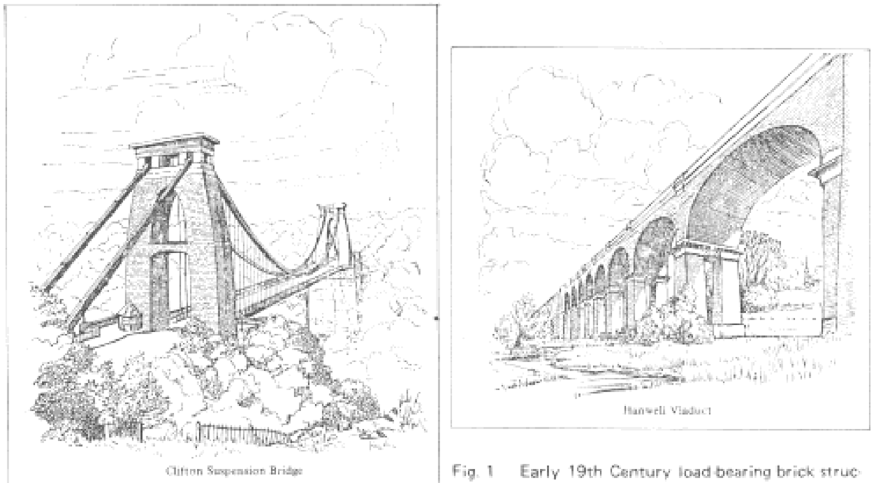
THE CASE FOR LOAD-BEARING BRICKWORK

Britain and Europe contain many examples of load-bearing brick structures built in the early and mid-nineteenth century that are still in daily use despite more than a century and a half of exposure to damp and aggressive industrial atmospheres. The brick arch bridges, viaducts, tunnel linings and retaining walls of the early railway system in Britain provide examples of the excellent durability of load-bearing brick structures under the most adverse service conditions. For example, Fig. 1 shows Hanwell railway viaduct, a brick arch structure built in the 1830's and still in daily use, and

The brick towers of Clifton suspension bridge, built in the 1830's and still carrying traffic today.


Clifton Suspension Bridge

Hanwell Viaduct

Fig. 1 Early 19th Century load bearing brick structures still in use today

Brickwork load-bearing structures have been replaced more and more in this century by structures of reinforced concrete and structural steel. Why, then, should we concern ourselves with calculated load-bearing brickwork as a construction material of the present and future? There are a number of answers to this question?

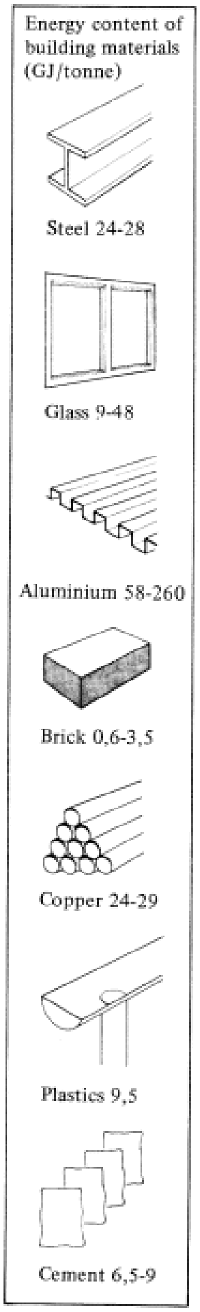
(i) In this era of rapid depletion of metallic ores and other mineral resources it should be noted that brick is made of cheap, abundant raw material that requires little in the way of beneficiation and purification before use. The raw clays used in brick manufacture are probably the most abundant and easily won of all those raw materials used to manufacture materials of construction.

(ii) With the current fuel crisis in mind and the certain knowledge that fuel will become even scarcer and more expensive in future, it is interesting to note that brick is a low energy material (Ref. 1). The production of brick consumes only 0,6 to 3,5 GJ per tonne whereas the production energy requirement of steel is 24 to 28 GJ per ton and that for cement is 6,5 to 9 GJ per ton (see Fig. 2).

The building of a brick structure, being labour-intensive, is also a low energy activity in terms of fossil fuel requirements. Finally, because of the good thermal insulating properties of brick (brick has a thermal conductivity of about 0,7 Wm-1 OC-1 as against 1,1 Wm-1 OC-1 for normal dense concrete (Ref. 2) a properly designed brick structure will exclude heat during hot weather and retain heat during cold, thus reducing energy requirements for cooling and heating.

(iii) Cost studies carried out in the United States of America (Ref. 3), Switzerland (Ref. 4), Australia (Ref. 5) and the United Kingdom (Ref. 6) have shown that for medium rise apartment buildings (10 to 18 storeys in height) a load-bearing brick structure may, depending on local conditions, be 10% to 15% cheaper than an equivalent reinforced concrete or steel framed structure.

In one case (Ref. 7) a multi-storey structure was designed as a reinforced concrete frame with brick infilling. A reappraisal of the design showed that structurally, the frame was unnecessary. It was omitted, the building was erected in load-bearing brickwork and the equivalent of R17 per sq. metre of floor area (1964 prices) was saved.


Energy content of building materials (GJ/tonne)

The many Victorian structures of 4 to 6 storey height standing in London, other European cities and the United States today, bear witness to the wide-spread use of load-bearing brickwork construction in the late nineteenth century. Most of the early American "skyscrapers" were built in load-bearing brick (Ref. 8). The constructional feats of this era culminated in the completion in Chicago of the Monadnock Building, a sixteen storey structure of load-bearing brickwork.

A plaque on the building describes it as "the final triumph of traditional masonry construction" and so it was. Load-bearing brick structures were, at that time, designed by traditional rule of thumb methods with no real knowledge of the potential strength of the material. As a result, the walls of the Monadnock Building were 2m thick at the base. This excessively massive construction could not compete with the highly efficient steel framed and, later, reinforced concrete framed structures coming into use at that time and load -bearing brick construction virtually became obsolete until the early 1950's.

Following research into the strength of structural brickwork carried out mainly in Britain and Switzerland, construction of structures in calculated load-bearing brickwork started in the early 1950's. Now the picture was very different. An early example of rationally designed loadbearing brick structures was a group of three 12 storey flat buildings erected in Basle, Switzerland between 1951 and 1953 (Ref. 4). The outer load-bearing walls are only 380mm thick while internal loadbearing walls are 180mm thick for the first two floors, reducing to 150mm for higher floors. In 1957 an 18 storey block of flats was completed in Zurich (Ref. 7) in which the outer load-bearing walls were again only 380mm thick a far cry from the 2m thick walls of the Monadnock building.

