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**DESIGN OF INTERLOCKING BRICKS  
FOR ENHANCED WALL CONSTRUCTION  
FLEXIBILITY, ALIGNMENT ACCURACY  
AND LOAD BEARING**

**A thesis submitted in partial fulfilment of the requirements of  
the degree of Doctor of Philosophy in Engineering**

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## **ABSTRACT**

The worldwide housing shortage has stimulated a search for appropriate, easy, fast and cost-effective new ways of wall construction. Among many technologies found to have promise is mortarless technology using dry-stack interlocking bricks/blocks.

This thesis is about such mortarless walling technology and in particular: how to improve wall-construction flexibility, the effects of brick irregularities on wall alignment accuracy and wall behaviour (stiffness, strength) when subject to lateral forces.

The flexibility of mortarless technology (MT) has been enhanced by the development of new bricks (centre-half bat and tee brick): the introduction of closer bricks led to the formation of two new bonds (patterns) namely Shokse and Lijuja bonds. It is now possible to construct more than half-brick-thick walls, to attach more than half-brick-wide piers (buttresses) onto walls, and, using special bricks, to construct polygonal and curved walls using interlocking bricks.

Three methods (theoretical modeling, physical experiments and computer simulation) were used to analyze the effects of brick imperfections on wall alignment accuracy. Theoretical analysis confirmed that brick moulders should concentrate on achieving parallel top and bottom faces rather than achieving true square-ness.

Physical column assembly compared three brick-laying strategies namely: “random”, “reversing” and “replace”. The columns assembled using the “reversing” and “replace” strategies realized alignment improvement factors of 1.6 and 2.9 respectively over “random” strategy. The research also revealed that grooving, to prevent bricks making contact near their centre lines, improved column alignment by factor 2.13 and stiffness by factor 2.0, thus allowing construction of longer and higher walls without strengthening measures.

In order to attain alignment accuracy in accordance with BS 5628-3:2005 in a dry-stack mortarless wall, this research recommends using full bricks with top and bottom surface irregularities not exceeding  $\pm 0.5\text{mm}$  for un-grooved bricks, and up-to  $\pm 0.9\text{mm}$  for grooved bricks.

Further analysis was undertaken with respect to resource-use implications (cement, water, soil) of employing MT. Using MT will save 50% of wall construction cost and 50% cement consumption, which ultimately will reduce 40% of carbon emissions.

## **DECLARATION**

This declaration confirms that this thesis is original and sole work of the author alone.

The thesis does not include any previous material submitted by any other researcher in any form not acknowledged as required by existing regulations.

No material contained in this thesis has been used elsewhere for publication prior the production of this work.

This declaration also officially affirms that this thesis is being submitted for the degree of Doctor of Philosophy of the University of Warwick only and not to any other similar institution of higher learning for the same purposes.

## LIST OF ABBREVIATIONS AND VARIABLES

Note: Variables are in Italics

$\frac{1}{2}B$	Half bat
$\frac{3}{4}B$	Three-quarter bat
$A_{ef}$	Effective surface area
$A_{nom}$	Nominal surface area
BIB	Burnt Interlocking Brick
$B_n$	Number of bricks selected from a set
$B_s$	Set of bricks
BS	British Standards
$C\frac{1}{2}B$	Centre half bat
C1	Column built using random strategy
C2	Column built using reverse strategy
C3	Column built using replace strategy
CEB	Compressed earth bricks
CSSB	Cement soil stabilised blocks
C: S	Cement to Soil ratio
$D$	Spacing between brick contact points
$E$	Young's modulus of brick material
Eq	Equation
FB	full brick
$F_{const.}$	Constant load
$f_{cw}$	Wall compressive strength
$g$	Mass due to gravity
$G$	groove width
GB	Grooved brick
GBC	Grooved brick column
$h$	Intermediate height of structure
$H$	Height of a structure
$I$	Second moment of area of brick face

ISSB	Interlocking soil stabilised brick
IB	Interlocking brick
$L$	Brick length
$LL$	Liquid limit
$LS$	Linear shrinkage
$M$	Moment
MBC	Mortarless brick construction
$M_f$	Moment caused by applied force
MPa	Mega Pascal
$M_w$	Moment caused by weight
$N$	Number of courses
NB	Normal brick
NBC	Normal brick column
NHBRA	National Housing and Building Research Agency
OMC	Optimum moisture content
$O_{st}$	Osteomophic
OPC	Ordinary Portland cement
P&D	Protrusions and depressions
$S$	Sensitivity
SD	Standard deviation
ST	Stack
$t$	Thickness/Height deviation from ideal
$T$	The ideal brick thickness/height
TB	Tee brick
TE	Theoretical equation
T&G	Tongue and grooved
TIB	Tanzanian interlocking brick
VITA	Volunteer in Technical Assistance
$w$	Weight
$W$	Brick width (depth of column/wall thickness)
$x$	Horizontal deflection of the top brick from wall plumbline

$y$	Height error of structure (wall/column)
$\alpha$	Internal angle between brick bottom and front surface (refer figure 6.1)
$\beta$	Internal angle between brick top and front surface (refer figure 6.1)
$\chi^2$	Chi-Square
$\delta$	Horizontal deflection of the front top edge of the $i^{\text{th}}$ course from its bottom edge
$\gamma$	Role 'wedge' angle formed by top and bottom surfaces of a brick
$\eta_o$	Ratio of effective to nominal areas
$\lambda$	Brick-set size divide by column/wall height (n – course number)
$\omega$	An interface angle between to merged surfaces
$\theta$	Face angle formed by deflected $N^{\text{th}}$ course in reference to plumb line
$\rho$	Density
$\sigma_\gamma$	Standard deviation of wedge-angle
$\sigma_{ef}$	Effective stress
$\sigma_{nom}$	Nominal stress



# CHAPTER 1

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

#### 1.1.1 HOUSING DEFICIT

Housing is one of the basic human needs and is usually ranked third after food and clothing. In most developing countries housing is inadequate and the housing backlog has been increasing rapidly. One key reason for housing inadequacy is the increase in population Racodi (1997). It is estimated that the World's population is rising weekly by more than a million people, a rate that new construction does not match *Earth from the air*. [Online]. (URL <http://www.earthfromtheair.com.html>). 2004. (Accessed 15 December 2004) due to the high pace of urbanisation and socio-economic factors that include the rise in prices of land and building materials, Those classified as poor are the majority and they cannot afford proper housing *McAuslan (1985)*. The outcome of this can be seen by the poor quality of the houses of this majority in both urban and rural environments (*Gilbert & Gugler 1992, Basu 1988*).

The provision of affordable housing for the poor needs to be facilitated through the development of innovative strategies (*Webb 1983, Hamdi 1995*). The persisting problem for urban housing authorities in Africa is the worsening condition of slums and squatter settlements due to the high rate of population growth. Public provision of mass low-cost housing is always far below the actual demand *Maasdorp & Humphreys, (1975)*. The situation is being exacerbated because the more city facilities are improved; the faster is

rural-urban migration. This must not be considered for its negative impact only, but should be regarded as an inevitable and irreversible consequence of continuing development *Spence & Cook, (1983)*.

