Brick Diaphragm Walls - an alternative design for Industrial Buildings

By D. M. Humphries (Fellow) in conjunction with W. G. Curtin, FICE, FIStructE, MConsE, FIArb

This paper summarises the content of several papers given at a recent Brick Development Association seminar on the proposals for use of the brick diaphragm wall in industrial buildings.

GENERAL ENGINEERING PRINCIPLES AND BUILDING DETAILS

Introduction

Before describing the cost implications of the use of brick diaphragm walls in any building form, it is necessary to understand the basic principles of the design together with the application of this design/structure on the site. These descriptions are given immediately below by two experienced men from their respective disciplines, W. G. Curtin, FICE, FIStructE, MConsE, FIArb, and W. W. Harper, MIOB. Mr. Curtin, a Senior Partner in a Liverpool based practice of Consulting Engineers, describes the principle of design, whilst Mr. Harper, the Planning Manager with Tysons (Contractors) Limited, Liverpool, a substantial and well known Contractor in the Merseyside area, describes the application of the diaphragm wall on the site.

ENGINEER

Diaphragm Walls

The traditional way of building tall, single-storey, wide-span structures for factories, sports halls, garages etc. is to build them in steel. The majority of such buildings have their roofs supported by steel columns which have to be designed, fabricated by a specialist sub-contractor, delivered to the site, erected, plumbed and lined and braced. To keep the weather out the structure has to be clad with metal or asbestos sheeting, backed with an insulating material to keep the heat in and lined with a hard lining. Often the cladding, insulation and lining need a subsidiary steel framework to support them. Thus the resulting 'wall' requires four different materials, several sub-contractors, trades and operations. The frame, cladding, etc. requires maintenance, repairs and decoration and lacks brickworks, durability, economy, speed of construction and aesthetic qualities.

One alternative and, we suggest, better method is to use a brick diaphragm wall. The brick diaphragm wall is simply a wide cavity wall where the cavity is 1 to 2 bricks deep and the leaves of 102.5 mm brickwork are braced by cross ribs (also of 102.5 mm brickwork) at 1–1.5 m centres (see fig. 1).

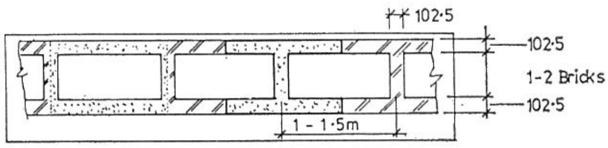
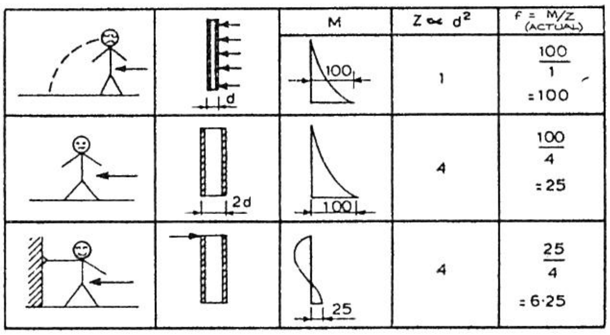
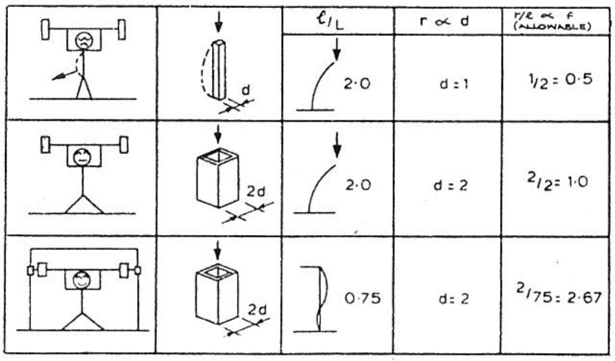


Figure 1



DIAPHRAGM WALL - LATERAL LOADING.

Figure 2



DIAPHRAGM WALL - AXIAL LOADING

Figure 3

It can be seen from figure 1 that the diaphragm wall acts structurally as a series of connected box or H sections which gives the wall an impressive increase in strength and resistance to both vertical loading from the roof and horizontal loading from the wind. The outer leaf forms the cladding; the inner leaf the hard lining; the void, the insulation; and the ribs acting with the leaves, the structure. Thus one material, using one trade, carried out by the main contractor, fulfills the four functions of structure, cladding, insulation and lining.

A simple way of describing the increase in the wall's lateral strength is shown in fig. 2, and its vertical strength in fig. 3.

The wall is propped at the top by the roof which can be of normal traditional construction using beams and purlins, (of steel, concrete or timber) but with the addition of extra diagonal bracing to form a 'lattice girder' (fig. 4.)

The 'lattice girder' transfers the wind force to the gable walls which act as shear walls (deep stiff beams) (fig. 5.)