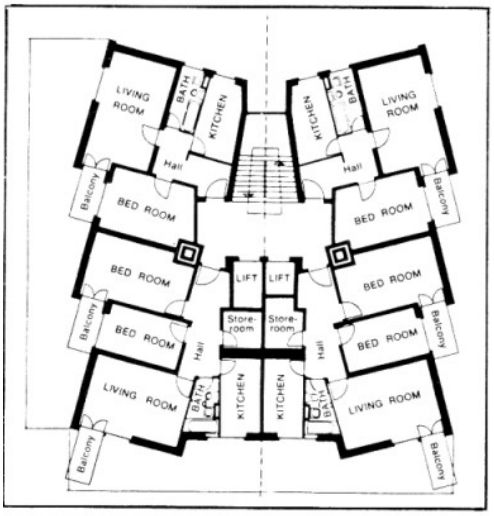


Fig. 3 Typical floor layout of 18 storey block of Flats completed in Zurich in 1957, in which the outer load-bearing walls were only 380mm thick.

A typical floor layout of the Zurich flats is shown in Fig. 3. In 1948, the British Standard Code of Practice CP I I I (1948) "Structural Recommendations for Load-bearing Walls"* was issued. Based on research carried out in Britain, this code of practice opened up possibilities that were tantamount to the birth of a new structural material and since that time very many load-bearing brick structures of 10 to 15 storey height have been successfully and economically completed (e.g. Refs. 10 & 11I).

To show how load-bearing brick construction has advanced in the United States of America the following example is of interest.

In 1969 a comparative study was made (Ref. 12) of seven different possible structural systems for a 15 storey elderly housing block. Possibilities included: a steel skeleton combined with various floor systems, a reinforced concrete skeleton with various forms of infilling and loadbearing brick construction.

All systems were highly competitive, but the load-bearing brick solution was chosen because of:
(a) built in fire resistance;
(b) built in sound insulation; and
(c) low maintenance.*

Exterior load-bearing walls are 300mm thick for the basement and first two floors after which they reduce to 200mm thick. Internal bearing walls are 200mm thick throughout. A typical structural floor plan of this building is shown in Fig. 4.

It may appear strange that in the highly industrialized United States, a labour-intensive construction method like load-bearing brickwork should prove competitive. The situation is summed up by the following quotation (Ref. 3), "Speed of construction and low initial cost are two more assets of this structural system. These items may seem incongruous with the use of a relatively small brick prism placed by hand. But this one unit does many things. It provides structure, separation or enclosure, finish, fire resistance, sound resistance and flexibility in design dimensions and form. At the same time construction variations are easily accommodated by the mason."

TYPICAL FLOOR—STRUCTURAL PLAN

Fig. 4 Typical floor structural plan of the 15 storey Episcopal House of Reading, completed in Reading, Pennsylvania in 1971. It is the tallest unreinforced load-bearing brick structure in the United States.

So far, only a few buildings have been erected in South Africa using load-bearing brick construction. As far as can be ascertained, load-bearing brickwork was chosen in each case because it was believed to offer economic advantages over other forms of construction. In one example, an eight storey apartment building recently erected in Durban, (Ref. 13), the use of load-bearing brick work was estimated to give a saving of 7 per cent over reinforced concrete framed construction.

In another case (Ref. 14), an hotel building in Rustenburg, the ground and first floors were built in reinforced concrete and contain the public areas, lounges, dining rooms, etc. The upper floors, containing the bedrooms, have repetitive floor plans and were constructed in load-bearing brick work. Figure 5 shows the floor plan of this building. All walls were load-bearing, the outer walls being of 280mm cavity construction, while inner walls are 114mm thick. Note the use of vertical internal service ducts which not only convey services but act as load-bearing elements.

To sum up the case for the use of load-bearing brickwork, this form of construction has been found in Europe and America to offer distinct advantages over other forms of construction for medium rise (up to 20 storey height) apartment type buildings. In the few cases where load-bearing brickwork has been used in South Africa it has been chosen because of the economies offered by the method.

Considering the way in which patterns of labour usage will probably change in South Africa in the future, as well as all the other factors in favour of brickwork, it is likely that this method of construction will become increasingly attractive in the years ahead.

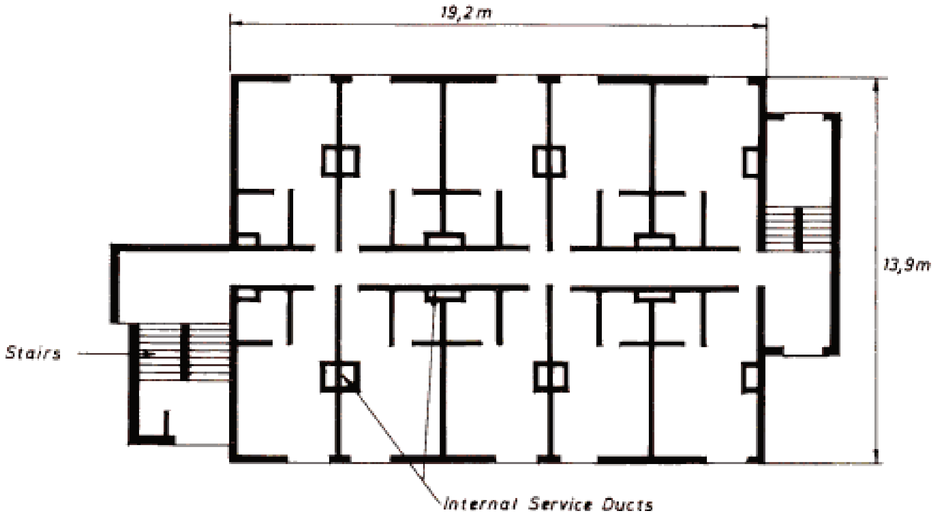


Fig. 5 Typical floor plan of hotel at Rustenburg.

GENERAL REQUIREMENTS OF A LOAD-BEARING BRICK STRUCTURE

(i) MATERIAL REQUIREMENTS

In a well-designed load-bearing structure, the brickwork should be stressed to its safe upper limit. It follows that the designer must be aware of the properties of the material he is de signing in and also of the safe stresses to which he can work at the design stage. Also, during construction, continuous checks of the quality and strength of the brickwork must be made to ensure that design requirements are being met. The strength of brickwork depends on the strength of both bricks and mortar and permissible stresses are established by means of strength tests on prisms and cubes of brickwork made with the proposed materials and under conditions as close as possible to those expected on site. In addition, brickwork is subject to movement, both as a result of loading and resulting from environmental effects. The designer must know of the existence and probable magnitude of likely movements.

(ii) STRUCTURAL REQUIREMENTS (Refs. 7 & 15)

Load-bearing brick structures are basically gravity stable. That is to say, they resist overturning forces by virtue of their self-weight. This is a consequence of the fact that unreinforced brick work, like unreinforced concrete, is strong in compression, but relatively weak in tension. The following structural requirements must be met:

(a) Differential settlement must be avoided. When soil conditions are difficult, piled or raft foundations should be used to limit differential movement. Alternatively, or in addition, movement joints should be incorporated into the structure so that differential movement can be accommodated without causing structural damage. Moisture, thermal and creep movements of the brickwork must also be designed for and accommodated.