### **1.1.2 POVERTY**

Despite the fact that most African countries have large resources of indigenous building materials, to date the housing situation has not improved, due to economic hardship. New housing by its nature requires capital. World trade market data shows that between 1990 and 2000 the capital of the 50 poorest countries fell from 4% to 2% of global capital *Earth from the air*. [Online]. (URL <http://www.earthfromtheair.com.html>). 2004. (Accessed 15 December 2004). Several studies have revealed that more than 50% of African people live below the poverty line, and more than 80% of the population living in rural areas have poor shelter as well as inadequate sanitation, transport and communication systems. About 70% of the urban population now lives in slums and squatter settlements, which lack the basic facilities for a decent life *World Bank, (1995)*. Worse, is the continent's dependence on imported building materials that are too expensive for the poor majority to afford.

*Example:* Tanzania is one of 20 poorest countries on earth. In the year 2000, the annual housing demand was about 800,000 units, but supply was below 20% of this figure. In that year there were about 9.8 million urban dwellers needing about 2.4 million housing units. The actual number of units built was only 0.6 million indicating a 75% deficit *URT – NHSDP, (2000)*. This poor situation is reflected in other developing countries.

### **1.1.3 APPROPRIATE HOUSING SOLUTIONS**

However, researchers worldwide have made significant efforts to find sustainable and affordable technologies to arrest the situation. The best approach so far is the development of technologies to increase the utilization of locally available building materials.

Appropriate solution for affordable housing will vary from one location to another. Some general rules, however, apply to construction methods and housing systems. Affordability and availability of course are the basic requirements for the low-cost housing industry (*Harlae and Marten, 1990, Laquian, 1983, Spence & Cook, 1983*). But, the cultural backgrounds and the particular needs of the communities must also be considered. With the increasing rate of unemployment in Africa, there is still a need for labour-intensive production methods in some parts of the industry. To enable the community to profit from construction projects, systems making effective use of unskilled labour and local resources are usually the most appropriate.

Development of appropriate technologies for the production of low-cost building materials of good quality will speed up the provision of affordable urban housing in developing countries. One such technology is the use of stabilised-soil bricks. These have been in use in developing (African) countries for many years and have passed various stages of improvement in the production processes and quality of the products.

### **1.1.4 EARTH WALLING**

Recent research has been conducted at Warwick University (*Gooding 1994, Kerali 2001, Montgomery 2002*) on building materials for low-cost housing, including literature reviews from the 18<sup>th</sup> century to the end of 20<sup>th</sup> century, on the use of earth or soil as a dominant building material. It was found that soil can be much improved through stabilisation. The

durability of cement soil stabilised blocks (CSSB) can further be improved by using best-practice curing regimes *Kerali, (2001)* and their strength increased by impact compaction, which gives better material consolidation than simple pressing *Montgomery, (2002)*. *Burroughs, (2001)* discussed selection of soil for wall construction and made a contribution to the development of stabilised soil for rammed-earth walls. A valuable survey by *Maniatidis & Walker, (2003)* shows clearly the development of rammed-earth construction worldwide. The economic analysis in these various studies suggests use of earth material for wall construction will continue and that such material will remain a cost effective and low-energy alternative to more 'modern' walling materials in the coming centuries.

### **1.1.5 MORTARLESS WALL BUILDING**

Mortarless brick construction, usually employing interlocking bricks, is growing in popularity round the world, indicative of acceptability. Mortarless techniques demonstrate the following advantages: increase of construction productivity (*Grimm 1974, Whelan 1985*), reduction in construction duration and labour (*Anand & Ramamurthy 2003, Ramamurthy & Nambiar 2004*) and reduced construction cost. Because of its technological simplicity and local resource dependence, mortarless-brick construction is more appropriate to many local communities than conventional mortared-brick techniques.

Designers have developed machines of different types (manually operated, hydraulic, electrically operated, automatic or semi-automatic) for producing different shapes and sizes of stabilised-soil bricks/blocks for Mortarless wall: *Allan block system, Auram system, Bamba systems and Haener blocks, Hydraform systems, Putra blocks and Solbric systems etc.* A variety of interlocking brick/block shapes was analysed by *Thanoon et al. (2004)*,

*Ramamurthy and Nambiar (2004)* concluded that a key requirement of interlocking bricks, if they are to improve construction by semiskilled labourers, is that they be *self-aligning*.

The Interlocking Stabilised-Soil Brick (ISSB) is a technology that pioneers the idea of dry-stacking bricks during construction; hence they are called mortarless bricks. *Montgomery, (2002)* assume mortarless construction is a good idea but only if it is used in conjunction with in-wall curing of very-low-cement homogenous blocks. For this technology to be successful the bricks require very high dimensional accuracy. The cost of construction of a wall using ISSB is estimated to be 40% lower than that using more conventional materials (*Etherington 1983, Hines 1992, Anand & Ramamurthy 2003*).

## **1.2 RESEARCH JUSTIFICATION**

Interlocking bricks may be made of fired clay or cement-stabilized soil (sand). They are usually manufactured by a process using presses rather than slop-moulds, in order to achieve greater uniformity. In Africa this would make them uncompetitive with conventional clamp-fired bricks, were not the latter being adversely affected by growing firewood scarcity, and the high price of the cement for the mortar.

Production and laying of ISSB are labour intensive, making use of unskilled labour. Apart from saving cost, this will create more jobs and empower youth. Moreover building with ISSB reduces the use of industrial products like cement and depends on local resources. It is considered to an environmental friendly technology, because it consumes less production energy, reduces deforestation, reduces the use of non-renewable resources and produce less waste from construction process than the main walling alternatives (fired bricks, cement-sand blocks) *Walker, (1995)*.

However concerning ISSB, little has been published about:

- Modes of deterioration,
- Failure mechanisms,
- Maintenance requirements,
- Construction procedures
- Architectural (design) flexibilities,
- The relationship between brick accuracy and wall alignment, and
- The stability and stiffness of mortarless wall (*Marzahn, 1999*).

These unknown parameters need to be established by experimentation.

The objectives of the work reported in this thesis were to investigate: -

- ISSB wall architectural flexibility in terms of patterns, bonds and buildable configurations.
- Factors that influence the accuracy of mortarless walls.
- Stability and stiffness of mortarless wall during and after construction.
- Maximum height and length of ISSB walling that can be managed before requiring strengthening,
- Economics of ISSB walls compared to conventional systems.

Forecasting the prospects for ISSB use in developing countries is difficult *Croft, (1993)* because existing building standards, regulations and rules create negative attitudes towards new technologies *Beall, (2000)*. However the adoption of new technologies requires enough time to prove their durability and advantages compared to existing ones, so it may take

decades before they are widely accepted (*Kua and Lee 2000, Spence & Cook 1983*). The role of the building industry should be both to develop and adopt beneficial changes *Housing Forum, (2001)*.