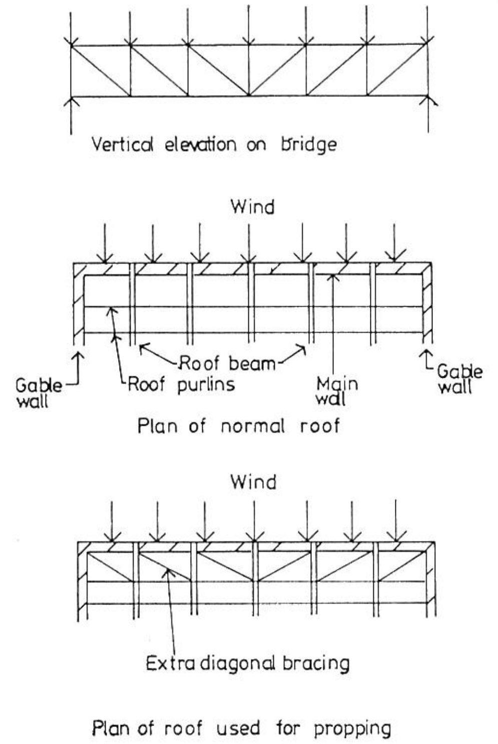


Figure 4

Roof and capping beams

In order to obtain the greatest economy in the total cost of the structure, the roof of such buildings should be used as a horizontal plate member to prop and tie the tops of the walls and transfer the resulting horizontal reactions to the transverse or gable walls.

A capping beam can be used on top of the diaphragm wall to transfer these forces into the roof deck and to overcome uplift forces from wind suction acting on lightweight decking. If necessary, the beam can also be used as the boom member of the roof plate. The roof deck can be of a variety of materials and supported in many ways. Depending on the spans involved, the most economical roof beams may be universal beams, castellated beams or lattice girders which can be spaced at centres to suit the most economical arrangement, taking into account the selected decking material. On long spans, a space deck can prove to be more economical in providing the necessary decking support.

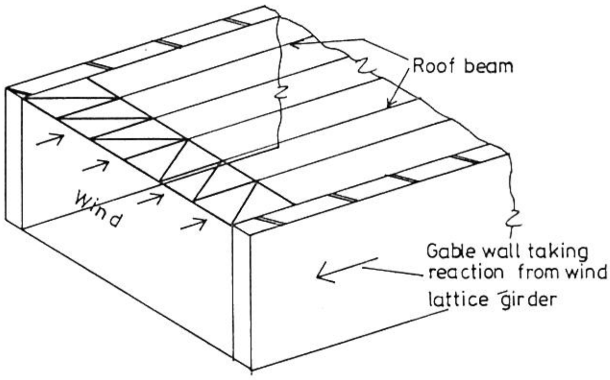


Figure 5

A space deck can also act as a suitable plate to transfer the propping loads to the transverse walls. Often the decking material, if suitably fixed, can be used as a plate in conjunction with the main roof beams. But where this is not the case, a horizontal girder can be incorporated using the concrete capping beams as boom members.

The capping beam at roof level can be constructed by either using in-situ concrete (on a permanent bridge shutter of asbestos or similar material) or by precasting the beam in bay lengths and using a suitable connection to transfer the forces at the joints. The capping beam is used as the seating and fixing for the roof structure, as shown in fig. 6. Probably the more successful method of constructing a capping beam is that of precasting, since this overcomes the problems of keeping the facing bricks clean, and the expense of the permanent shutter which is necessary for the in-situ solution.

Foundations

At foundation level, the pressures are so low with this form of construction that the use of a nominal strip footing is usually adequate, but this must, of course, be determined from consideration of the site's ground conditions (fig. 7).

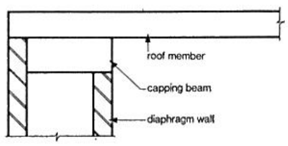


Figure 6

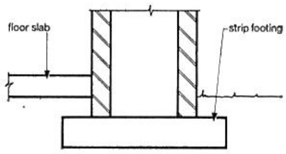


Figure 7

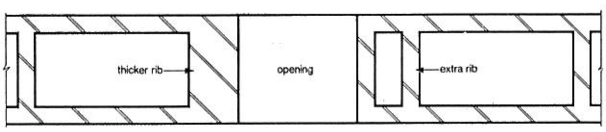


Figure 8

Opening in walls

Large door and window openings can create high local loading conditions from the horizontal wind loading and localised axial loads at beam bearings. The openings can be dealt with by providing a beam or lintel to carry the vertical load and by using local extra ribs or thicker ribs on each side of the openings (fig. 8).

Joints

Movement joints are required at the appropriate centres, in accordance with the normal recommendations for loadbearing brickwork dealt with in BDA technical publications and the recommendations given in CP121. Joints can easily be accommodated by double ribs, one at each side of the joint (fig. 9).

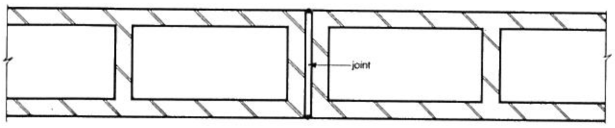


Figure 9

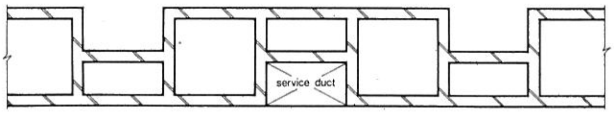


Figure 10

Services

Because of the large voids within diaphragm walls, it is possible to accommodate certain services within them. Care must be taken to see that the location and size of the holes do not cause local overstressing of the brickwork (bearing in mind that measures can be adopted in these positions). In addition, access to services and the possibility of corrosion must be carefully considered if maintenance costs are to be minimised. Service ducts can be incorporated in the wall (fig. 10). Such ducts should, of course, be ventilated when housing gas pipes.

