47.—Design and Construction of a Prestressed Brickwork Water Tank

By D. Foster
Structural Clay Products Ltd., Potters Bar, Herts.

ABSTRACT
At a brick factory which is using butane gas for firing its products, the need for cooling the gas storage towers in case of fire implies a demand for water far in excess of that possible from the mains. Thus, a water storage tank of 120,000-gal capacity was provided.

The tank is circular, 40-ft dia. internally and 16-ft deep. It is constructed of 9-in. brickwork on a normally reinforced-concrete slab 46-ft 9-in. dia. The 9-in. brickwork is prestressed vertically and circumferentially and built on a sliding joint base. An external decorative skin of 4½-in. brickwork provided external shuttering for a grouted cavity, making an overall wall thickness of 15⅝ in.

Vertical and circumferential stressing steel consists of 0-276-in. wires in grouted ducts vertically and in the grouted cavity circumferentially.

1. INTRODUCTION
In 1967, G. H. Downing & Co. Ltd* opened a new factory at Chesterton, Staffs., firing high-quality facing and engineering bricks by butane gas. This required the installation of three 60-ft high by 8-ft dia. pressure storage vessels (Figure 1) and subsequently cooling water for these in the event of fire. Because mains supplies were inadequate a static water tank of 120,000-gal capacity had to be erected. Dr J. M. Plowman, who had previously experimented with the method, suggested that the walls be built in prestressed rather than reinforced brickwork. The many examples of thin-walled prestressed concrete tanks indicated that this would probably be as economical—and certainly far more interesting—than the alternative, already considered, of using a prefabricated steel section tank. (Certainly this would have been simpler for the company and it is therefore to their credit that they encouraged the prestressed brickwork proposal, especially when it was realized that it was a relatively untried medium.)

* A member firm of Structural Clay Products Ltd.

Entwurf und Konstruktion eines Wasservorräthälers aus vorgespanntem Ziegelmauerwerk
In einem Ziegelmauerwerk, das seine Öfen mit Butan-Gas beheizt, wird für den Fall eines Schadensfeuers zwecks Kühlung der Gasvorräthälder eine Wassermenge benötigt, die weit größer als die von der Hauptwasserleitung beigesteuert ist. Darum wurde ein WasservorräthstANK mit rund 545 m³ Inhalt erforderlich. Der kreisförmige Tank hat einen inneren Durchmesser von rund 12 m und ist ca. 4,8 m tief. Er besteht aus einer 22,5 cm dicken Ziegelmauer auf einer Platte aus bewehrtem Beton mit gut 14 m Durchmesser. Der 22,5 cm dicke Ziegelmauerwerk ist vertikal sowie im Umfang vorgespannt und auf Basis einer elastischen Fuge gebaut. Eine dekorative Aussenhaut aus 11,5 cm dickem Ziegelmauerwerk stellt die äussere Verschaltung eines ausgegossenen Hohlraumes dar, so dass die Gesamtdicke der Wand 39,5 cm beträgt. Der senkrecht und peripher wirkende Spannstahl besteht aus Drähten mit rund 7 mm Durchmesser, er befindet sich in den vergossenen senkrechten Kandlen bzw. in dem vergossenen umlaufenden Hohlraum.

Figure 1.—View of partly finished tank and butane towers.

287
2. GENERAL DESIGN CONSIDERATIONS

2.1 Site

The location of the structure is shown in Figure 2. It had to be as near as possible to the gas storage tanks to keep pipe work to a minimum but it was not allowed to be built on the concrete apron used for stacking the product. The soil is made-up ground sloping rapidly away into the old clay pit and consisting, in the main, of reject bricks from the old factory which the modern plant replaced. The allowable load on the soil is about 0·5 to 0·75 tonf/ft².

2.2 Dimensions of Tank

By plotting height against diameter and by estimating costs of the reinforced-concrete base and the brickwork it was determined that with an internal diameter of 40 ft and a height to water level of 15·25 ft, the required capacity would be achieved as economically as possible. Allowing for wall thickness and projection the overall diameter of the base is 46 ft, and the resulting area implies a unit load on the soil within that allowed. The general arrangement adopted is shown in Figure 3.