### 1.3 RESEARCH METHODOLOGY

The research recorded in this thesis employed three main methods, namely:

1. Literature review
2. Survey of existing structures built of ISSB (mortarless bricks) and design of a more (architecturally) flexible form of ISSB.
3. Analysis, and experimentation;
  - a. Theoretical analysis of dry-stacking of interlocking bricks,
  - b. Physical testing of using half-scale interlocking bricks and
  - c. Computer simulation of dry-stacking interlocking bricks into walls and columns.

### 1.4 STRUCTURE OF THE THESIS

The thesis is presented in seven chapters as follows:

**Chapter 1** introduces the research topic, constructs the rationale for the study, and develops the objectives of the research.

**Chapter 2** has the literature review that surveys the existing knowledge of “Mortarless Technology”, and presents a history of interlocking bricks. The review identifies the knowledge gaps that determined the work developed in chapters 3 to 7.

**Chapter 3** discusses the benefits of using MT to minimise environmental impact. It analyses the cost comparison between mortarless technology and conventional.

**Chapter 4** describes the many patterns/bonds used by tradition bricklaying (compared to the only one bond used by mortarless technology before this research). The design of new ISSB parts enabled the invention of two new brick-bonds and the application of ISSB to a wide range of conventional bonds. The chapter demonstrates the performance improvement in the construction of variety of joints, thicker walls, and different wall configurations i.e. polygon, curve etc.

**Chapter 5** discusses the types of brick irregularity, their causes and remedial measures to reduce them.

**Chapter 6** describes the series of laboratory experiments performed in this research. It addresses the variables to be measured and the measuring techniques that were employed to obtain the required test results. It relates theoretical analyses to physical experiments and scrutinises disagreements between them with the help of the computer model. It draws conclusions concerning the relationship between the variability of a wall and the accuracy of the ISSBs with which it is built.

**Chapter 7** theoretically analyses the difference between solid column and dry-stacked column subjected to lateral forces. It relates theoretical analysis to physical experiment.

**Chapter 8** summarises and comments on the thesis findings. The chapter also highlights the applications of the research findings and identifies areas for further research.

**The References** are presented at the end of the thesis.



# CHAPTER 2

## 2.0 LITERATURE REVIEW FOR MORTARLESS CONSTRUCTION

This part of the thesis will go through the development history of interlocking bricks and the existing techniques, technologies and practices. It will try to identify the knowledge gaps in our topic of interest (“*Mortarless Technology*”- *MT for wall construction*) for planning the studies that constitute the new contribution reported in subsequent Chapters.

### 2.1 HISTORY OF INTERLOCKING BRICKS

Mortarless technology is directly associated with interlocking bricks: so the two terms will be used interchangeably. In this work we are going to deal with use of interlocking bricks, stacked dry to build a wall while observing building construction rules of proper bonding. *Bonding* is the arrangement of bricks in an interlocking pattern that result in a stable wall. The *stretcher bond* was the only (main) such pattern used in interlocking brickwork before this research.

The history of interlocking bricks started in the early 1900s with the construction of toys for children’s *McKusick (1997)*, *Love and Gamble (1985)*. Among the first inventors of toy systems that contributed to the mortarless technology (arrangement of parts that construct ideal structures) were:

- The Englishman Frank Hornby (1863 – 1936) of Liverpool, with Meccano sets.
- A.C Gilbert (1884 – 1962) of Salem, Oregon with Erector sets.

- Charles Pajeau who invented Tinker Toy construction sets in 1913. He was a stonemason from Evanston, Illinois, USA.
- John Lloyd Wright who invented Lincoln Logs in 1920.
- Ole Kirk Christiansen (1891 – 1958), who invented Lego.

From the beginning most toy mechanisms were designed to teach the principles of creativity and were a tool for learning scientific, engineering and architectural principles. The original materials used for toy construction were tin, metal, wood and clay, though now most toys are made from plastic. Of these various systems, Lego has the most similarity to walling. *“An Interlocking Brick construction for toys (Automatic Binding Brick) was first developed in Denmark in 1949. In 1951 the “Automatic Binding Brick” was renamed as “Lego Mursten” “Lego Brick” in English”, and first produced commercially in 1958” (Museum of American Heritage. [Online]. (URL <http://www.moah.org/exhibits/archives/buildex.html>). 2005 march 9. (Accessed 16 March 2006).*

The 1958 version of interlocking bricks with stubby cylinders and matching studs moulded into the surface allowed the Lego bricks to be firmly attached to one another (<http://inventors.about.com>). In 1967 a simplified version called “Duplo” bricks was launched: is the latest version available in variety of sizes, shapes and colours that form the basis for mortarless technology using interlocking bricks/blocks (*The history of Legos. [Online]. (URL <http://www.shop.lego.com>). 2006. (Accessed 21 March 2006).*

Since 1970s the interlocking mortarless bricks/blocks for house construction, made from sand-cement, stabilised soil and burnt/baked soil, have been pioneered in Africa, Canada, the Middle East and India.

## 2.2 INTERLOCKING MORTARLESS BRICKS/BLOCKS FOR HOUSE CONSTRUCTION

Interlocking bricks/blocks (IBs) can be produced as solid, perforated or hollow bricks. The demarcation between hollow and perforated bricks depends on the surface area of holes. If they occupy less than 25% of the surface area, they are called *'perforated bricks'*, if more we define them as *'hollow blocks'* (BS 6073-1:1981 clause 3.3). We can characterise bricks in terms of their solidity as follows: -

- The more solid the brick the more material required and the more powerful the press needed to attain enough brick density, but less binder will be needed for satisfactory brick strength.
- The more perforations, increasing up to 50%, the more binder will be required in the mix to achieve the higher strength needed for thin membranes formed onto a hollow block.

The two solidity characteristics of blocks above, each have extreme conditions that increase cost of blocks. The best percentage of perforation is that which minimise some combination of weight, material and the power requirement of the press. To reduce the cement/sand ratio in the mix for hollow blocks, the size of perforations should be reduced.

Interlocking requires a variety of shapes/parts to construct different wall joints. The existing commercial interlock designs have different configurations (Ramamurthy & Nambiar 2004, Dyskin et al. 2005, Thanoon et al. 2004, Croft 1993, Harris et al. 1992) and thus vary the number of part-bricks necessary to perform the same construction operations. Table 2.1 divides interlocking bricks/blocks into two groups, according to their locking systems. Category A bricks have interlocks that restrict movement both horizontally and transverse to

the wall surface, Category B bricks allow horizontal movement and only limit transverse movement during wall assembly.

Interlocking bricks have three types of locking (jointing) methods; Tongue and Groove (T&G), Protrusions and Depressions (P&D), and Topological non-planar locking. The T&G and P&D are the typical locking methods, while topological method is not a popular one.