Sound and thermal insulation

Since the mass of the wall is similar to that of a normal cavity wall, the sound insulation is similar. The 'U' value is also similar to that of a normal cavity wall but, because of air circulation which can take place within the larger void and since the ribs create 'cold bridges', the value is increased slightly. (The increase is estimated to be about 10%). If extra thermal insulation is required, it is a simple matter to introduce insulating material into the voids.

Architectural design

The junction between the wall and the roof of the building can be treated in many different ways.

It is not essential for the diaphragm wall to be designed with flat faces on each side and, particularly on tall buildings, a fluted arrangement can be neatly incorporated in the structure (fig. 11) thus creating more interesting elevations.

Depending on the cost implications and appearance requirements, it is possible to use either bonded joints between the cross-ribs and leaves or butt joints with designed shear ties. The bonded joint is sometimes preferred, but this depends on the architectural requirements relating to headers being visible on the faces of

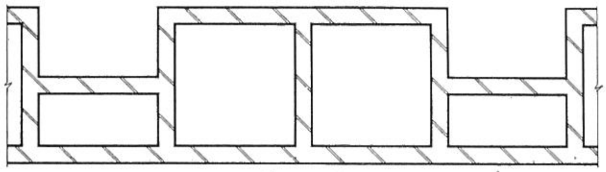


Figure 11

the brickwork. The headers can be used as a feature and can incorporate a different coloured brick to that of the stretchers. In some cases, the labour costs for providing bonded brickwork have been more than those for unbonded joints containing shear ties. However, the economics of this appear to vary from job to job. If unbonded cross-ribs are used, the shear ties must be designed to take the vertical shear forces and must be sufficiently durable to resist corrosion.

A variety of facing bricks can be used for diaphragm walls and the ribs can, if required, be constructed using a different brick. Provided, of course, that the two different bricks have compatible thermal and moisture movement characteristics.

CONSTRUCTION

Cavity cleaning

The problem of mortar droppings, etc. within the voids of the walls becomes less as the width of the void increases and, in most cases, elaborate methods of cleaning out the voids are not necessary provided that nominal care is taken during construction.

Temporary propping

Like most other walls, the diaphragm is in a critical state during erection prior to the roof being constructed and fixed. During this period, the contractor must take the normal temporary precautions such as propping the walls with the bricklayers' scaffolding, or other means, to ensure that the walls remain stable.

Damp proof courses

Horizontal damp proof courses should be selected to give the necessary shear resistance to prevent sliding and should not squeeze out under the vertical load. Vertical damp proof courses are not normally required in diaphragm walls provided that bricks and mortar of suitable quality are selected to suit the conditions. If very severe conditions of driving rain are anticipated, engineering bricks can be used for the cross ribs. Vertical damp proof course membranes which prevent tying of the brickwork should be avoided, because of the problem of transferring the vertical shear forces.

Structural design

The main calculation involved in the design of diaphragm walls is for the critical condition of combined dead and wind loading. This takes into account the maximum uplift and maximum tensile stresses. The compressive stresses involved when the combined dead, superimposed and wind loading is applied are, in general, so low that the selection of a suitable brick and mortar is based mainly on tensile resistance and the minimum requirements for durability and absorption.

Calculations are carried out on a trial and error basis, by adopting a trial section and then checking the stress condition. For a more detailed discussion and worked examples see 'Brick Diaphragm Walls in Tall Single-Storey Buildings' published by the Brick Development Association.

Experience and performance of diaphragm walls

At least twelve diaphragm wall projects have been built and more are under construction.

The buildings already constructed have in the course of 1976 alone survived:

(a) The gales in January which produced the highest wind gust speeds on record.
(b) The summer drought which was, again, the worst on record with air temperatures of over 30°C and external wall temperatures of 45°C.
(c) The rainfall in September which was three times the normal average.

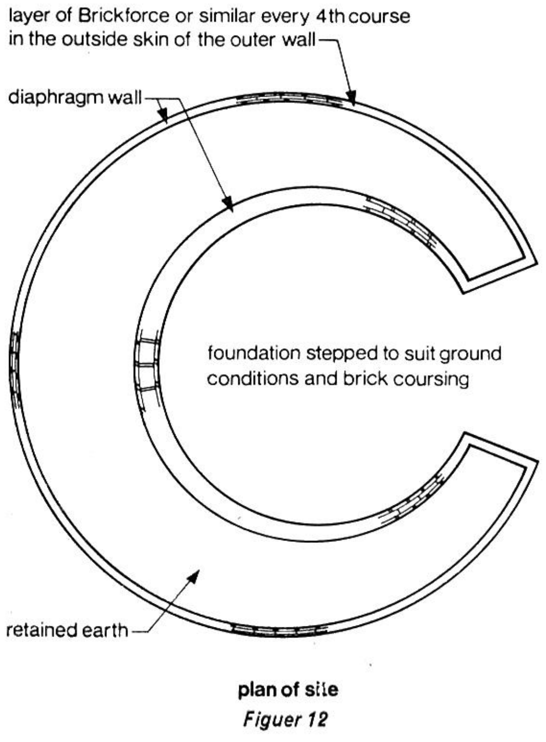
These buildings have all performed successfully and no problems have developed as a result of the method of construction.

Other applications

Although the diaphragm wall was developed for tall single-storey, wide-span, structures, it has applications in other fields, particularly where lateral loading is more significant than vertical loading. For example, a diaphragm has been used as a mass-retaining wall on a site which had a large amount of demolition rubble. The rubble was used to fill the cavity, and a cheap and strong mass-retaining wall was constructed. The wall was constructed in 1970 as part of a landscape development. (figs. 12 and 13).