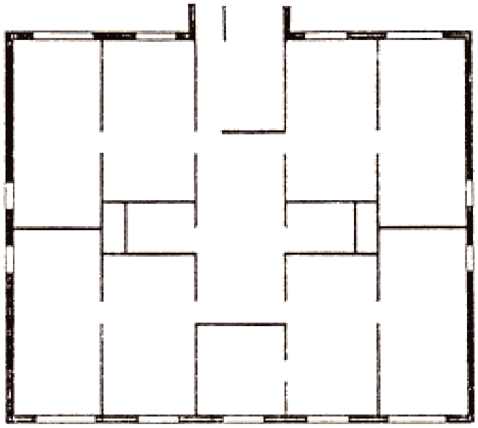


Fig. 6a Example of cellular structure

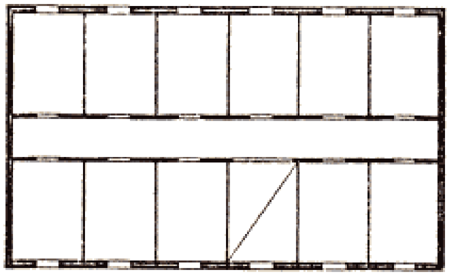


Fig. 6b Example of crosswall construction

(b) To avoid eccentric loading, the plan formation should, ideally, repeat itself on each floor level. This does not preclude the use of reinforced concrete construction at ground or ground and first floor levels to provide spacious column free foyers, assembly areas, etc.

(c) The walls and wall intersections should be arranged to provide shear resistance to horizontal loading due to wind, etc. This can be done either by means of cellular construction or cross-wall construction. (Figs. 6a & 6b).

(d) The arrangement of windows is important and "hole in wall" fenestration gives greater rigidity to the building than "strips" of windows separated by vertical brick panels.

(e) Ducts for services should be designed and built in. Haphazard chasing of walls to install plumbing, electrical conduits, etc. cannot be allowed to weaken the structure.

(f) Appropriate measures must be taken to prevent rain penetration through exterior walls. Materials and structural requirements will now be considered in greater detail. Test methods are well described in Refs. 16 and 17 and the reader is referred to these for further details.

PROPERTIES OF BRICKS

(i) THE STRENGTH, ELASTICITY AND FAILURE STRAIN OF BRICKS

Brickmaking clays consist mainly of the minerals kaolinite, quartz (i.e. crystalline silica) and muscovite mica (Ref. 18). During firing the kaolinite breaks down to form (at about 980˚C) free silica and y-alumina and then (at about 1100˚C) the y-alumina breaks down to form mullite and more free silica. Once the temperature rises above 12000C the free silica forms crystals of cristobalite.

Simultaneously, starting at 800oC, the mica breaks down progressively to form a glass together with crystals of mullite. Hence the fired clay consists of a matrix of three crystalline components, quartz, cristobalite and mullite, bonded together with glass. The strength of the product depends to a large extent on interlock and inter growth of crystals and on the quantity of glass bonding material produced.

It follows that the strength of a brick depends mainly on the firing temperature and on the composition of the raw clay.

Firing temperatures for building bricks range from 950˚C to 1250˚C while compressive strengths can range up to 120 MPa. Fig. 7a shows typical relationships between the compressive strength and firing temperature for bricks made of two different clays (Ref. 19). The elastic modulus of brick may increase to a marked degree with firing temperatures as shown in Fig. 7b while Fig. 7c shows the relationship between compressive strength and elastic modulus. It will be noted that up to a compressive strength of 80 MPa, elastic modulus is directly proportional to strength. This fact has two consequences:

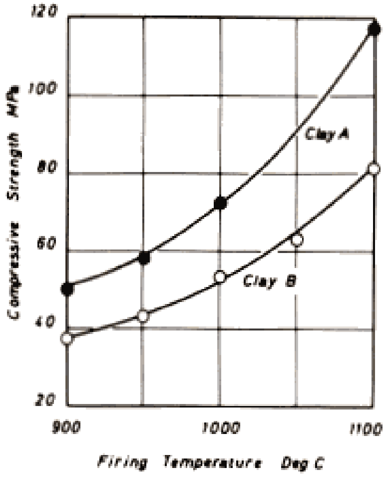


Fig. 7a Ref. 19

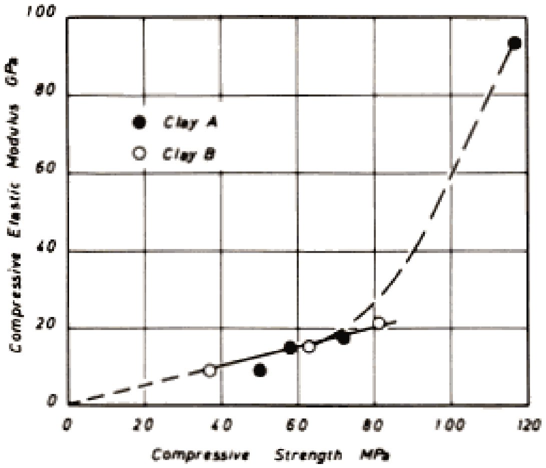


Fig. 7c Ref. 19

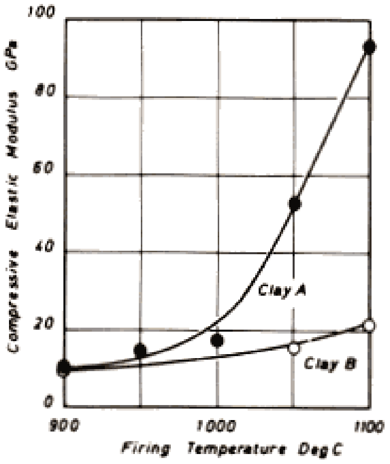


Fig. 7b Ref. 19

(a) Regardless of strength, the failure strain of bricks in compression is always about 4.10-3. Similar behaviour is evident in tension although the tensile breaking strain is probably only about 0,2.10-3. The figure of 0,2.10-3 represents the upper limit to the failure strain of concrete and is probably of the same order as the actual tensile failure strain for brick. Bricks therefore fail when a limiting strain is reached, regardless of the stress required to produce the limiting strain.

(b) Restraining a given amount of movement in a structure built of strong bricks will require a greater restraint stress or load than in a structure built of weaker bricks.

(ii) THERMAL AND MOISTURE EXPANSION OF BRICKS

Two environmental effects have a particular influence on bricks. These are thermal and moisture movements. The coefficient of thermal expansion of brick may vary considerably with direction in the brick, depending on how the raw clay was shaped.