**Table 2.1 Categories of interlock-brick systems**

<b>Category A Both horizontal and transversal brick movements restricted</b>	<b>Category B Free horizontal and restricted transversal movements</b>
Auram	Alan block
Bamba	Hydraform
Haener Interlocking System	Solbric
Osteomorphic	
Sparlock System	
Tanzanian	
Thai	

Before involving ourselves in the descriptions of interlocking bricks/blocks, let's be acquainted with the terms used in brickwork.

### **2.2.1 DEFINITIONS**

For the purpose of this research as per BS 6073-1:1981 clause 3.1.2, a *“brick is a masonry unit not exceeding 337.5mm in length, 225mm in width or 112.5mm in height”*. Units with more than these measurements to any of the sides are termed blocks. The following definitions also apply.

<b>Bat</b>	is a piece ( <i>formed by cutting perpendicular to the face</i> ) of a brick with a reduced length.
<b>Brick</b>	size measure equal to the length of one brick
<b>Centre-half</b>	is the piece ( <i>formed by cutting perpendicular to the brick face</i> ) of a brick left after removal of both end quarters.
<b>Closer</b>	is a piece ( <i>formed by cutting parallel to the brick face</i> ) of a brick with reduced width.
<b>Half brick</b>	a length equal to the width or half-length of a brick.
<b>Quarter brick</b>	a length equal to half the width or quarter the length of the brick
<b>Half-brick wall</b>	is a wall with thickness equal to half the length of the brick, e.g. a wall of bricks laid as stretchers.
<b>One-brick wall</b>	is a wall with thickness equal to a brick's length, e.g. a wall of bricks laid as headers

## 2.2.2 INTERLOCKING HOLLOW-BLOCKS

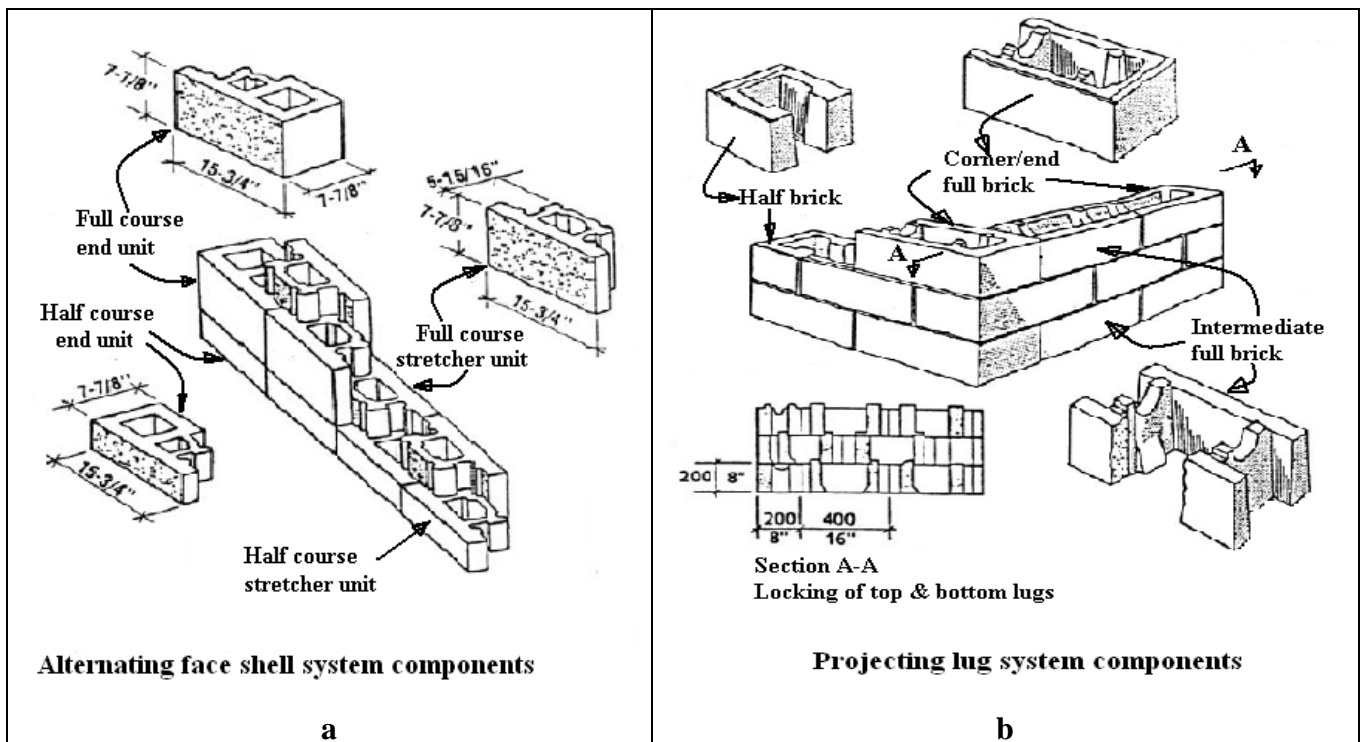
Interlocking hollow-blocks are made from sand-cement that can compete with conventional technologies in terms of quality, strength and cost. There are many promising types of interlock blocks in Canada, to mention just a few:

- Alternate face-shell components figure 2.1a, known as Sparlock system *Hines*, (1993).
- Projecting lug system components figure 2.1b, known as Haener system *Gallegos*, (1988) and *Harris et al.* (1992).

Figure 2.1 shows Canadian interlocking hollow-blocks with general measurements of 16" x 8" x 8" (400 x 200 x 200mm) representing more than thirty existing types as discussed by

Thanoon et al. (2004), and Ramamurthy & Nambiar (2004). Most of the interlocking hollow-blocks are used to replace formwork for casting reinforced concrete walls. The Sparlock system allows placement only of vertical reinforcements while the Haener system provides for both horizontal and vertical reinforcements. The normal material mix ratios (cement to sand/aggregates) for producing hollow blocks are richer than 1:10 due to the high strength requirements of thin block webs, and to withstand the pressure transmitted on placing concrete grout. The diagrams (Figure 2.1) illustrate the assembly of block units and how they fit to build a wall or formwork of a wall.

**Figure 2.1 Interlocking hollow-blocks**



The popular types of interlocking brick/block in Africa and Asia are made from stabilised-soil and are meant for low-cost housing. The following designs exist in the market: Thai interlocking brick; Solbric, Hydraform and Bamba Systems from South Africa; Auram system from India and Tanzanian type (see diagrams in Sections 2.2.3 to 2.2.8).

The above listed types of interlocking bricks were invented by different people at different times to reduce mortar costs, enhance construction productivity and wall characteristics (accuracy, stability and strength); achieved by the proper choice of production method, wall construction technique, and locking mechanism.