Diaphragm walls could also be used as sound reflectors on motorways in urban areas. At the present moment, some reflectors are going up in steel, precast concrete and timber and it is thought that brick diaphragm walls would be cheaper, certainly more durable, and have greater aesthetic appeal. They may also be used for farm silos for storage of grain, potatoes, etc.

With knowledge and experience the applications will increase. Research on the behaviour of diaphragm walls is being carried out at the Department of Civil Engineering of the University of Liverpool, with financial support from Brick Development Association.



plan of site

Figuer 12

CONTRACTOR

Construction Technique for Diaphragm Walls

As already stated the method of construction using a portal steel frame requires a large number of sub-contractors and various trades to carry out the different sections of the work. Each sub-contractor has to be organised and co-ordinated to come on site at the precise time that he is needed to complete his small section of work on the "wall". Should any one trade be held up or delayed in starting it affects the following trades and so lengthens the contract time since each one is inter-related and dependent on the other.

These specialist tradesmen travel over a wide area of the country, going from site to site and invariably delays occur. With the diaphragm wall method of construction 90% of the work can be accomplished by any middle or even small sized firm of competent general contractors, thus giving far better continuity. This last item is of the utmost importance, especially where Local Authorities are concerned, as they can select a local contractor and as his share of the contract would be far larger using the diaphragm method, this can help to alleviate the unemployment in the area.

The advantages of the diaphragm method over the portal frame construction starts at the commencement of the design as shown in the pre-contract bar chart (fig. 14). It clearly shows a considerable time period, as in the traditional type of construction the steel frame has to be ordered from a nationalised industry or drawn from a steel stock-holder (with luck) and delivered to the sub-contractor's works; even after this there is quite a lengthy period of time required for prefabrication. By comparison there is virtually no delivery time for bricks. In this day and age most brick manufacturers can guarantee deliveries of numerous types of facing and common bricks, ex stock say 7 to 14 days.

"I hear the brick diaphragm walling will have to be of the highest standard".