2.3 Choice of Wall Thickness

The requirements governing the choice of wall thickness were:

(a) The strength of the brickwork, both vertically and circumferentially.

(b) The ease of incorporating the necessary vertical reinforcement.

(c) The permeability of the brickwork.

(d) The possibility of corrosion of the tendons.

These requirements are clearly interrelated. For maximum economy a single 4½-in. nominal—4¼-in. actual—wythe would have been ideal. However, its disadvantages are only too clear:

(a) Perforated bricks would be necessary so that vertical steel could be incorporated in the wall thickness. This implied a pattern of perforation such that the superimposition of successive courses would form ducts at intervals for the vertical tendons, and hence a degree of accuracy on the site which might prove difficult to attain.

(b) Bricks would have to be threaded individually over tendons—clearly a clumsy arrangement.

(c) If, to avoid (b), the bricks were made with slots instead of holes, then the circumferential strength would be seriously weakened. One type of perforated brick (Figure 4) gave a mean strength of 1690 lb/in² and a range of 1110 to 2340 lb/in² when tested on end, compared with a mean of around 8000 lb/in² when tested on bed.

(d) The protective cover to the vertical tendons would be relatively small. It was known that failures of hoop tendons where protected by sprayed mortar coatings had occurred on prestressed concrete tanks; due, probably,
was lacking and it was requested that existing stocks be used.

A 9-in. actual bonded thickness was adopted (Figure 6). In this arrangement solid bricks in Flemish bond give the possibility of vertical spaces every 6½ in. By increasing the thickness of the collar joint (the centre vertical joint parallel with the wall face) ½-in.-dia. sheaths could readily be incorporated.

In this 9-in. wythe the cables are at least 4 in. from the water. It was thought that the hydraulic head was too great to leave even this thickness unprotected, so it was decided to render the tank internally with one of the cement-styrene-butadiene compounds* now available, which

![Figure 4](image-url)  
**Figure 4**—Brick tested on end.

![Figure 5](image-url)  
**Figure 5**—Suggested slotted brick.

are claimed to have high adhesive and waterproofing properties. This arrangement, together with the grouting of the cables in their sheaths, was deemed to be a reasonable safeguard. Many reinforced-brickwork water-retaining structures have been built in the USA without, apparently, any reported failures and the writer has examined a number of these without noticing signs of deterioration even where the brickwork is unprotected.

### 2.4 Junction of Walls and Base

It was decided at the beginning to build the walls on a sliding joint rather than to fix them to the reinforced-concrete base, primarily on the grounds of simplicity of

---

*Revinex 29V40, by Revortex Ltd.*
Design and Construction of a Prestressed Brickwork Water Tank

Frictional restraint is unavoidable.

3. PROPERTIES OF MATERIALS

3.1 Bricks
The bricks used were 'Staffordshire Blues' a Class-A engineering brick to BS 3921. The mean strength of a sample crushed on end was 11,990 lbf/in² with a range of 8,600 to 15,420 lbf/in². The strength on bed is similar. The initial rate of absorption (suction rate) was not measured but is certainly very low on the basis of previous determinations with a brick of this kind.

3.2 Mortar
The mortar used for the stressed wall was 1:4:3 ordinary grade Portland cement:hydrated lime:sand, the sand complying with BS 1200.

3.3 Brickwork
Three laboratory 9-in. brickwork cubes were made from the bricks and mortar to be used. Their crushing strengths at 28 days were 4900, 5780, and 6190 lbf/in². Three mortar cubes had crushing strengths at 28 days of 2700, 2180, and 1950 lbf/in². Site brickwork cubes were not made. While the strength of the brickwork itself was not measured directly, extensive tests on walls and brickwork cubes have indicated that for this mean strength of cubes, a wall strength under axial loading of between about one-half to two-thirds of the cube strength may be expected.

Although no experimental determination of the E value was made, brickwork of this strength and quality has been taken as 3.0 x 10⁶ lbf/in². LENCZNER has shown that with similar strength brick and mortar it is 3.5 x 10⁶ lbf/in² but the maximum allowed by CP 1116 is 2.33 x 10⁶ lbf/in². However, this was deemed to be too conservative.