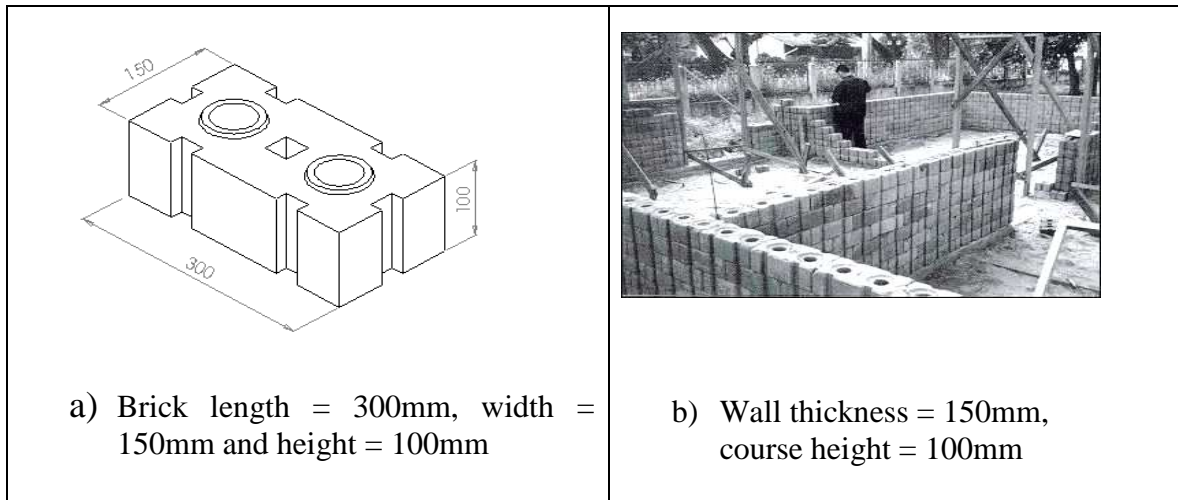
### **2.2.3 THAI INTERLOCK BRICKS**

The Thai interlocking brick (Figure 2.2) with dimensions 300 x 150 x 100mm, was developed in the early 1980s, by the Human Settlement Division of the Asian Institute of Technology (HSD-AIT), Bangkok, in co-operation with Thai Institute of Scientific and Technical Research (TISTR). This is an interlocking brick as defined in Section 2.2.1 (BS 6073-1:1981), although the developer calls it a block.

The Thai interlocking brick is produced using a modified CINVA-Ram manual press developed in Colombia in 1956 (*VITA 1975*). Figure 2.2b shows a wall with vertical grooves run through the full height that provide good keys for render. Vertical holes also run through the full height of a wall, serving the following purposes:

- They reduce weight
- They can house reinforcement or mortar to increase wall stability at chosen locations (corners, junctions, opening ends etc.)
- They may be used for electrical and communication conduits.

**Figure 2.2 Thai interlocking brick**



The grooves may however increase the amount of render required for internal plastering. The holes in combination with the grooves may reduce the overall strength of a brick and hence the strength of the wall built using these bricks. The locking mechanism is not well secured as the knobs and depressions are too small (<5mm). The strength of such interlocks depend on surface render, or on grout filled into vertical holes with additional reinforcements if need arises.

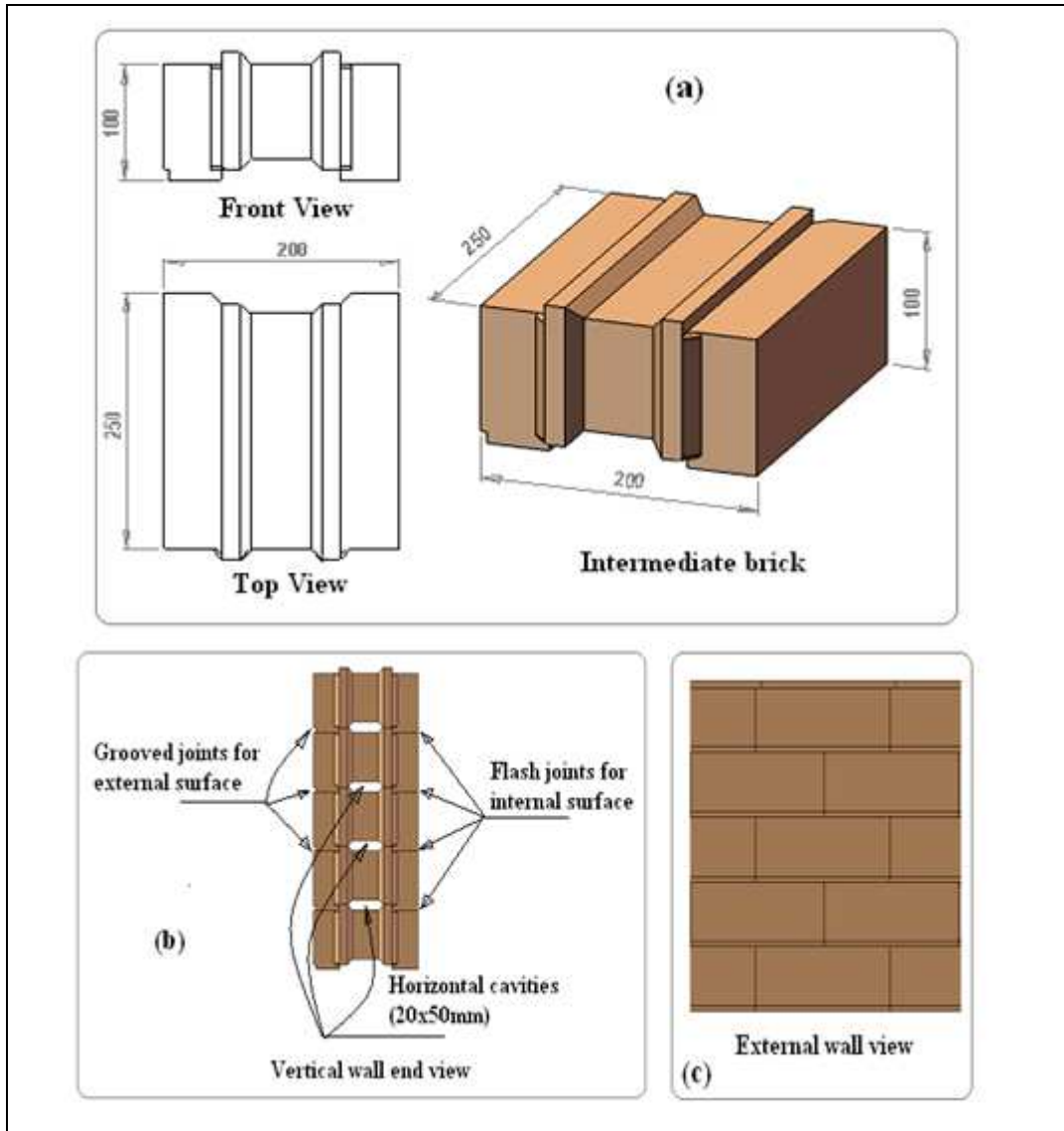
#### **2.2.4 SOLBRIC SYSTEM FROM SOUTH AFRICA**

The SOLBRIC system uses solid interlocking bricks (Figure 2.3a), formed by pressing on their ends (the compacting stroke moves parallel to the longer side), with guided or controlled width and height. In bricklaying, SOLBRICs are arranged at the normal bed surface (Figure 2.3c). The size of a SOLBRIC is 250 x 200 x 100mm. SOLBRIC provides small horizontal cavities between the courses (Figure 2.3b) in which conduits and pipes can be installed or reinforcements placed to strengthen the wall at certain locations (cill and lintel levels). The SOLBRIC wall has a flat internal surface and externally a pointed joint surface (Figure 2.3b) from the chamfered edges of the bricks on one side. The flat internal surface of SOLBRIC



reduces the thickness of required plaster mortar and the external pointed joint makes the external appearance attractive. However this difference means that bricks may not be reversed (front to back).