Average values of the co efficient of thermal expansion lie within the range 3,6 to 7,2.10-6 per deg. C (Refs. 19 and 20). After firing, all bricks expand to a greater or lesser degree as they take up moisture from the atmosphere. The expansion continues to occur for many years at an exponentially decreasing rate. For example, bricks from the Western Cape Province exposed to the natural atmosphere for five years were found to be continuing to expand at the end of this period (Ref. 21).

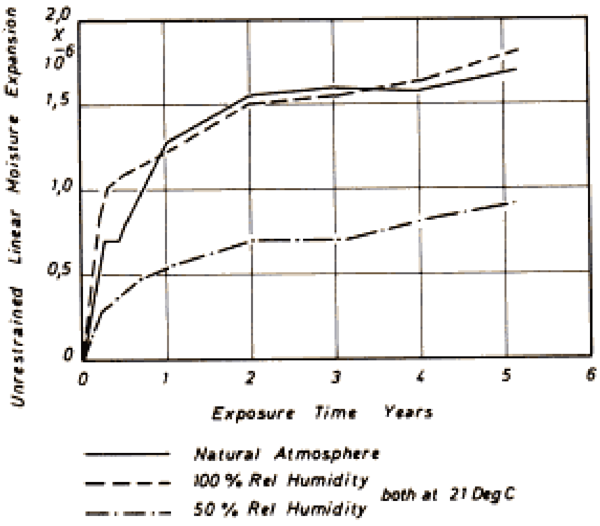


Fig. 8a Ref. 21

A typical time-expansion curve for a severely expansive brick exposed to the atmosphere is given in Fig. 8a which also illustrates the effect on the time-expansion curve of differing availability of water, i.e. differing atmospheric humidity.

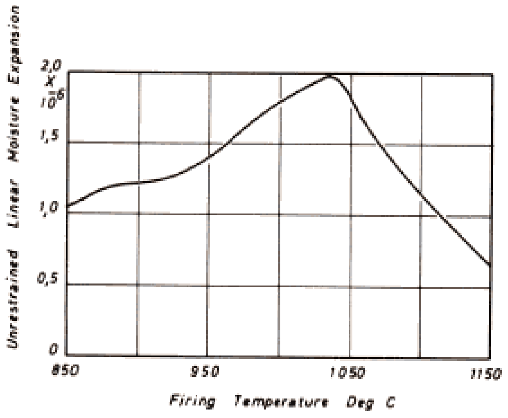


Fig. 8b Ref. 22

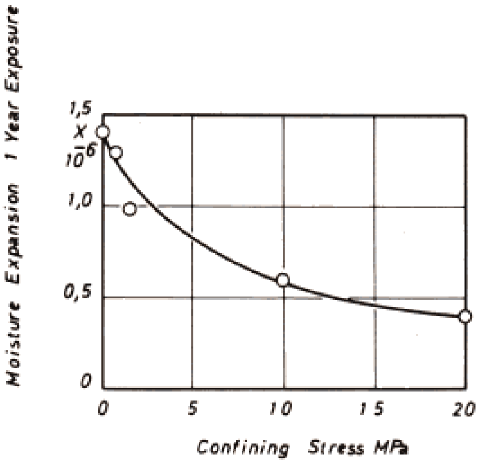


Fig. 8c Ref. 22

Fig. 8b shows that the amount of expansion is related to the firing temperature. The potential expansiveness appears to reach a peak at a range of firing temperatures depending on the composition of the raw clay (Refs. 19 and 22).

Peak expansiveness appears possible at any firing temperature between 900 and 1100 deg. C, while the magnitude of the peak expansion may vary from 0,2.10-3 to 2.10-3 or more (Refs. 16 and 23).

The moisture expansion of brick can be restrained mechanically (Ref. 22). However, the stresses required to achieve this are large more than 20 MPa in some cases (see Fig. 8c) and it is more practical to make allowance for the movement by means of movement joints incorporated into the structure than to attempt to restrain the movement. The expansive constituent of the brick is thought to be the glass bonding matrix (Ref. 18).

As the firing temperature increases, the quantity of expansive glass increases and so does the potential expansion. However, the specific surface area of the glass decreases continuously as the firing temperature rises. This reduces the potential expansion at higher firing temperatures. It is obvious from the rapid expansion of bricks at small times show in Fig. 8a that freshly fired bricks should not be used and that pre-wetting of bricks before use would be beneficial in reducing residual expansion.

When designing a brick structure, it must be remembered that moisture expansion takes place in all three principal directions. Expansion in the width of a wall does not generally matter, but allowance must be made for expansion in both length and height. The potential expansiveness of a particular type of brick can be assessed by subjecting it to an accelerated test procedure in which the brick is steamed or boiled (Ref. 22). However, latest duration of about three weeks is required to produce most of the expansion even under these accelerative conditions.

(iii) DURABILITY OF BRICK

The main environmental effects that may cause damage to bricks are frost action and efflorescence of soluble salts. Efflorescence is the visible effect of crystallization at the surface of the brick of soluble salts migrating under an evaporation gradient. Most clay bricks contain a small percentage of soluble salts, the more common being calcium, magnesium and sodium sulphates. These salts may have been present in the raw clay or may have formed during firing by the oxidation of pyrite present in the clay, or by reaction of sulphur in the coal used for firing with calcium or magnesium carbonates in the clay. Alternatively, salt contamination may arise by capillary action from groundwater or from substances stacked against a wall. For example, in the Witwatersrand area, salt contamination can occur if bricks come into contact with mine dump sand which may contain up to three or four per- cent of soluble salts. Efflorescence from this source is very commonly seen on brick paving bedded in mine sand.

Another possible source of soluble salts is the use of high magnesium lime in mortar. This may provide magnesium to react with sulphur trioxide in the air forming magnesium sulphate.

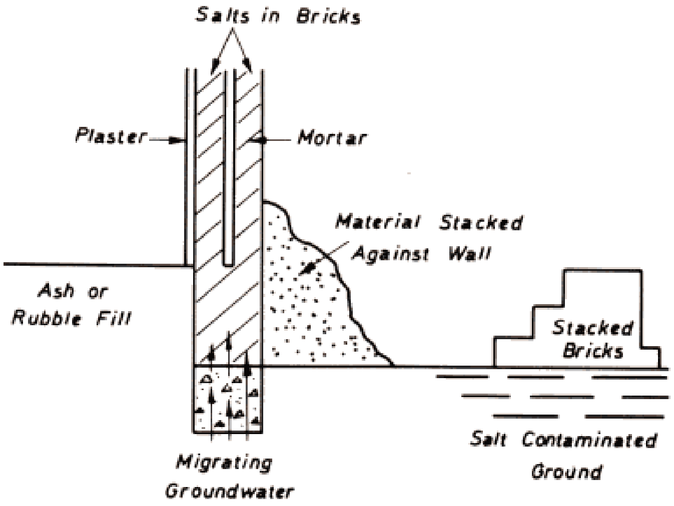


Fig. 9 Ref. 20

The results of efflorescence may simply be harmless unsightly staining. Alternatively, efflorescence may actually cause spalling of the surface of the brick. Highly soluble salts and especially magnesium sulphate, are more disruptive than less soluble salts such as calcium sulphate. Fig. 9 summarises the possible sources of soluble salts that may cause efflorescence (Ref. 20).

