bending due to significant lateral loading (from retained earth or water, extreme wind loading etc) bending tensile stresses result. To resist the tensile stresses the walls require strengthening - just thickening - is uneconomic and prices brickwork out of the market. The alternative of changing the geometric section (i.e. box piers, diaphragm and fin walls, cruciform columns etc.) increases the section modulus, decreases the tensile stress and very considerably extends the structural application of brickwork. But the applications are still limited and the design still governed by brickwork's low tensile strength - and brickwork's high compressive strength is under-exploited and under-developed. Post-tensioning reverses this and makes brickwork highly cost-competitive.

Concrete, too, is strong in compression and weak in tension - so engineers reinforce it to carry the tensile stresses or prestress it to eliminate them. It is glaringly obvious that the same basic concepts can be applied to brickwork. The concept is not new - reinforced brickwork was used by Marc Brunel in the 1820's in England, by Sir Alexander Brebner at the turn of the century in India and it is not uncommon now in America. Victorian engineers repaired cracked structures by inserting steel rods through the structure, then heated and anchored the rods. As the rods cooled and contracted they 'post-tensioned'

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the structure.

Despite these precedents reinforced brickwork, and particularly prestressed brickwork has lagged far behind concrete. This is hardly surprising since relatively few engineers have appreciated even plain brickwork as a structural material, fewer are taught brickwork structural design and practically none have continuously developed prestressed brickwork. There is little design information particularly for prestressed brickwork, even less research carried out under the supervision of experienced engineers and almost no papers on practical experience with the techniques - for successful engineers are often too busy producing structures to produce papers!

2.0 REASONS FOR PRESTRESSING

The anology with concrete can be pushed too far - they are different materials and the appropriate technologies differ. Prestressed concrete is not nearly so common as reinforced. It calls for high-strength concrete, more sophisticated technology, needs greater level of skilled supervision, is more complex to design etc. The reverse is true in brickwork.

Concrete is relatively isotropic and homogenous, it shrinks with age, is subject to significant creep, under tensile strain minute hair cracks are closely and evenly distributed. But brickwork is not isotropic or homogenous, it can expand with age, the creep is relatively low and the tensile cracks are not so minute and they concentrate at the brick/mortar interface.

So prestressed concrete is more expensive and complex than reinforced but generally prestressed brickwork can be cheaper and simpler than reinforced. Concrete to be prestressed is often 3 - 4 times as strong as the grade of concrete to be reinforced. Most bricks have easily 3 - 4 times the strength of their equivalent in concrete block.

Efficient prestressing calls for structural sections with high Z/A ratios and radius of gyration e.g. Box and I sections, Tee beams etc. - and not solid rectangular sections. Such sections are expensive to shutter in concrete but are simple to form in brickwork.

It can be shown that a post-tensioned brick box-section has 60 times the bending resistance of a normal equivalent solid brick wall! This truly massive increase in strength results in the technique's cost-competitiveness.

3.0 POST-TENSIONING METHOD

The site technique is simple. To produce, say, a vertical prestressed cantilever to resist lateral loading high-tensile steel rods are anchored in the concrete base, a cavaity wall is built up around the rods and then capped. When the mortar has reached its design strength the rods are tensioned with a torque spanner and anchored at the top, and that, basically is that. The technique is so simple that small, country builders who would find reinforced concrete difficult and steelwork fabrication and erection impossible, have very successfully built post-tensioned brickwork. (They were deliberately not told that they were building post-tensioned brickwork since this would have made them apprehensive and caused them to raise their prices. Instead they were given helpful specifications and clear structural drawings).

Little practical use seems to have been found for pretensioning,(so far), with its attendant complexities of numerous tendons, curved ducts, complicated fabrication, curing time etc. (And in concrete the bulk of pretensioning has been used in factory made precast elements such as floor beams etc.).

The major application, by the authors', in brickwork has been in post-tensioning. Quite reasonable levels of prestress can be induced by the simple technique of torque and for higher levels of prestress a jacking system can be used.