**Figure 2.3 SOLBRIC interlock brick**



Although the SOLBRIC interlocking brick system seems to be easy to use, the shape of the bricks and the parts made from the machine make it possible to build only the external walls because there is no means of connecting partitions i.e. of making a tee or cross joints. The small thicknesses (<15mm) of the vertical and horizontal tongues that provide the

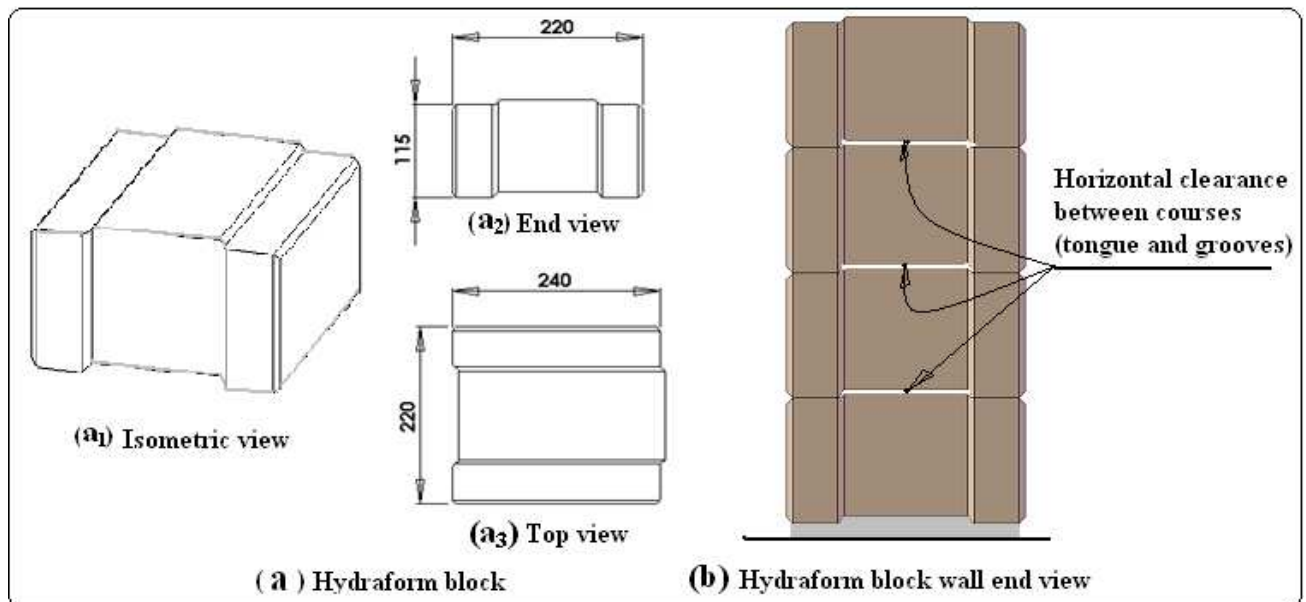
interlocking are questionable due to the material used (soil stabilised with cement that is brittle in nature).

### 2.2.5 HYDRAFORM SYSTEM FROM SOUTH AFRICA

Hydraform is the simplest type of interlocking block (Figure 2.4) in shape, when interlocked makes a tongue and grooved joint at the sides and top and bottom. Being free to slide along the course horizontally, it can be pushed along to achieve tighter perpends (vertical joints)

Figure 2.5.

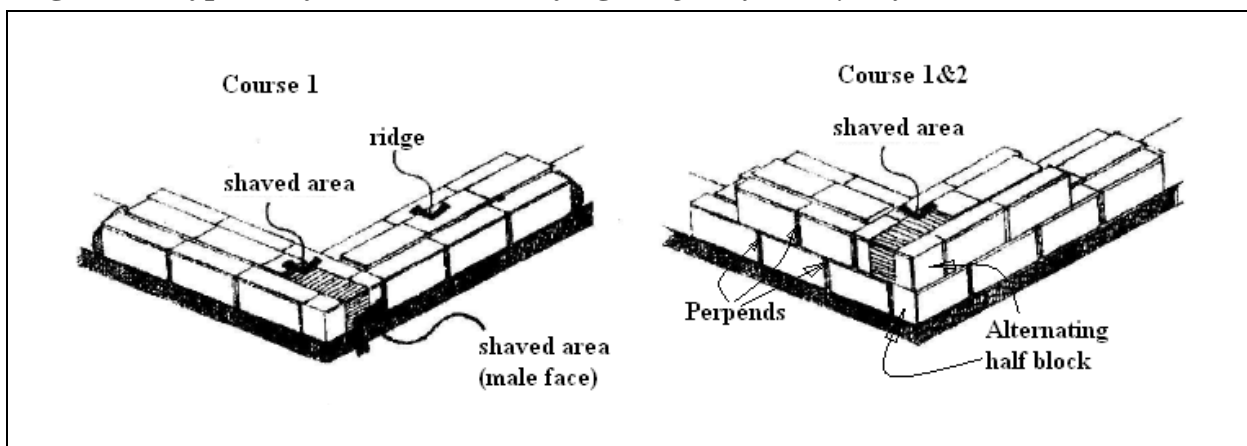
**Figure 2.4 Hydraform block**



Hydraform block is moulded by pressing along its length from the ends, as for the SOLBRIC. It is also a solid block, but slightly shorter, wider and thicker in size (240 x 220 x 115mm) than the SOLBRIC (Figure 2.3). The stability of the wall built from the Hydraform blocks is not provided by the locking mechanism but by the width and weight (massiveness) of the block. In production they require considerable power to mould (compress) due to their large volume, 30% more soil is used compared to the other five reported types. Moreover the

compression must be sufficient to allow a fresh block to withstand the squeezing forces occurring when it is manually moved from machine to the curing area. A powerful (moulding pressure 4MPa to 10MPa) and expensive motorised machine (*Hydraform Manual, 2004*) is required to compact such a volume of soil. This can be compared to the cheaper manual presses (with pressures under 2MPa) used to produce Bamba, Tanzanian and Thai types (*VITA 1975, Weinhuber 1995*).