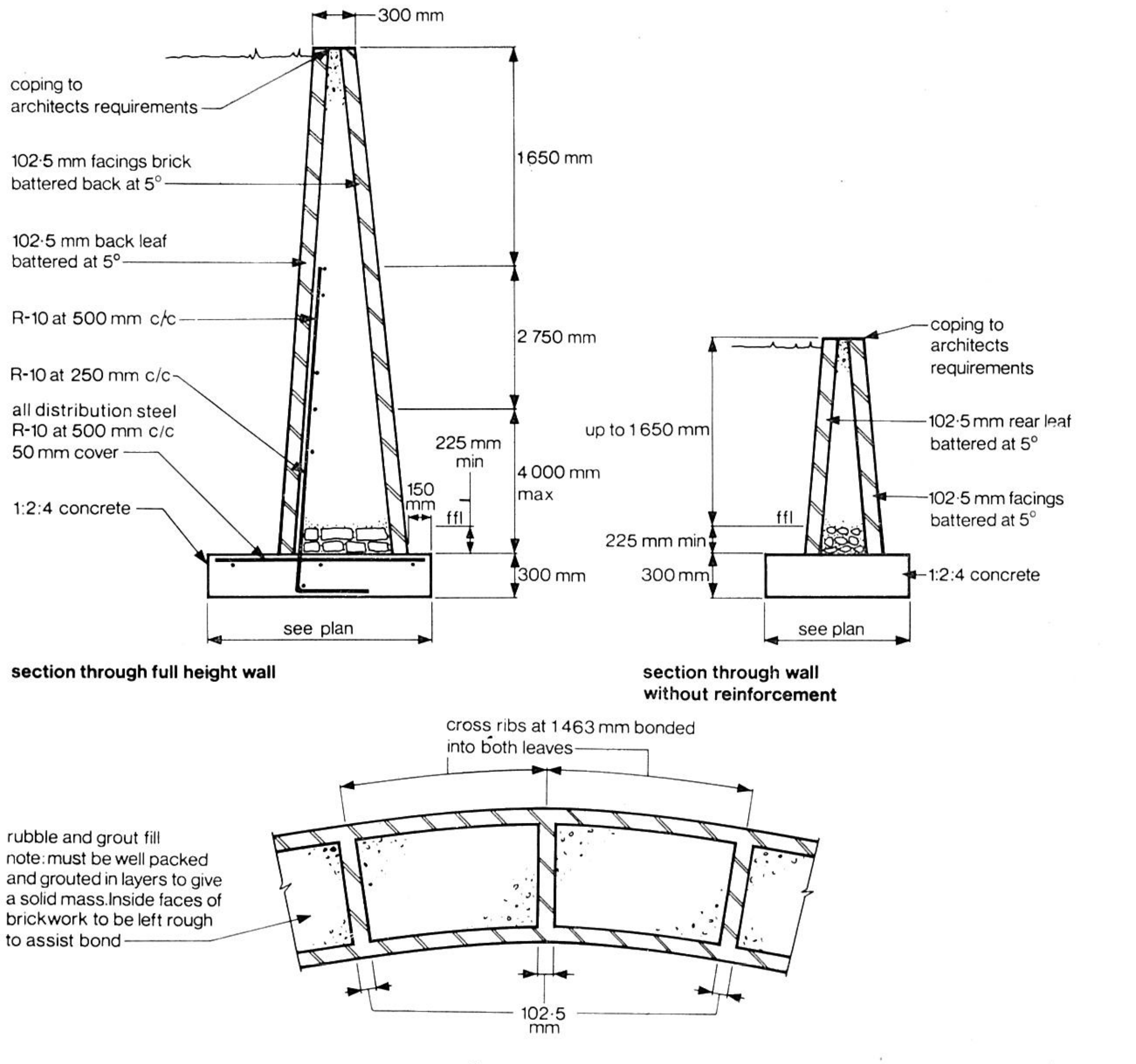


Figure 13

Shown adjacent (fig. 15) is a construction bar chart which shows a comparison between the two methods of construction. It is self explanatory, but could be argued over for hours. They were both almost identical sized contracts.

With the traditional method of construction we found that the steel frame sub-contractor would never admit that he employed sub-contractors, and sometimes lump labour for fixing of the vertical cladding and roof sheeting; but from the lack of control that he executed over them it was quite obvious.

Consequently the contract lagged behind between weeks numbers 8 to 19. As can be seen it dragged on the 26 weeks while the diaphragm walled building was completed in 19 weeks.

The further advantages then continue on site, as with the traditional method large and deep column bases have to be excavated, with all the trials and problems of keeping the excavation free from water. By comparison, the diaphragm construction can be founded on a wide strip footing more often than not in quite a shallow trench, as the calculations show the pressures are surprisingly small with this type of construction.

It must also be remembered by the general contractors that with the diaphragm construction it is not necessary to provide storage space for such components as asbestos or metal wall cladding; also the secondary linings and insulation most of the latter will require undercover storage. These are always difficult materials to store; invariably the sub-contractor delivers them to site far too early in the contract, and the general contractor being responsible for their storage is often blamed and is forced to pay for any damages incurred.

Also, it is well known that asbestos and other externa

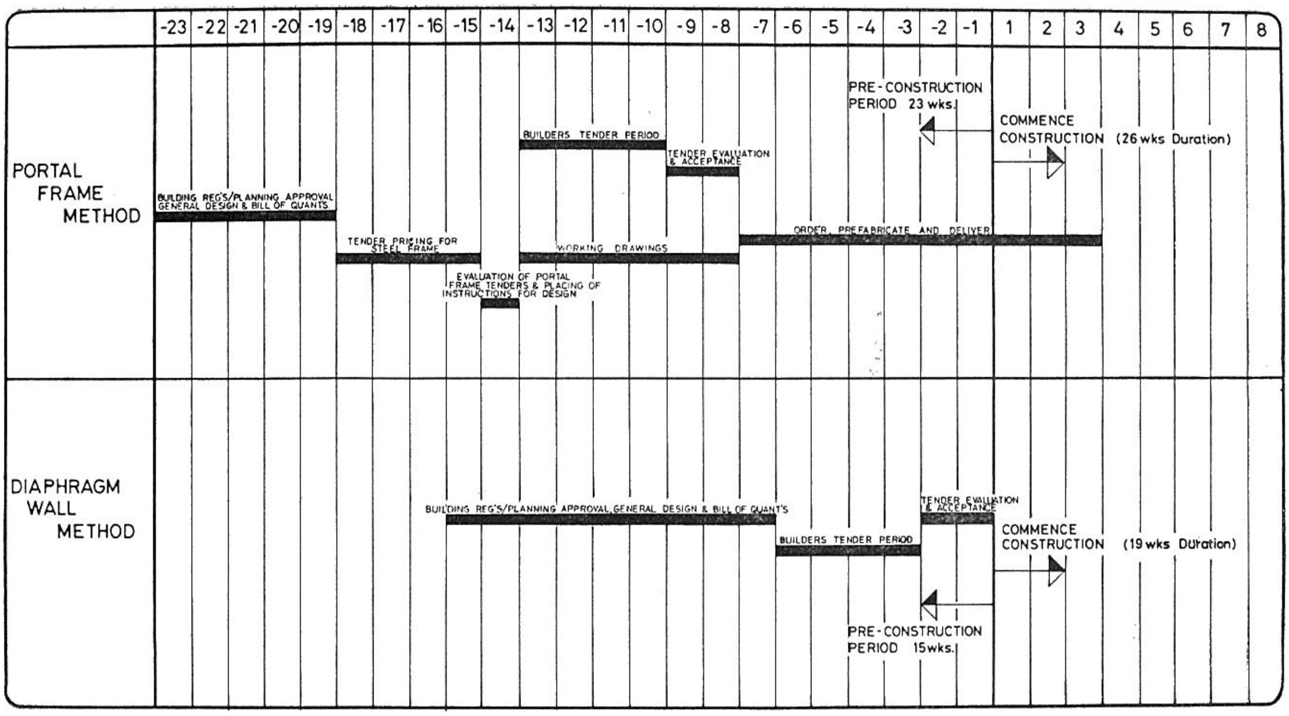
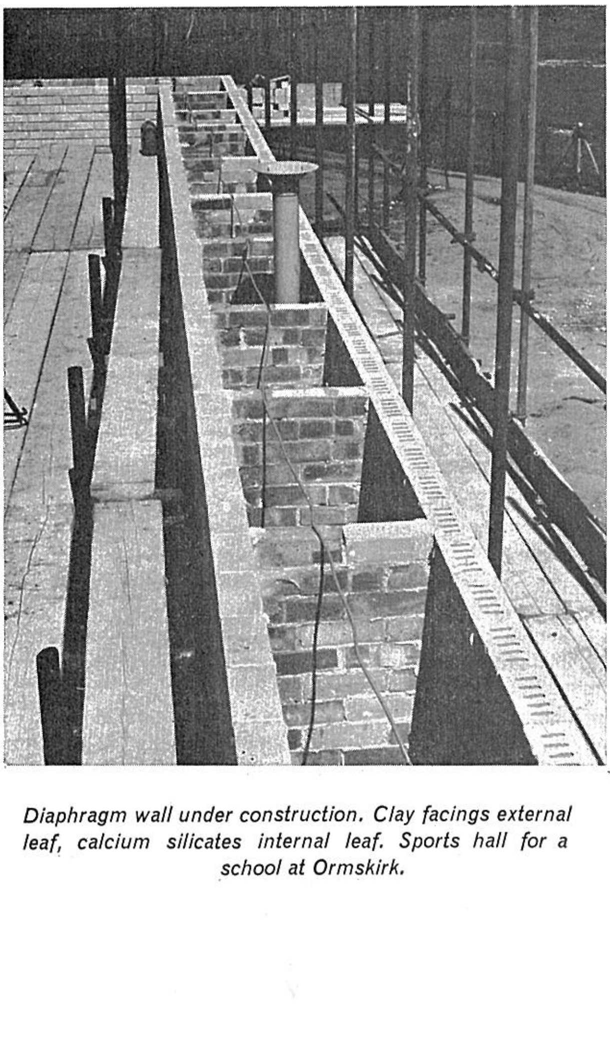