4.0 ADVANTAGES OF PRESTRESSED BRICKWORK COMPARED TO REINFORCED

The case has been discussed elsewhere (ref.1) but it may be helpful to outline it here. Whilst the authors' made extensive use of reinforced brickwork in the 60's they have since the late 60's made more and more use of post-tensioned brickwork. It is well-known how difficult it is to obtain reliable cost-information, even with detailed cost-surveys, so there are no hard and fast rules. But in general post-tensioned brickwork is cheaper than either reinforced brickwork or blockwork - and reinforced blockwork tends to be cheaper and simpler than reinforced brickwork. (The authors' fail to understand the British brick industry's relatively large research investment into reinforced brickwork which will tend to aid its major competitor - the concrete block industry).

Primarily brickwork is a "walling" material and vertical prestressed walling is simpler to construct and supervise than reinforced. Reinforcement, to act structurally, must be bonded to the brickwork and this requires adequate compaction of good quality grout or mortar. The adequate compaction of grout, keeping grout lifts clear of mortar droppings, prevention of excessive hydrostatic head, prevention of grout leakage and trapped air pockets, maintenance of proper cover to the reinforcement etc. etc. is not simple.

Further, since brickwork is weak in tension (and its contribution not relied upon in design) all the brickwork below the neutral axis merely ensures composite action or provision of cover - so much of the brickwork's valuable compressive strength is wasted. (In hollow concrete blockwork the blocks act as permanent shutters and are relatively simple to grout up - and grout could be cheaper than brickwork). In prestressed brickwork all the brickwork is in compression so that brickworks' compressive strength is fully exploited.

Not only have the authors' found that it is generally cheaper, simpler and more structurally efficient to prestress brickwork, rather than to reinforce it, it is also likely that it will be more durable. Since normal brickwork can crack under bending tensile stress so too can reinforced brickwork. If significant cracks penetrate the grout the reinforcement can corrode. In prestressed brickwork the tensile stresses - and thus the tensile cracking - can be eliminated and this reduces the corrosion problem.

It is patently obvious - to any experienced engineer - that it is more structurally efficient to prestress brickwork than to reinforce it and, too, the applications are wider. The above may be hammering home the obvious to many experienced engineers but it has been done since established technology tends to persist in the face of new. (And some researchers prefer to clear and widen a trail blazed by others rather than open up a new avenue).

5.0 SOME APPLICATIONS BY THE AUTHORS

The first application by the authors was for a tall piered wall in 1968. The wall was subject to severe wind loading which would have caused unacceptably high bending tensile stresses so the piers were post-tensioned. (It is interesting to note that the fin wall concept, (ref 2), had not been derived by the authors at that time - if it had it is possible that it would have been used instead)

New ideas beget new problems which beget new needs for research. Following the normal procedure of the practice in developing a new technique, a number of simple site tests were carried out and when the techniques had been proven in practice and a sufficiently large contract received by the authors' practice to afford somewhat more sophisticated research this was done, (ref.3). The tests were designed not merely to confirm 'ideas' but, much more importantly, to extend the technique by extrapolation of the test results.

The post-tensioned cavity wall technique was applied to a wide variety of structures but there is a limit to the height and load-bearing capacity to which such cavity (or solid) walls can be built because of their relatively low Z/A ratio and radius of gyration.

In the early '70's it was appreciated, of course, that such sections as the diaphragm wall (ref. 4), fin wall (ref. 3) and several others with their structurally efficient sections would be ideal for prestressing. Since there was no access to adequate research resources or funds to carry out accurate and refined research into such sections - let alone prestressing them - progress was somewhat delayed. Nevertheless adequate site testing by the authors enabled them to build such walls up to a height of 10m. Through the Brick Development Association,basic research was started in the mid '70's into the structural behaviour of plain diaphragm walls (ref.5). The results were gratifying, extrapolated and extended by further site testing so that prestressed diaphragms, fins etc. were constructed. (It may be of interest to note that the authors' practice received an award for civil engineering innovation and in addition the first author was awarded a Royal Society Industrial Research Fellowship at the University of Manchester Instituteof Science and Technology to develop the work).