**Figure 2.5 Typical Hydraform block-laying** (*diagram from Hydraform Manual 2004*)



The Hydraform blocks require some 'shaving' and/or chopping (Figure 2.5) if two blocks have to be laid perpendicular to each other (*this could have been included in the production process for time-saving at site*). A half bat to cover the tongue/male (Figure 2.5) is also required (*Hydraform Manual 2004*).

The longitudinal course joints (Figure 2.4b) of the blocks have a clearance of 1-1.5mm between the tongue/ridge and groove of the mating blocks. The reason behind this 'play' is easy of longitudinal sliding, to simplify the block-laying in order to achieve tight perpends (Figure 2.5). Apart from being stacked dry all other wall construction operations are as conventional bricklaying i.e. any compensation blocks are cut manually at site.

## 2.2.6 BAMBA SYSTEM FROM SOUTH AFRICA

The Bamba interlocking brick (Figure 2.6) is perforated, with protrusions and depressions. The top and bottom faces of Bamba brick have negative symmetry: configurations opposite to each other that allow them to fit (lock).

**Figure 2.6 Bamba interlocking brick**

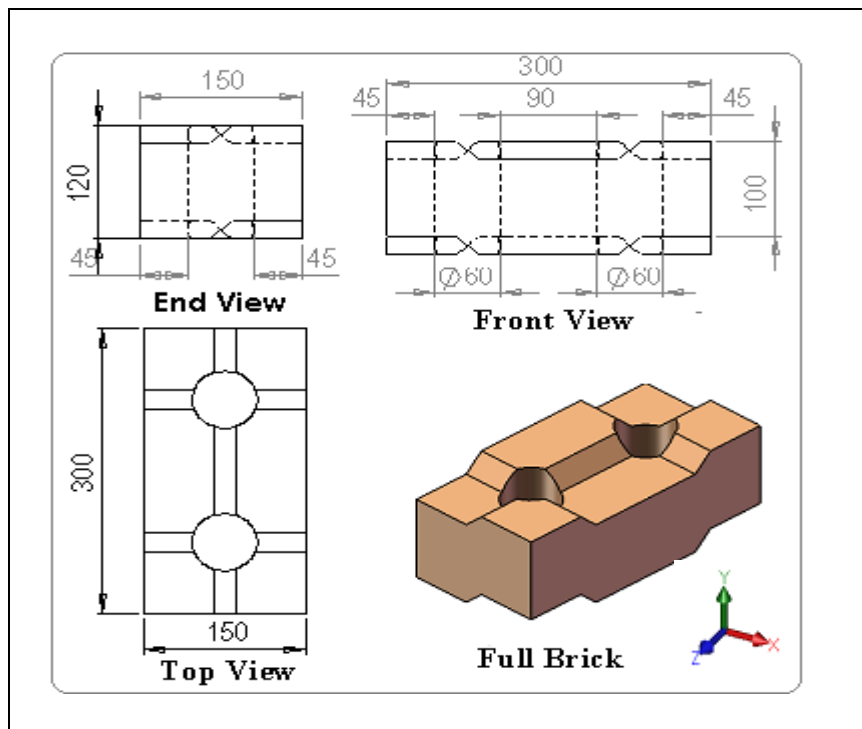
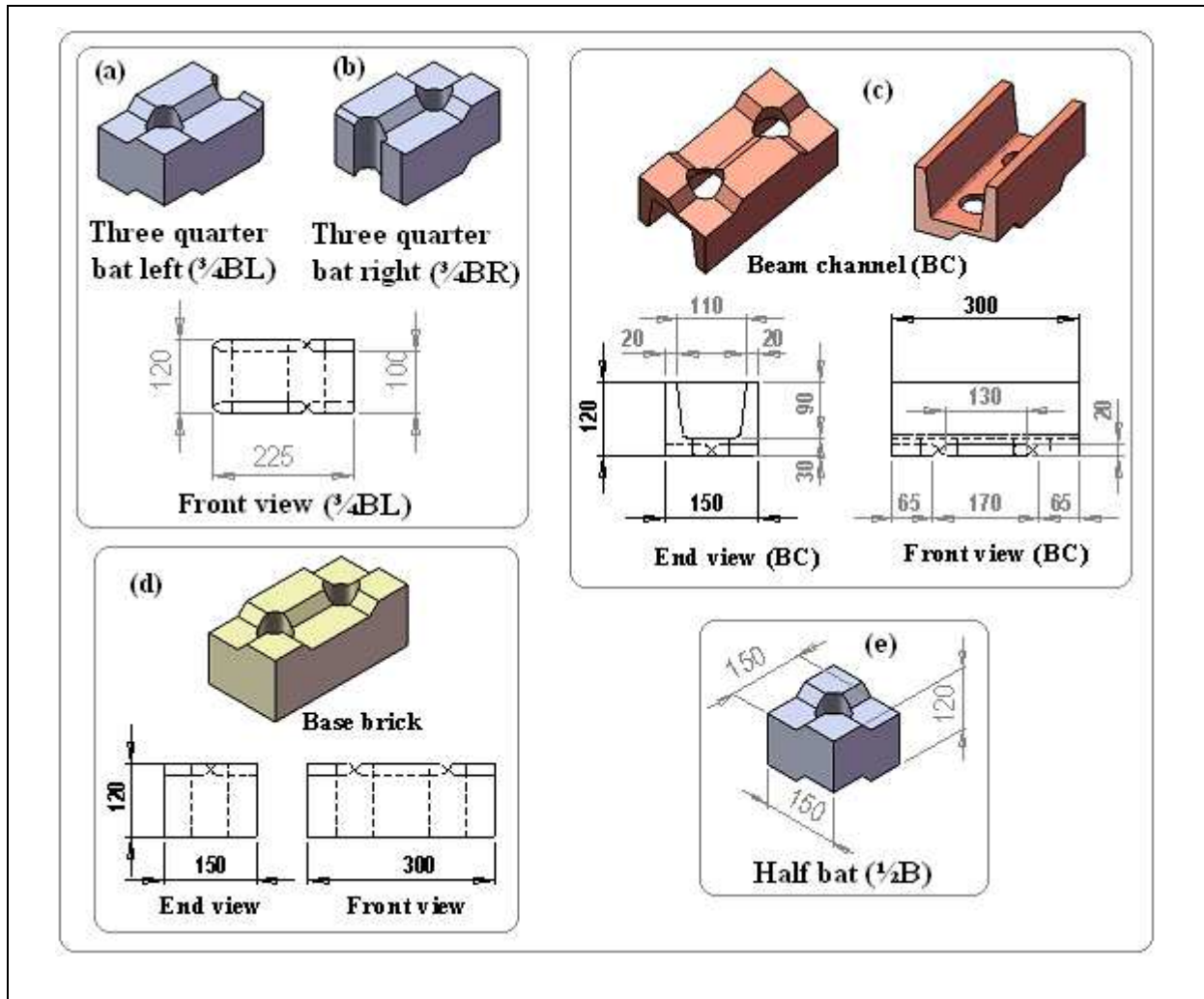


Figure 2.6, if the brick is rotated 180 degrees around its Z-axis, the bottom view will appear as top view; this give the option of reversing to find a better orientation or position during brick-laying.