Figure 14



Diaphragm wall under construction. Clay facings external leaf, calcium silicates internal leaf. Sports hall for a school at Ormskirk.

wall cladding crack and are damaged easily. The repair of this type of damage is always a source of constant irritation between the architect and builder, especially during the maintenance period.

Once the diaphragm walls have been constructed, not being restricted to the portal frame the architect is given considerable variation in the choice of roof finish. The roof can consist of either concrete beams pre-cast or pre-stressed, a space frame, steel lattice beam or castellated beams. For a sports hall I would venture to suggest a more novel construction, this being a glue laminated beam with a timber boarding finish topped with 12 mm of insulation and 19 mm asphalt.

In my opinion there is no doubt that the diaphragm wall method of construction is far swifter than the traditional method. It is a stronger construction, has smoother and more flowing lines and gives the building an aesthetic and maintenance free appearance. It is not as susceptible to vandalism as it presents the vandal with a smooth clear surface externally with no projections, therefore no hand or toe holds whatsoever. It gives a far greater resistance to the vandals' bricks and stones than the traditional method of cladding and is therefore an ideal type of construction for the four categories of building already named.

QUANTITY SURVEYOR COST IMPLICATIONS

Introduction

My Partnership has been involved, during recent years, in a number of sports hall projects, some of the most successful being designed on the diaphragm wall principle (either by good design or by good fortune!).