Typical of such applications was for a tall single-storey Sports Hall subject to severe differential settlement due to mining subsidence (ref.6). A diaphragm wall was prestressed to eliminate the in-plane tensile stresses resulting from the settlement. Another typical application was to strengthen an existing retaining wall by toothing in and bonding on post-tensioned fins. A not uncommon application could be when an industrial client needs to extend an existing steel-framed shed type structure. The existing gable wall can be strengthened and provision made for crane gantries and the like by the addition of post-tensioned fins. If the new gable wall has to be built so that at a later date the structure can be still further extended, then prestressed, or even reinforced, brick box-columns can be built. (Post-tensioned brick box and other column sections have obvious applications in industrial 'shed' structures). Cost surveys will almost certainly show savings in construction costs and time over the traditional, and unthinking, use of expensive structural steelwork.

Recent research, again mainly funded by the Brick Development Association, at UMIST (ref.7) on relatively high levels of prestress on a tall diaphragm wall show that there is a wide range of applications for the technique. Preliminary cost studies indicate that post-tensioned brickwork could replace reinforced concrete retaining walls. The authors hope to start work soon on a large retaining wall project for a public authority in cooperation with a government research organisation.

Further research work on investigating the collapse mechanism and behaviour of post-tensioned brickwork (ref.8) has stimulated the authors application of the technique to site prefabrication of prestressed box-beams and other sections. Research work on the problem of the vertical shear strength of brickwork, first noticed by the authors' (and discussed in ref.5) in diaphragm and fin wall design, is being undertaken at Dundee University with the cooperation of the authors' practice and the BDA. Whilst much work had been done on shear, racking etc. this particular problem had not been investigated - probably because it is of little importance to the engineer in normal wall design - and it does not lend itself to easy solution by simple site tests. Though the problem, for the same section, is eased by post-tensioning, further work will be necessary to provide firmer guidance on the more advanced of the authors applications and to extend them.

It is not possible in such a brief paper to outline all the applications (this has been sketchily done in ref.9 and it is proposed to do so in ref.10

but it may be of interest to note that the technique has wide application in tall single-storey structures, open-plan multi-storey buildings, civil engineering projects etc. The technique has obvious applications in pre-fabricated brickwork and its full potential has not yet been appreciated.

6.0 THEORY, DESIGN AND CONSTRUCTION

Basically the theory is the same as for prestressed concrete i.e. the application of compressive stress, P/A by prestressing to eliminate the tensile stress due to bending, M/Z. The well-known equation for combined stress, f is $\frac{P}{A} \pm \frac{M}{Z}$

where P = prestressing force, M = applied bending moment

A = cross-sectional area, Z = section modulus

The design procedure for light to medium levels of prestress is dealt with elsewhere (refs 11 and 12) and when further adequate funding for the authors' proposed future research is obtained and the work completed and applied the procedure for high levels of prestress will be published.

Nevertheless it may be of interest to outline the procedure here.

The more critical design case is $f = \frac{P}{A} - \frac{M}{Z}$. To eliminate the tensile stress, (or reduce it to 'safe' levels) it is necessary to increase P and or Z. For f to equal zero P/A must equal M/Z and there $P \times \left(\frac{Z}{A}\right) = M$. The need for a high Z/A ratio is immediately apparent.

The compressive stress $f = \frac{P}{A} + \frac{M}{Z}$ must not exceed the compressive strength of the section. The compressive strength depends not only on the brick-work's properties but also on the slenderness ratio of the section. The greater the radius of gyration, r, ($= \sqrt{\frac{I}{A}}$, where I = second moment of area), indirectly and not proportionally, the greater the compressive strength. To prevent buckling instability, or reduced compressive loading, of the compression flange at a lower stress than the brickwork's potential, then a high radius of gyration is advisable. For structural efficiency, economy of material and labour and weight-saving, it is apparent that a high r/A ratio is also advisable. This can be achieved for example with a Tee section, such as the fin, or an I or box-section, such as a diaphragm. Solid square or rectangular sections are rarely used in prestressed concrete and it needs little reflection on the part of a design engineer to note that

such sections are obviously not structurally efficient.