The SCPI code allows a maximum of 3.0 x 10⁶ lbf/in².

3.4 Concrete
The concrete for the base was 1:2:4 nominal with an assumed 28-day works cube strength of 3000 lbf/in². That for the ring beam was 1:6:3:2 nominal with a corresponding preliminary cube strength of 5400 lbf/in² and a works strength of 3600 lbf/in². The average strength of two cubes taken from the site while casting the top beam was 4420 lbf/in² at 28 days.

4. CALCULATIONS*

4.1 Base Slab
Calculations for the base slab follow normal procedure using ordinary reinforced concrete in accordance with the relevant British Standard Codes of Practice. They would be out of place in the present text but at least the following point is worth noting.

CP 2007 requires that any reinforced-concrete section in a liquid-retaining structure should be so proportioned that in any face in contact with the liquid the tensile stress in the concrete (designed as though the steel were not there) does not exceed a permissible figure. For 1:2:4 nominal concrete mix this is 175 lbf/in² for direct tension and 245 lbf/in² for tension due to bending. The purpose of such restriction is, of course, to provide resistance to cracking.

*To slide-rule accuracy.
4.2 Walls

4.2.1 Stresses in Walls: Circumferential

Weight of water = 62·5 lb/ft\(^3\)
Head of water, say, 15-75 ft
Internal diameter of tanks, 40·0 ft
Hoop tension at base of wall = \((15·75 \times 40·0 \times 62·5)/2 = 19700\) lbf

\text{Vertical stress required} = 87·3 + 45·3 - 238\text{ lbf/in}^2

Compression due to self weight of wall = \(0·58 \times 16·75\) (height to top of coping) \times 100
\(= 9·35\) lbf/in\(^2\)

\text{Vertical stress required} = 87·3 + 45·3 - 9·35
\(= 123·3\) lbf/in\(^2\)

4.2.2 Stresses in Walls: Vertical (CP 2007, Clause 318)\(^1\)

Allowance for bending induced by differential hoop stressing, i.e., partially wound hoop steel must be provided to resist this. Also, with the tank full, CP 2007 requires (Clause 318 b iii)\(^5\) a residual compression at all points of at least 100 lbf/in\(^2\).

\(M\) (max) = \(WL/7·8\)
\(M = WL/2 - 15·6 = 6744 \text{ lb. in.}\)

Section modulus of wall = \(bd^2/6 = 12 \times (8·625)^2 / 6\)
\(= 149 \text{ in}^3\)

\text{Compressive stress due to bending} = 6744/149 = \(\pm 45·3\) lbf/in\(^2\)

\text{Compression due to self weight of wall} = \(0·58 \times 16·75\) (height to top of coping) \times 100
\(= 9·35\) lbf/in\(^2\)

\text{Vertical stress required} = 87·3 + 45·3 - 9·35
\(= 123·3\) lbf/in\(^2\)

4.2.3 Losses in Steel Prestress

Before determining the layout of the steel it is necessary to ascertain losses. In doing this certain assumptions have had to be made about some brickwork characteristics for which there is very little experimental evidence. Attention is drawn to these assumptions as they occur.

4.2.3.1 Vertical steel losses

(i) Relaxation of steel itself = \(15\ 000\) lbf/in\(^2\)

(ii) Elastic contraction at transfer:

\[
= \frac{(9·33 \times 123·3)}{2} = 575\ \text{lbf/in}^2
\]

\text{Total hoop compression required at base} = 291 lbf/in\(^2\).

\(\text{Total hoop compression required at base} = 291\) lbf/in\(^2\).