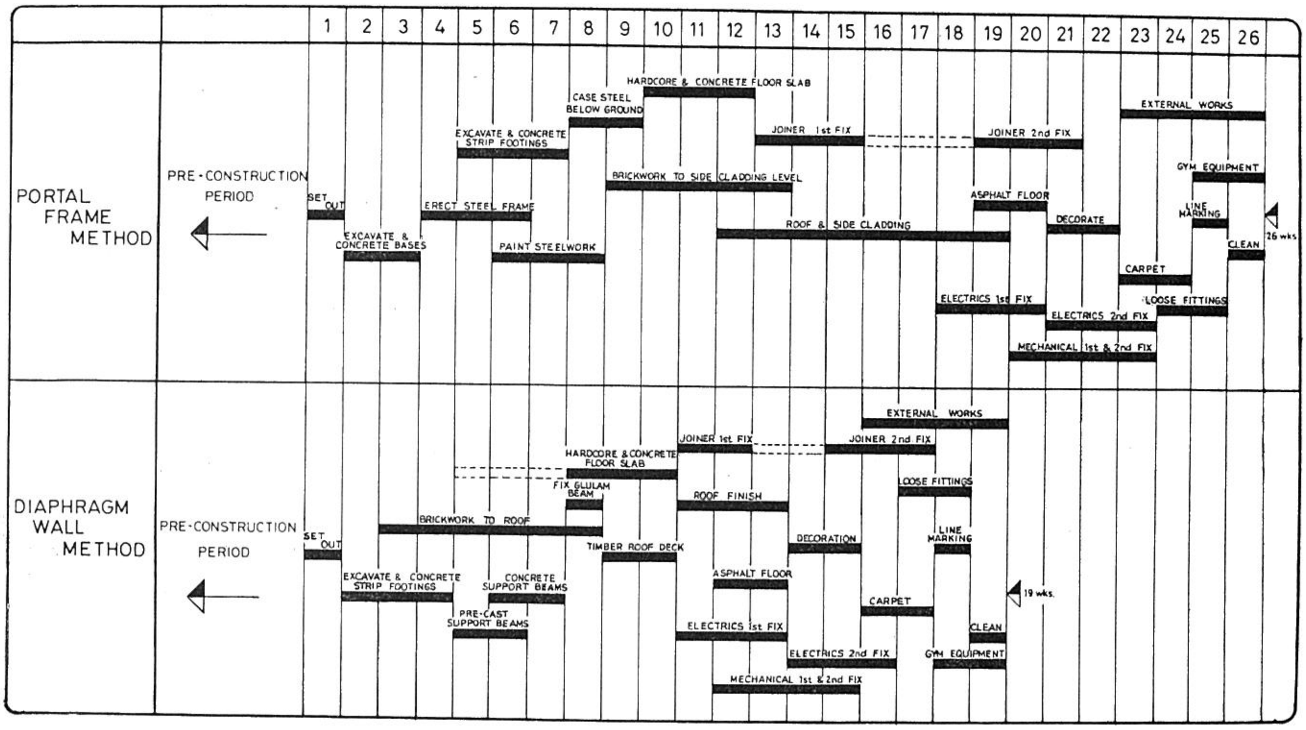


Figure 15

Consequently, I know through real experience that, given the usual requirements in the brief, i.e.:

(a) Moderately good quality building standards,
(b) Solid, smooth and easily maintained internal wall surfaces,
(c) Fairly tall buildings, but only of a medium to small span,
(d) Reasonably 'light and airy' internally with top natural ventilation,

then apparently one of the most simple solutions can be a load-bearing brick external wall with a 'roof-lid' of various types.

Stating the obvious, a flush internal brick face (or blockwork if so desired!) offers a very satisfactory 'game-surface', along with an easily maintainable material, and a simple solution for the many, very necessary, internal wall fixings.

Naturally, having had this experience, you can imagine my surprise when it was suggested to me that the method of diaphragm walls could be applied in the industrial field. I was, to say the least, sceptical!

Industrial Buildings

For the past ten years I have been very much involved in the design and construction of industrial buildings for the property developer, Government agencies, and also for the industrialist direct. My initial cost advice always started the same way when being involved in the very first design team meetings, i.e. I would say "What is the span? – Keep to 'the standard' 6 m grid for stanchion positions", naturally assuming that the resultant design would involve a steel (or sometimes precast concrete portal (propped or clear) frame. I had it firmly in my mind that the designer, for sound economic reasons, would always have to use a 'framed' solution to his problem, and that really our work was contained to obtaining the most economic frame in that particular tender climate, and then carrying out cost exercises to advise the designer on the cheapest acceptable metal cladding and asbestos/metal roof decking. We were very often 'troubled' to find that some of the elevations had to be brickwork, due to very understandable building control, and/or fire regulation requirements! In any event, a great deal of the steel portal legs had to be encased in some material or other, but we accepted this as one of those anticipated costs when designing an industrial unit.

I describe all this because I must confess the penny hadn't truly dropped that perhaps all these 'difficult', 'costly' brick elevations could be used, in the diaphragm form, to support the roof! – even when building industrial warehouses and factories!

Industrial Building Cost Examples

So initially, with my colleagues' help, I carried out two cost comparison examples. For the traditional construction we based the design, and therefore the costs, upon typical units that are found being designed and built by Government agencies. We felt that this was a fair standard for the exercise, as it represented the example of buildings being erected at this time (cost consultancy, in my view, should be mindful of particular design, as well as tendering climates).

BRIEF DESCRIPTION OF THE WORKS INCLUDED WITHIN EACH ELEMENT

TRADITIONAL CONSTRUCTION

Elem. No.

1. Supervision, small tools and plant, site accommodation, insurances and scaffolding.
3. Reduce level, trench and stanchion base excavation. Reinforced concrete floor slab thickened out for perimeter and party walls. Concrete stanchion bases.
4. Structural steel portal frame including decoration.
6. Steel 'Z' purlins supporting roof coverings comprising corrugated asbestos cement sheeting, insulation and overpurlin plasterboard lining and incorporating approximately 10% Filon roof lights, complete with necessary asbestos rainwater goods.
9. 270 mm thick cavity brick perimeter walls 1 m high with facing bricks externally and fair faced commons internally and capped with a precast concrete coping. Cladding above wall comprises pvc coated galvanised steel sheeting, insulation and plasterboard internal lining including all necessary mild steel sheeting rails.
10. Standard timber window frames complete with glass and decoration.
11. Plywood faced flush type exit doors with softwood frames, softwood glazed panel entrance doors with softwood frames and galvanised steel folding shutter type loading doors all including necessary decoration.
13. One brick thick full height party walls with half brick thick encasing to internal columns, all in commons fair faced and flush pointed.

DIAPHRAGM WALL CONSTRUCTION

Elem. No.

1. Supervision, small tools and plant, site accommodation, insurances and scaffolding.
3. Reduce level and trench excavation. Concrete strip foundation for perimeter walls. Reinforced concrete floor slab thickened out for party walls. Brick diaphragm perimeter walls up to ground level.
6. Castellated steel roof beams complete with necessary bracing, steel 'Z' purlins supporting roof coverings as described under Traditional Construction and including decoration.
9. Brick diaphragm perimeter walls full height with facing bricks externally and fair faced commons internally with reinforced precast concrete ring beam at high level.
10. Standard timber window frames complete with glass and decoration.
11. Plywood faced flush type exit doors with softwood frames, softwood glazed panel entrance doors with softwood frames and galvanised steel folding shutter type loading doors all including necessary decoration.
12. One brick thick full height party walls with piers capped with padstones to carry roof steel.