The structural efficiency of the prestressing force, P, can of course be greatly increased by applying it eccentrically to the centroid of the section, and it is of course necessary to check the ends of the section for principle stress, local bearing stress, shear lag etc. as it is in prestressed concrete. This is not so simple in brickwork since it is an isotropic.

The usual losses of prestress must be allowed for in design and construction. The loss due to elastic contraction can be calculated if the E value (Youngs Modulus) for the brickwork is known. But since from the authors experience the E value can vary between 500 - 1000 times the characteristic strength of the brickwork, brickwork of the same strength can have different E values and the height of the section, the method of loading, etc affect the E value, such calculations can be somewhat unreliable. It is simpler to compensate for the loss on-site by 'topping-up' the prestress. Losses due to creep in the brickwork can be crudely assumed to equal half that in concrete. Losses due to friction are non-existent or minimal in straight rods in straight voids and anchorage losses are low in post-tensioning systems - and again can be compensated for. The losses due to relaxation of the steel appear to be the same in brickwork as they are in concrete.

There can be gains in prestress due to moisture and thermal expansion of the brickwork but since these are likely to be low, variable and uncertain it is suggested that such gains should not be relied upon. The designer should however check that such gains do not over-stress the brickwork and the rods.

The stress distribution should be checked at initial stressing, under applied loading, after-losses, etc. and particular care must be exercised with asymetrical sections with eccentric prestress.

Some designers have apparently based the design stress on the direct compressive strength , f_k, of the brickwork but since the section is under bending action and the length of the 'strut' action of the compression flange is short and the brickwork 'restrained' then the authors would suggest that a design stress may be based on a value between 1.0 to $1.25f_k$ depending on the ratio of direct and bending stress (see ref. 11). (In any case the factors of safety in structural brickwork are extravagantly and unnecessarily high, in the authors opinion).

The construction techniques are again similar to those in concrete in that phased sequence of prestressing can be employed (and would probably be necessary in multi-storey construction). Rod curtailment would be practically the same as also would be rod extensioning. Protection of the rods from corrosion is naturally vital and this can be achieved by painting with bitumen, or similar, and wrapping in proprietary waterproof tape. Galvanising of the rods is not recommended as stress cracking of the film can occur. The rods can also, if thought necessary, be protected by grouting but care must be taken to ensure adequate and full continuous cover with the correct grade of grout. Consideration could be given to the use of stainless steel in conditions of severe exposure. Though such rods are about four times the cost of normal high-tensile steel rods the 'extra-over' cost per square metre of completed wall is not significant and the resulting structure is still likely to be highly cost competitive with reinforced concrete or structural steelwork.

7.0 RESEARCH NEEDS

It is not proposed to discuss these here since they are dealt with in detail elsewhere (ref. 13). However, it may be pertinent to point out that whilst much has been done in reinforced brickwork, certainly enough to give designers reasonable guidance, practically nothing has been done on prestressed brickwork. Much needs to be done on prestressed brickwork and it will almost certainly be more valuable to the brick industry than continuing work on reinforced brickwork. This is not to suggest that such work should cease, or to denigrate it, but to establish a sense of proportion and value of priority. As mentioned above the authors' practice has found a greater application of reinforced masonry to hollow concrete blockwork and prestressed masonry to clay brickwork.

8.0 CONCLUSIONS

We are dealing, in effect, with a 'new' structural material in prestressed brickwork which maskes highly efficient use of brickworks' major advantage of high compressive strength. The technique has been found by the authors experience on several hundred projects (of a wide variety of structures built by contractors of differing experience and size) to be very cost competitive, simple and fast to erect and durable under the severest weather conditions encountered in Britain.

Even with the present knowledge there is a vast scope for its application but the full potential has not yet been appreciated and much more practical experience combined with appropriate and cooperative research is necessary to achieve this.

Structural brickwork is still an under-developed, under- appreciated and under-researched material - post-tensioned brickwork is even more so. It is hoped that this too short paper will stimulate design engineers and researchers to exploit and explore together this valuable technique.

9.0 REFERENCES

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