\text{Allowance for bending due to frictional restraint: with a sliding joint this is assumed to be equal to half that if the foot were pinned.}

\[ M (\text{max}) = \frac{WL}{7.8} \]

\[ M = \frac{WL}{2} - 15.6 = 6744 \text{ lb. in.} \]

\[ \text{Section modulus of wall} = \frac{bd^2}{6} = 12 \times (8.625)^2 / 6 \]

\[ = 149 \text{ in}^3 \]

\[ \text{Compression due to self weight of wall} = 0.58 \times 16.75 \text{ (height to top of coping)} \times 100 \]

\[ = 9.35 \text{ lbf/in}^2 \]

\[ \text{Vertical stress required} = 87.3 + 45.3 - 9.35 \]

\[ = 123.3 \text{ lbf/in}^2 \]

\text{Loss due to relaxation of steel itself} = 15\ 000 \text{ lbf/in}^2

\text{Elastic contraction at transfer:}

\[
= \frac{(9.33 \times 123.3)}{2} = 575\ \text{lbf/in}^2
\]

**Note:** The elastic contraction is half where post tensioning is used and/or where wires or bars are not all stressed simultaneously.

(iii) Creep of brickwork: The creep of brickwork under such low stresses will be almost negligible. For post-tensioned concrete the loss per unit length

\[ = \frac{0.25 \times 10^{-6} \times 6000}{247} \]

\[ = 238 \text{ lbf/in}^2 \]

(iv) Shrinkage of brickwork: Clay bricks do not shrink, but joints do. Vertically, the proportion of height represented by the joints is one-seventh (\(\frac{1}{7}\) in./2\ in.). If the joint is considered to have the same shrinkage as concrete then the loss will be given by:

\[ \text{Coeff.} \times E \text{ of steel} \]

\[ = \frac{7}{200 \times 10^{-6}} \]

\[ \text{Loss} = \frac{200 \times 10^{-6} \times 28.0 \times 10^6}{7} = 800 \text{ lbf/in}^2 \]

(v) Losses due to slipping while anchoring: Say 6\% of final applied load

\[ = 0.06 \times 0.65 \times 100 \times 2240 \]

\[ = 8700 \text{ lbf/in}^2 \]

**Note:** In prestressed cylindrical liquid-retaining structures the maximum allowable stress in tendons is 65\% of ultimate.\(^1\) The percentage of the applied load is determined from the manufacturer’s recommendations for the type of anchorage. The range for the equipment used here is not linear but varies from 10\% at very low forces to 5\% at normal working loads. At 6\% it is a surprisingly high figure compared with the other losses.

\[ \text{Total relaxation loss per in}^2 = 25\ 313 \text{ lbf/in}^2 \]

\[ \text{Loss per wire (0.276-in. dia.)} = 0.0598 \times 25\ 313 = 1520 \text{ lbf} \]

This loss per wire can be added to the prescribed working maximum per wire so that the residual force is equal to this maximum. From the residual must be deducted the frictional loss to obtain the design stress. Max. = 0.65 \times 13\ 400 = 8700 \text{ lbf per wire (13\ 400 lbf is the ultimate for one wire of 100 tonf/in}^2\text{ steel).} 8700 + 1520 = 10\ 220 \text{ lbf = force at jack.}

(vi) Loss due to friction in the duct: This is given in CP 115\(^8\) (and CP 2007\(^7\)) by the formula

\[ P_a = P_d e^{-Kx} \]

where

\[ P_d = \text{prestressing force at } x \text{ ft from the jack} \]

\[ P_a = \text{prestressing force at the jack} \]

\[ e = 2.718 \]

\[ K = \text{constant depending on type of duct (5 \times 10^{-4} here).} \]

For this case it is sufficiently accurate to assume that
Design and Construction of a Prestressed Brickwork Water Tank

\[ e^{-Kx} = 1 - Kx \] and since \( K \) is given, then
\[ P_s = P_a \left[ 1 - (5 \times 16.75 \times 10^{-4}) \right] \]
\[ = P_a \left( 1 - 0.008 \right) \]
loss = -0.008 \( P_a \)

Now \( P \) is the force required at the jack, which is 10,270 lb.