PROPERTIES OF MORTARS (REFS. 15 & 16)

(i) WET MORTAR

An ideal mortar should possess adequate workability when wet, i.e. it must flow easily when spread and wet the surface of the bricks. It should cling to vertical surfaces, yet resist deformation once a brick has been bedded into it. The water retention of wet mortars is important. Mortars with a low water retention lose water easily when they come in contact with an absorptive brick and hence lose workability, making laying difficult. Moisture retention can be improved by attention to the grading of the mortar aggregate or by adding finely ground plasticizers such as limestone, clay or lime.

(ii) HARDENED MORTAR

The initial stiffening of a mortar immediately after laying a brick in it is caused by capillary absorption of the water from the mortar by the brick. Hardening subsequently takes place by hydration of the cement and, very slowly, by carbonation of the lime content of the mortar. It is preferable that the strength of a mortar be less than that of the bricks laid in it. This is to ensure that any cracking that occurs because of movement will occur in the mortar joints (where it is relatively easy to repair) rather than in the bricks. Lime-rich mortars have the virtue of gaining strength more slowly than cement-rich mortars and hence have a greater capacity for accommodating construction and post-construction movements.

They also have a greater capacity for autogeneous healing than that of cement rich mortars. The compressive strength of a mortar as measured by cube tests may be used as an index of quality, but is not of great practical importance.

Mortar is used in thin layers sandwiched between rough brick surfaces and the triaxial constraint imposed by the bricks gives an in situ mortar layer a compressive strength that is invariably many times greater than the minimum required. Of more importance is the tensile bond strength between mortar and brick as this influences the shear, bending and compressive strength of brickwork as well as its permeability to rain penetration. Two important factors that affect bond strength are:

(a) the "suction" of the bricks or their capacity for absorbing water; and
(b) the water retention of the mortar.

Bricks with a high suction laid in mortar having a low water retention may absorb water from the mortar to such an extent that bond strength is impaired. Wetting of bricks with a low suction, however, also impairs bond strength by increasing the water-cement ratio of the mortar at the brick-mortar interface.

(iii) DURABILITY OF MORTAR

Mortar may be subject to attack by efflorescence of soluble salts in the same way as brick.

In addition to this, Portland cement mortar is susceptible to sulphate attack caused by sulphur pollution of the air or by sulphates in solution. Generally, stronger less pervious mortars are more resistant to chemical attack. However, if the possibility of sulphate attack is known to exist, it may be advisable to use sulphate resisting cement. The mortar in brick masonry is generally relied on to protect metal ties and reinforcement from corrosion. This it does by means of the highly alkaline environment it provides. How- ever, the hardening of lime by carbonation gradually reduces the alkalinity of a lime mortar thus lessening the corrosion protection. This should be borne in mind if brickwork is to be exposed to particularly corrosive conditions.

PROPERTIES OF BRICKWORK

(i) THE STRENGTH OF BRICKWORK IN COMPRESSION

Brick masonry, being a composite material of brick and mortar, has properties that are related to those of its constituent materials, but not directly so. The following are the main factors affecting the strength of brick masonry:

(a) The strength of the bricks

Other things being equal, the strength of brickwork is approximately proportional to the square root of the strength of the bricks. Available experimental relationships between brickwork cube strength and brick strength are shown in Fig. 10a (Refs. 15 and 24). It will be seen from this figure that the strength of brickwork cubes appears to have an upper limit of about 40 MPa, regardless of brick strength. The diagram also gives an indication of the effect of mortar strength on the strength of brickwork. The strength of a brick wall compressed axially is approximately 0,7 of that of a brickwork cube.

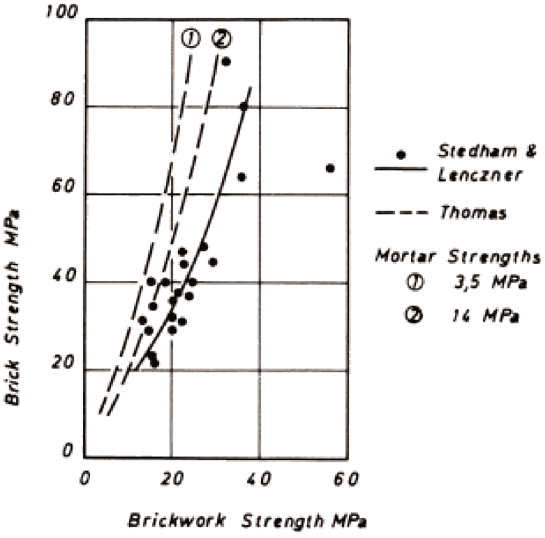


Fig. 10a Refs. 15 & 24

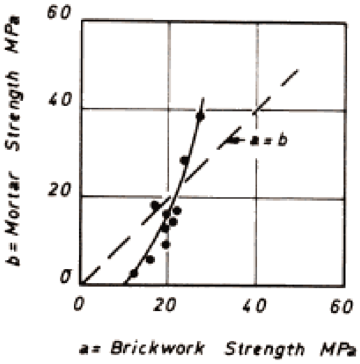


Fig. 10b Ref. 15

(b) The strength of the mortar

With a constant brick strength, the strength of brickwork is approximately proportional to the fourth root of the mortar strength. Fig. 10b shows an experimental relationship between these two variables. It should be noted that with mortars having a strength of less than about 20 MPa, the brickwork strength exceeds the mortar strength. This is surprising until it is remembered that the mortar strength is measured by means of cube tests, whereas the mortar within the joints of a brickwork cube is subjected to triaxial compression and can therefore sustain a higher stress without failing. The strength of the bricks used in compiling Fig. 10b is, unfortunately, not known (Ref. 15).

(c) Other Factors

The time of curing, the thickness of the mortar joints, the water suction of the bricks and workmanship all influence the strength of brickwork.

Approximately 80 per cent of the long term strength of brickwork is reached within 7 days, 95 per cent within 14 days and virtually 100 per cent within 28 days. Reducing the thickness of mortar joints causes the strength to increase and vice versa. In one series of tests, a decrease in joint thickness from 16mm to 3mm resulted in an increase of strength from 15 to 23 MPa. (Refs. 15 and 26). It is therefore important to keep joints, horizontal joints in particular, as thin as possible.