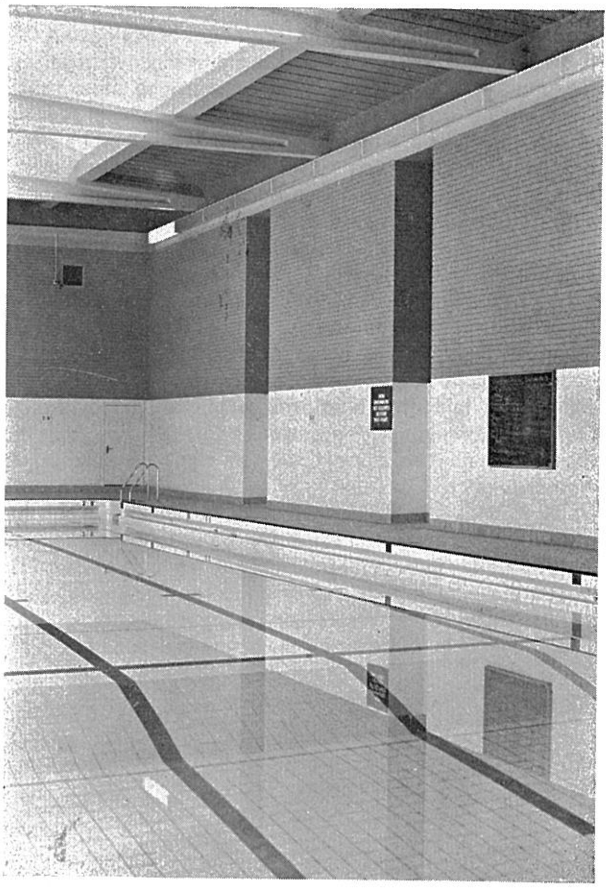
COST EXAMPLE 1
SUMMARY OF ELEMENTS

		TRADITIONAL CONSTRUCTION		DIAPHRAGM WALL CONSTRUCTION	
	Building Area – 2250 m²	Element Cost	Cost/m²	Element Cost	Cost/m²
Element No.	Element Description	£	£	£	£
1.	Preliminaries	8,321	3.70	10,317	4.59
3.	Substructure	20,917	9.29	18,572	8.25
4.	Frame..	13,437	5.97	—	—
6.	Roof	21,846	9.71	32,282	14.35
9.	External Walls	17,115	7.61	23,574	10.48
10.	Windows	550	0.24	1,290	0.57
11.	External Doors	3,615	1.61	3,540	1.57
12.	Internal Structural Walls ..	—	—	9,846	4.38
13.	Internal Walls	9,359	4.16	—	—

NOTES:

(a) Diaphragm wall construction in above example is approximately 5% more expensive.

(b) Toilet accommodation, heating and electrical installations, drainage and external works would remain similar in capital cost for each type of construction and are therefore not included above.



Swimming pool, Turton School. Roof structure is pre-cast concrete beams 6m centres supporting a domed roof light.

There will be those who will view these examples as yet another quantity surveyor's hypothetical exercise. True, these are based on 'general' price information but do have the advantage of being based upon accurate quantities and with a 'second estimator's opinion' (i.e. Tyson's estimating department!).

However, the point of this paper is not to provide a complete alternative to the designer of industrial buildings but merely to suggest a real viable alternative method of construction, which with further nationwide usage, will provide flexibility of choice.

We were convinced that this alternative would only stand examination of costs for large, tall industrial buildings, i.e. building which had great areas of wall enclosures. No so. A recent 'real' pre-contract design/cost estimate exercise has shown that the small 'starter factory' may also be considered for use of the design.

Quantity Surveyor's Observations

It would be very wrong of me if I didn't tell you of some of the questions and points that come to the mind of a Quantity Surveyor when faced with this type of construction. I was truly surprised with my cost exercises, which proves one can never be too sure, but I must stress that there will be different types of Contractor who will probably not agree that the diaphragm wall construction is competitive. However, as we have seen, Mr. Harper is quite convinced that his Company is happy to build diaphragm walls competitively, and it would be a brave man to say his Company was wrong! I think that the average Contractor's attitude is generally going to be the same as Mr. Harper's, that is, if they have a good spread of tradesmen, then they are very happy to take on the so-called 'brick' job.

Some Contractors will cry, "What about the speed, and what about getting roofed in quickly, as you do with a framed building?" Well, besides saying brickwork isn't always very slow, and can be quite the opposite, what does one want to get an industrial 'shed' roofed in

COST EXAMPLE 2

SUMMARY OF ELEMENTS

		TRADITIONAL CONSTRUCTION		DIAPHRAGM WALL CONSTRUCTION	
	Building Area – 1440 m²	Element Cost	Cost/m²	Element Cost	Cost/m²
Element No.	Element Description	£	£	£	£
1.	Preliminaries	5,949	4.13	7,447	5.17
3.	Substructure	14,253	9.90	12,745	8.85
4.	Frame..	13,901	9.65	—	—
6.	Roof	20,509	14.24	28,399	19.72
9.	External Walls	7,450	5.17	16,053	11.15
10.	Windows	3,330	2.31	3,210	2.23
11.	External Doors	861	0.60	861	0.60

NOTES:

(a) Diaphragm wall construction in above example is approximately 4% more expensive.

(b) Toilet accommodation, division walls, heating and electrical installations, drainage and external works would remain similar in capital cost for each type of construction and are therefore not included above.