\( \therefore \) Friction loss = 0.008 \( \times 10 \times 220 \) = 82 lb

\( \therefore \) Residual force per wire for purposes of determining the number of wires = 8,700 - 82
\[ = 8,618 \text{ lbf} \]

### 4.2.3.2 Hoop steel losses

(i) Relaxation
\[ \text{Force supplied} = 2 \times (\text{wires}) \times 8,618 \]
\[ = 17,236 \text{ lbf} \]

(ii) Elastic contraction
\[ \text{Modular ratio} \times \text{Stress in brickwork} \]
\[ = \frac{9.33 \times 291}{2} \]
\[ = 1,350 \text{ lbf/in}^2 \]

(iii) Loss due to creep
\[ = \frac{17 \times 291 \times 28 \times 10^6}{10^6 \times 4.27} \]
\[ = 562 \text{ lbf/in}^2 \]

(iv) Shrinkage.
\[ \text{Circumferentially, the joints form } \frac{3}{8} \text{ of the work. Thus the coefficient must be multiplied by } (3/69) \]
\[ \text{Loss} = \frac{3 \times 200 \times 10^{-6} \times 28 \times 10^6}{69} \]
\[ = 244 \text{ lbf/in}^2 \]

(v) Loss due to slippage while anchoring—\( \text{as before} \)
\[ = 8,700 \text{ lbf/in}^2 \]
\[ = 25,856 \text{ lbf/in}^2 \]

Total relaxation losses per wire, \( \text{i.e. before friction} \)
\[ = 0.0598 \times 25,856 = 1,542 \text{ lbf} \]

Required force per wire at jack
\[ = 8,700 \text{ (max. working allowed)} + 1,542 \]
\[ = 10,242 \text{ lbf} \]

From this must be deducted the loss due to friction.

(vi) Loss due to friction due to circular tendons—\( \text{per tendon} \). From CP 115,\(^8 \) friction loss is given by the formula
\[ P_s = P_a e^{-\gamma x/R} \]
where \( P_s \) = the resultant stressing force at point \( x \)
\( P_a \) = prestressing force at the tangent point near the jacking end
\( e = 2.718 \)
\( R = \text{radius of curvature} = 20 \text{ ft} \)

For steel riding on steel as in this job \( \mu \) is given as 0.25
Distance \( x = \frac{1}{4} \) circumference = \( \pi D / 4 \)
\[ \mu x = \frac{0.25 \times \pi \times 40}{20 \times 4} = 0.391 \]
\[ P_s = P_a \times 2.718^{-0.391} \]
\[ = P_a \frac{1024}{1.476} = 6990 \text{ lbf} \]

### 4.2.4 Layout of Stressing Steel

#### 4.2.4.1 Vertical steel layout

The possible spacing of the vertical steel is governed by the bonding arrangement (Figure 6). From this it will be seen that wires in pairs could be spaced at a minimum of 6\( \frac{1}{2} \)-inch centres—giving the maximum number of wires. Try 13\( \frac{1}{2} \)-inch centres.

\[ \text{Force required} = 13.5 \times 8 \times 625 \times 123.65 \text{ lbf} \]
\[ = 14,400 \text{ lbf} \]

\[ \text{Force supplied} = 2 \times (\text{wires}) \times 8,618 \text{ lbf} \]
\[ = 17,236 \text{ lbf} \]

which is clearly adequate (Figures 6 and 7).

#### 4.2.4.2 Hoop steel layout

The hoop steel required can best be determined by tabulation (Table 1).