As mentioned earlier, the water suction of bricks, by affecting the strength of the mortar and the mortar-brick bond can influence the compressive strength of brickwork.

The difference between good and bad workmanship may make a difference of 25 to 35 per cent in the strength of brickwork (Ref. 17).Cavity walls have been found to have a strength of about 70 per cent of the strength of individual leaves built and tested singly. This is thought to be due to the fact that it is more difficult to achieve the same standard of workmanship with a cavity wall than with a single 115mm leaf. Also, the strength of a cavity wall is governed by that of the weaker leaf, e.g. premature buckling of one leaf built out of plumb can cause the whole wall to fail prematurely.

(d) Brickwork bond

A series of tests on walls built of 1/6th scale bricks laid in a variety of different bonds (Ref. 27) has shown that there is no significant difference in strength between walls built in different bonds.

(ii) THE MECHANISM OF BRICKWORK FAILURE IN AXIAL COMPRESSION

Brickwork tested in compression normally fails by vertical tensile splitting. This type of failure is quite common in brittle materials subjected to uniaxial compression and can be simply explained as follows:- Ct For both bricks and mortar, Poisson's ratio v is about 0,1S. Assuming that the Young's modulus of brick is the same in compression and tension,. it follows that where [std deviation t] and [std deviation c] are, respectively, the tensile and compressive stresses in the brick.

Because the tensile strengths of both brick and mortar are only about 0,1 of the corresponding compressive strengths, the tensile strength will be reached before the compressive strength and vertical splitting will occur. If the compressive strain in the brickwork is the sum of C then the induced horizontal strain is

(iii) STRENGTH OF BRICKWORK IN TENSION

The most convenient way of measuring the tensile strength of brickwork is by means of the indirect tension or cylinder splitting test on a disc of brickwork (Ref. 15). Typical results of this type of test are shown in Fig. 11, which clearly indicates the influence of joint orientation on tensile strength. It appears from the diagram that tensile bond failure (e=900) occurs at about one half of the tensile strength of the bricks (e=00).

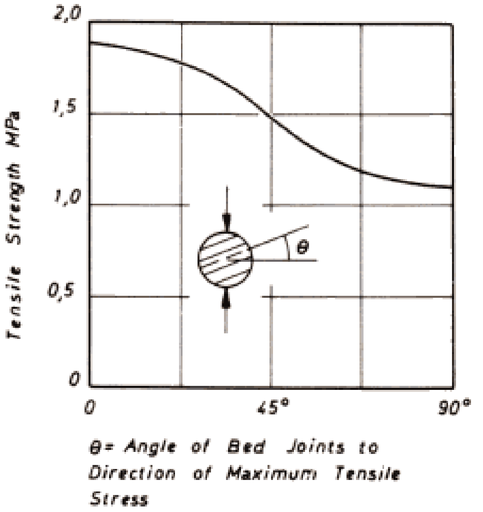


Fig. 11 Ref. 15

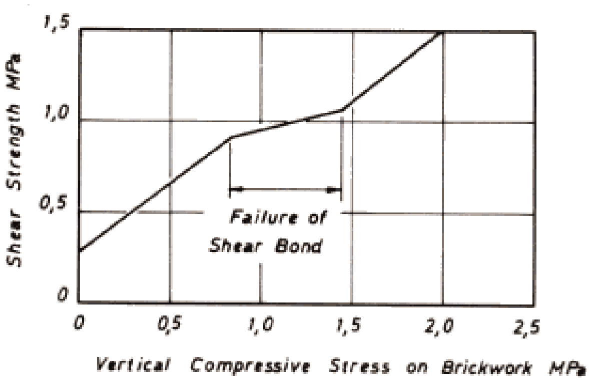


Fig. 12 Ref. 7

(iv) STRENGTH OF BRICKWORK UNDER SHEAR OR RACKING LOADS

The racking resistance of brickwork increases as:

(a) the shear bond between brick and mortar increases; and
(b) the vertical compression increases.

Perforated bricks provide a mechanical shear bond between adjacent courses, and the shear strength of the mortar is the limiting factor in shear bond development. Shear bond increases linearly with normal load up to a limit dictated by the strength of the mortar.

Under high vertical compressions, failure may occur by diagonal tension through the bricks. Fig. 12 shows an experimental relationship between vertical compressive stress and the shear strength of brickwork (Ref. 7).

(v) MOVEMENT OF BRICKWORK

As with most other non-metallic structural materials, brickwork strains under load, the strain being both stress and time dependent. Strains also occur due to changes in temperature and absorbed moisture.

The two components of load-dependent strain are the elastic and the creep strains. Little appears to be known of the elastic properties of brickwork. It is known, however, that the stress-strain relationship for brickwork is non-linear and that the Young's modulus increases with increasing strength. The strength and hence Young's modulus of the mortar has a significant effect on the Young's modulus of the brickwork. The major portion of the creep strain takes place within about 4 months.

The magnitude of the creep strain may vary from 20 to 40 per cent of the elastic strain for brickwork laid with strong mortar to 50 to 80 per cent for weaker mortars. Typical relationships between elastic and creep strains and applied stress for different mortars are shown in Fig. 13. (Mortar proportions are cement : lime : sand by mass).The coefficient of thermal expansion of brickwork is about 6.10-6 (0Q-1 in a horizontal direction, but may be up to 1,5 times this value in a vertical direction. Vertical expansion at any point is restrained only by the weight of superincumbent brickwork, but horizontal expansion is generally at least partially restrained and thermal stresses will develop.

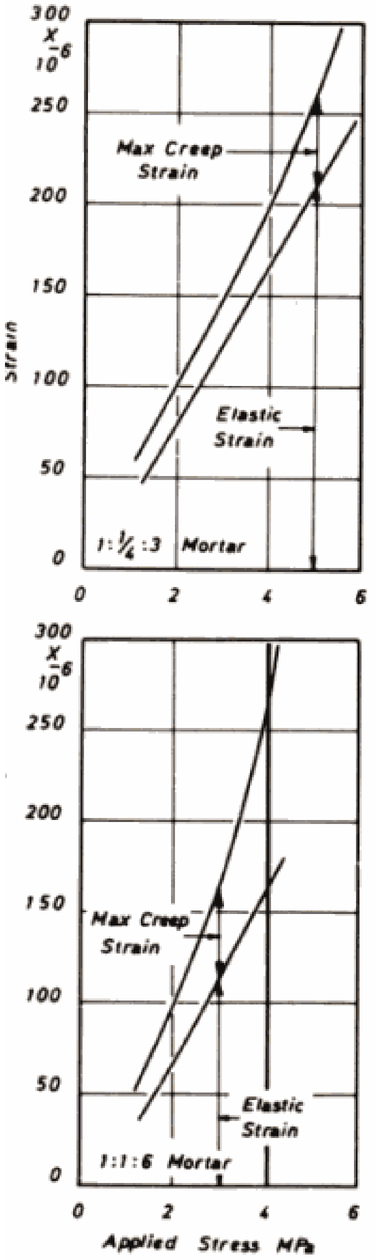
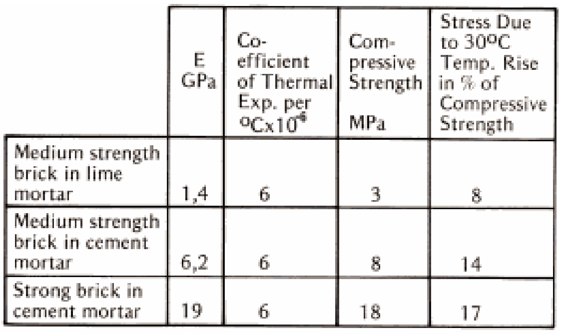