<table>
<thead>
<tr>
<th>Depth ( D ) of ( \text{water (ft)} )</th>
<th>Hoop tensile force ( (lb) )</th>
<th>Total force ( * ) required including residual of ( 10,350 \text{ lbf} )</th>
<th>No. of ( 0.276 \text{-in. wires per ft} )</th>
<th>No. of wires installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.75</td>
<td>19,700</td>
<td>30,050</td>
<td>5.6</td>
<td>8</td>
</tr>
<tr>
<td>14.75</td>
<td>18,500</td>
<td>28,850</td>
<td>5.2</td>
<td>8</td>
</tr>
<tr>
<td>13.75</td>
<td>17,200</td>
<td>27,550</td>
<td>5.1</td>
<td>7</td>
</tr>
<tr>
<td>12.75</td>
<td>16,000</td>
<td>26,350</td>
<td>4.8</td>
<td>7</td>
</tr>
<tr>
<td>11.75</td>
<td>14,700</td>
<td>25,050</td>
<td>4.5</td>
<td>7</td>
</tr>
<tr>
<td>10.75</td>
<td>13,500</td>
<td>23,850</td>
<td>5.0</td>
<td>6</td>
</tr>
<tr>
<td>9.75</td>
<td>12,200</td>
<td>22,550</td>
<td>4.8</td>
<td>6</td>
</tr>
<tr>
<td>8.75</td>
<td>10,950</td>
<td>21,300</td>
<td>4.5</td>
<td>6</td>
</tr>
<tr>
<td>7.75</td>
<td>9,700</td>
<td>20,050</td>
<td>4.2</td>
<td>6</td>
</tr>
<tr>
<td>6.75</td>
<td>8,450</td>
<td>18,800</td>
<td>4.0</td>
<td>6</td>
</tr>
<tr>
<td>5.75</td>
<td>7,200</td>
<td>17,550</td>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td>4.75</td>
<td>5,950</td>
<td>16,300</td>
<td>3.4</td>
<td>4</td>
</tr>
<tr>
<td>3.75</td>
<td>4,700</td>
<td>15,050</td>
<td>3.2</td>
<td>4</td>
</tr>
</tbody>
</table>

\( * \) The residual hoop stress required is 100 lbf/in\(^2 \) when the tank is full.

\( \therefore \) Force per foot of height
\[ = 12 \times 8,625 \times 270 \]
\[ = 10,350 \text{ lbf} \]

The layout of these wires—and the vertical steel—is shown on Figures 6 and 7. The increased number over that calculated is due to revisions of the latter—which resulted in an increased allowable force per wire—and also to the method of anchorage. The anchor blocks, which are of Meehanite, accommodate four wires in each direction and are spaced up the wall to give the nearest to the desired arrangement. The actual spacing is shown in Figure 7(a). It will be seen (Figure 3) that two twin jacks are needed to stress any one cable and that stressing is to be alternated at 90\(^\circ \). Thus, four wires are tensioned and locked at positions 1 and then the next four at positions 2.

### 5. CONSTRUCTION

The following notes record the problems encountered to the time of writing during the construction of the tank.

#### 5.1 Sequence of Erection

The erection procedure proposed was as follows.
Excavate, lay hardcore of broken brick and lay a 3-in.-thick cement-sand as a blinding.

Lay foundation steel, cast the slab and form the upstand.

Form the sliding joint at the base of the inner 9-in. wall.

Set formwork for bottom reinforced-concrete ring beam and locate its steel.

Erect scaffolding and top template and then locate vertical stressing steel, anchors and spirals. (It was intended originally to stress the wires from the top, fixing the tapered sleeves into the anchors at the bottom before doing so, but after the erection of the walls. This proved impracticable so the vertical cables were stressed and the bottom anchorages made before delivery as complete sheathed wires incorporating grout tubes).

Build the inner brickwork and cast the top beam.

Carry out vertical stressing when the top beam, and hence all the inner wall, is 28 days old.

Locate and stress the hoop steel.

Form the watertight joint between the bottom ring beam and the concrete upstand from the base.

Render the inside of the tank with the Revinex 29Y-40 mix in two coats to the manufacturer's directions.

Fill tank and check for leaks.

Build external walls and grout the cavity.
5.2 Comment
So far this programme has proved practicable but carelessness on the part of the bricklayers and scaffolders has caused some trouble and there was one mishap which caused further delay. Figures 8–12 show the work done so far and the following notes on these are given in conclusion.

Figure 8: After casting the base slab and upstand a useful amount of rain water collected and fortuitously served to help cure the slab and keep shrinkage to a minimum.

Figure 9: The tank walls, when about 3-ft high, were rising well out of plumb because the bricklayers were following the vertical cables which had not been held properly by the templates.

Figure 10: After the top ring beam was cast care was not taken in removing the wooden plugs which formed the holes for the top anchors to the cables. Some of the sheaths were blocked as a result and high-pressure air was needed to clear them.

Since the conference the tank has been completed (Figure 13).

REFERENCES
2. BRITISH STANDARDS INSTITUTION, Bricks and Blocks of Fired Brick-earth, Clay or Shale. B.S. 3921:1965.
5. LENCZNER, D. This volume, page 44.