Fig. 13 Ref. 15

An idea of possible magnitudes of thermal stress is given in the following table (Ref. 20) in which complete restraint of thermal movement and no stress relaxation are assumed.

It is clear from the table that compressive failure of brick- work is unlikely to be caused by a temperature rise. As the tensile strength of brickwork is only about one tenth of the compressive strength, however, tensile cracking caused by a fall in temperature is quite possible. Also, differential thermal movement between the inner and outer leaves of a cavity wall may cause both horizontal and vertical bending in the wall and tensile cracking of the cool leaf. Structural damage caused by moisture expansion of brickwork is fairly common and several examples are cited in Ket. 23.



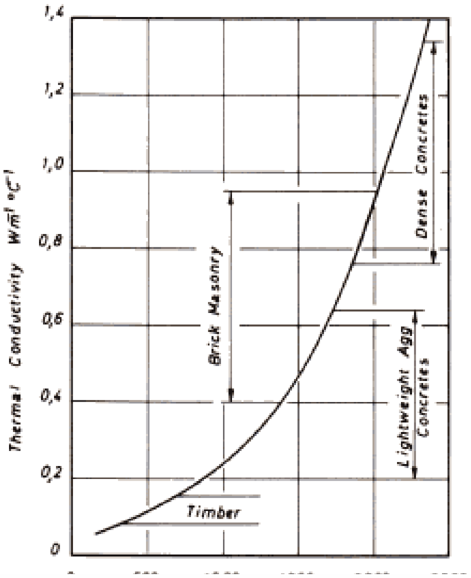
	E GPa	Co-efficient of Thermal Exp. per ^{o}Cx10^{-6}	Compressive Strength MPa	Stress Due to 30^{o}C Temp. Rise in % of Compressive Strength
Medium strength brick in lime mortar	1,4	6	3	8
Medium strength brick in cement mortar	6,2	6	8	14
Strong brick in cement mortar	19	6	18	17

In one case a 225mm x 300mm reinforced concrete column was sheared off at its base because of the expansion of a long face brick wall abutting it. In another the fairly strong bricks in a brick retaining wall were crushed by expansive forces. Where bricks are not expansive, cracking may occur due to shrinkage of the mortar.

Horizontal shrinkage also caused minor vertical cracks. An investigation of stresses in load-bearing brickwork (Ref. 28) has indicated that shrinkage stresses in brickwork may be of the same order of magnitude as stresses arising from superimposed loading. Damage of this sort can be controlled by the provision of movement joints. Minimum requirements for movement joints are dealt with in the codes of practice (e.g. Ref. 9). The minimum spacing and width of such joints should be calculated in accordance with individual conditions. Ref. 29 gives details of typical movement joint designs.

(vi) THERMAL AND SOUND INSULATION OF BRICKWORK

It was pointed out earlier that two of the virtues of brick masonry are their relatively high thermal and sound insulating properties. The thermal insulating properties of materials are related to their density as shown schematically in Fig. 14 (Refs. 2 and 30). That of brick masonry is intermediate between the conductivities of dense concretes and lightweight aggregate concretes.



Thermal conductivity depends on the moisture content of the material and increases with increasing moisture content. Under British conditions (Ref. 2) it has been suggested that the conductivity of the outer leaf of a cavity wall is about one third greater than the inner leaf.

A similar state of affairs probably applies in winter rainfall areas of South Africa. The transmission of sound through a wall is governed principally by the mass per superficial area of the wall. Fig. 14 compares the sound reducing effects of brick masonry walls with concrete block walls and glass.

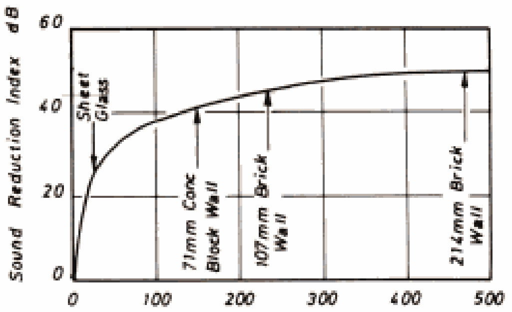


Fig. 14b Ref. 30

It is important to note, when considering this diagram, that a 5dB sound reduction is generally considered to be the minimum that is appreciable to the ear. Hence the sound reduction through a 214mm brick wall is only marginally better than that through a 107mm wall.

THE STRENGTH OF BRICKWORK STRUCTURAL ELEMENTS

In previous sections of this paper, the proper- ties of brick, mortar and brickwork have been considered as material properties. In what follows, the effects of structural geometry and type of loading will be considered.

(i) EFFECT OF ECCENTRIC VERTICAL LOADING ON STRENGTH OF BRICK WORK

Brickwork is a material strong in compression, but weak in tension. Tensile strengths of 0,1 to 0,2 MPa are sometimes assumed in design, but more usually, tensile strength is ignored. In practice, no matter how carefully a structure is designed, some load eccentricities will develop, e.g. If a wall carries a floor slab, deflection of the slab will concentrate load on the inner edge of the wall. Fig. 15 illustrates the theoretical reduction in the strength of a brick wall as the eccentricity of loading is increased and also shows typical experimental results on piers loaded eccentrically.

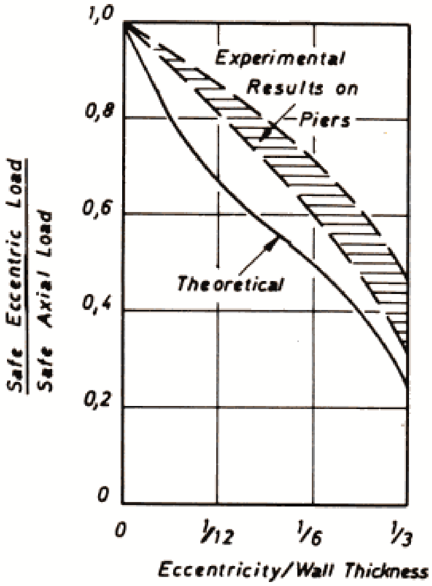


Fig. 15 Ref. 31

It is clear that the actual reduction in column strength due to eccentric loading is not as great as the theory indicates. This is probably due to the tensile strength of the brickwork which is ignored in the theory.

It should be noted that tests on model piers by Hendry (Ref. 31) gave results that in some cases lay below the theoretical line in Fig. 15.

(ii) EFFECT OF LATERAL LOADING ON STRENGTH OF BRICKWORK

Any wall may be subjected to lateral loading. Exterior walls are subject to wind pressure (Ref. 3). Interior walls may have material piled against them. Domestic gas explosives are another possible source of lateral loading (Refs. 27, 32, 33). Very often lateral loading may be the critical factor in the failure of a wall.

Lateral strength is closely related to the bond strength between brick and mortar. If the cement content of the mortar is increased, its tensile strength will increase, but the lateral strength of the brickwork will increase by a lesser factor (as bond is not directly related to tensile strength).

Edge support has a most important effect on lateral strength as the following data for 3m high walls will show: Note that increase in lateral strength exceeds the increase in wall thickness.

It is therefore most important to supply adequate lateral support to all walls. There is a fundamental difference in failure mechanism for (a) walls supported top and bottom and (b) walls supported all round. In (a), single tensile failure occurs along the mortar lines. In (b) "yield lines" running from corner to corner develop. Failure is not simply by mortar to brick bond failure but some bricks must fail in tension (or "kick" out) to form the yield lines.

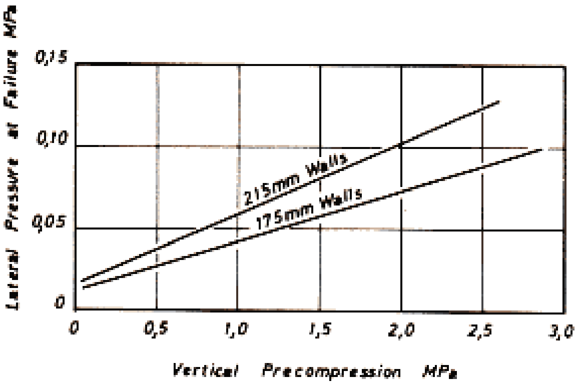


Fig. 16 Ref. 33

Vertical precompression also directly increases the resistance to lateral load (Fig. 16.)

(iii) EFFECT OF SLENDERNESS ON STRENGTH

The strength of a brick wall decreases as the slenderness ratio increases. The relationship is different, however, for single leaf walls and bonded walls. The reduction in strength is also influenced by the basic strength of the brickwork. In terms of failure stress, single leaf walls are stronger than bonded walls (i.e. the opposite effect of that for lateral loading). Fig. 17 shows some early test results (Ref. 24) obtained by loading test wall panels between knife-edges.

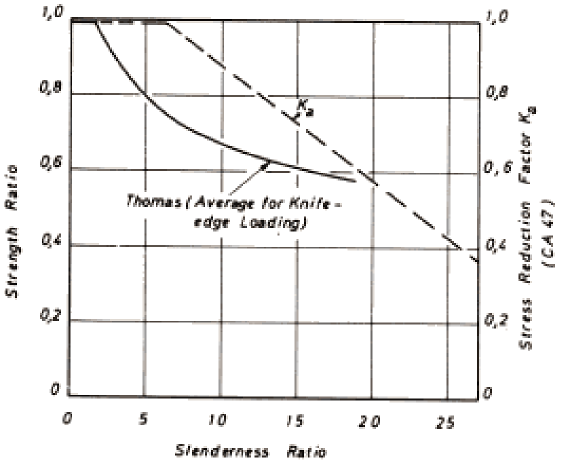


Fig. 17 Refs. 16 & 24

More recent tests (Ref. 34) have shown that the reduction in strength with in- creasing slenderness ratio for walls loaded between concrete slabs (the usual practical si- and Australian (CA 47) codes of practice. Stress reduction factors specified in CA 47 are shown for comparison in Fig. 17.) is less than that shown in Fig. 17. This fact is recognised in the British (CP 111)

(iv) ARCHING OVER OPENINGS AND DEAD LOADING ON BEAMS

A lintel or beam carrying a brick wall is invariably less stiff than the wall and therefore carries less than the superimposed weight of brickwork. The balance of the load is carried across the opening by arch action within the brickwork. Measurements reported in Ref. 28 showed that when a reinforced concrete beam supports brickwork, the load on the beam at midspan is negligible, the majority of the load being directed by arching into the vicinity of the columns supporting the beam. The commentary on the Australian

Code CA 47 (Ref. 16) gives advice on a reasonable loading assumption to account for arching.

PRINCIPLES OF DESIGN OF LOAD-BEARING BRICK STRUCTURES

Detailed design requirements for load-bearing brick structures are to be found in available codes on the subject (Refs. 9, 16 & 35) and only a brief summary of the general principles will be given here. Excellent detailed design information is also given in Ref. 36. This summary is very largely drawn from the commentary on the Australian Code CA 47 (Ref. 16). Brickwork is always designed to act in compression and is assumed incapable of carrying tensile stresses. Vertical dead and live loads are transmitted by load-bearing walls down the height of the building to the foundation.

Each storey-height of wall must carry the load transmitted to it from the above together with any bending moments transmitted from the floor slabs. Under this combination of load and bending moment, no tensile stresses should develop in the wall.

Lateral wind loads are transmitted to the load-bearing walls via the external cladding of the building and the floors. All lateral loads are resisted by the load-bearing walls acting as vertical cantilevers. Here also, no resultant vertical tensile stress can be allowed to develop in the walls.

Floors are assumed to be perfectly stiff in their plane so that all walls at a given level undergo the same lateral deflection under load and share the wind load in proportion to their individual stiffnesses.

The analysis of brickwork structures under wind loading is covered by Refs. 36, 37 & 38. It is usually impossible to safeguard against the possibility of holes being knocked in load-bearing walls to put in additional doors or windows during the life of the building by persons ignorant of the dangers involved. There is also a slight possibility that a load-bearing element might be accidentally removed during the life of the building by gas explosions, collisions with out of control motor vehicles, etc.

Failure of the whole structure can be averted if the floors and walls are de- signed to carry the additional loads that may come onto them in these circumstances. Refs. 27, 32 and 33 deal in great detail with design for such contingencies.

CONCLUSION

It is hoped that this article will have given some idea of the considerable amount of research and practical experiment that has gone into load-bearing brick structures in the past thirty years. Load-bearing brickwork is a well tried, versatile, durable and economical material with a successful past and a promising future.

CALCULATED LOAD-BEARING BRICKWORK

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