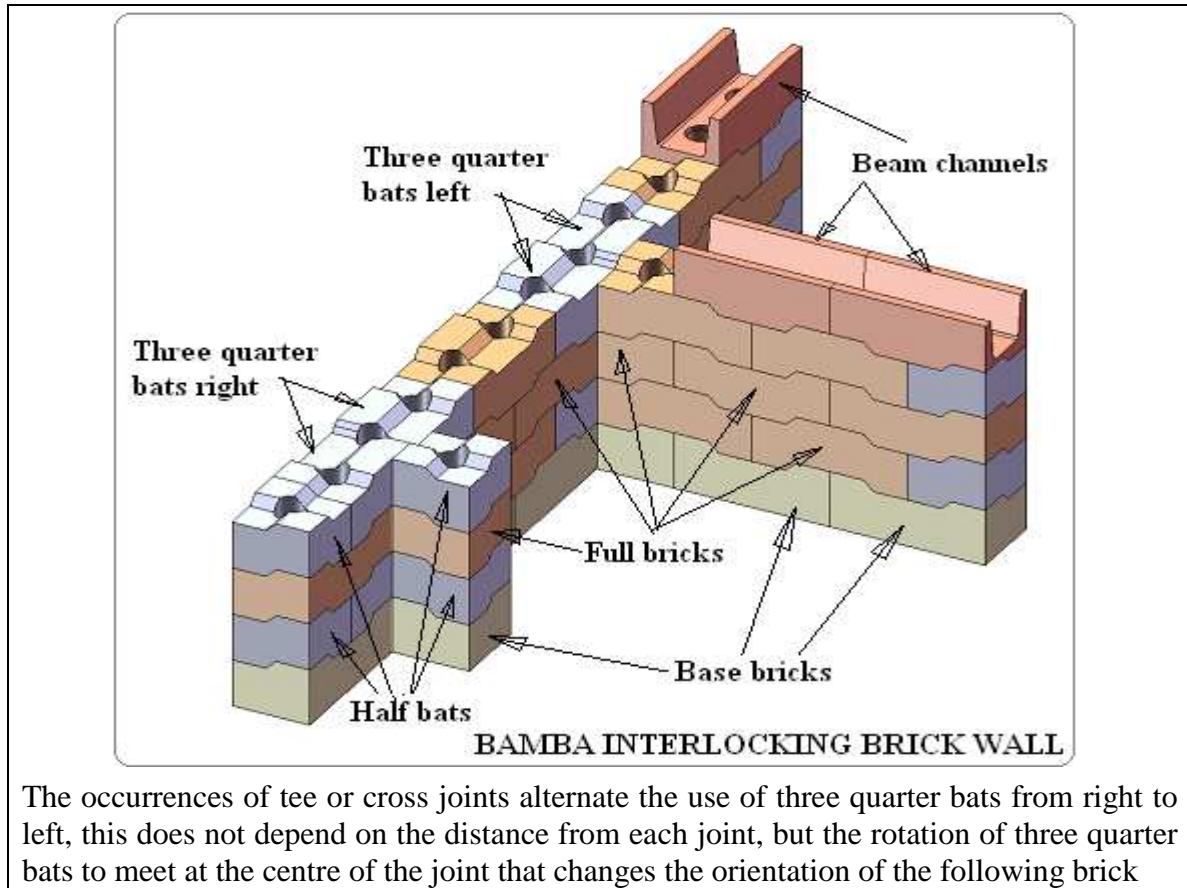
**Figure 2.7 Available Bamba brick parts in the market**



Bamba brick interlock better than all other types due to its shape, provided that high accuracy is maintained. This accuracy depends on: proper soil selection, proper determination of material mix (cement to soil and water to cement ratios), observation of good practice in production and curing. Though the shape can yield a rigid structure, it is very difficult to correct if bricks have defects. With these contradictory characteristics, the system is not fit for use in developing countries because it requires accurate machinery and high skills in soil selection to make sure that the production will be of one consistency. If every thing is perfect, you can lay the bricks of a whole house in a day, like a puzzle game. Otherwise, with low

accuracy in size and shape due its complicated configuration, it consumes a lot of time shaving and shimming to compensate for brick irregularities.

**Figure 2.8 the use of Bamba interlocking brick units in stretcher bond**

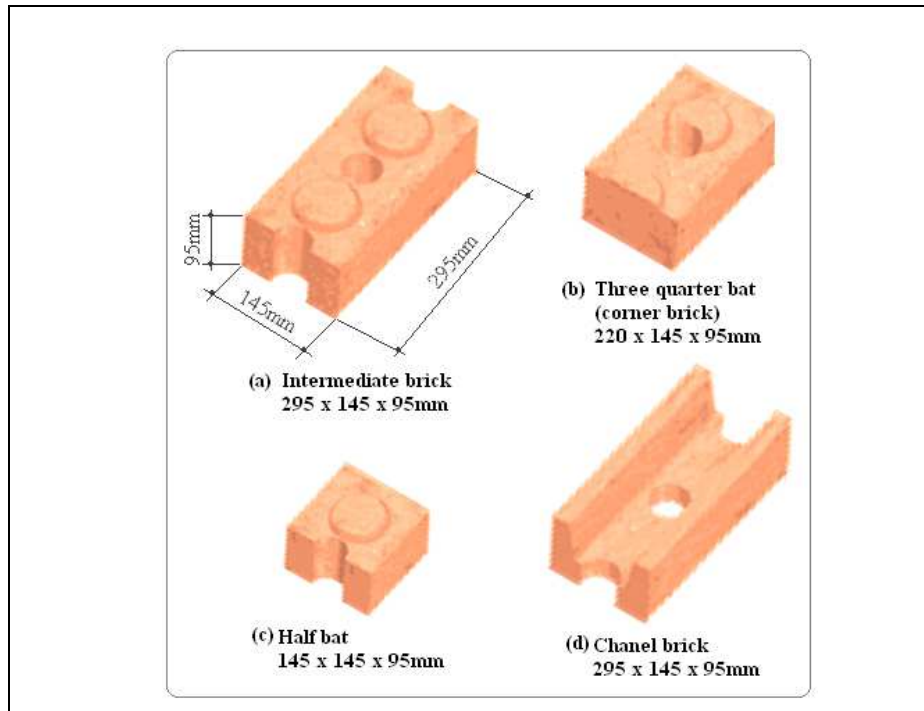


The author developed three-quarter bats Figure 2.7a and 2.7b (Kintingu 2003) for Bamba interlocking brick to perform tee and cross joints. The available Bamba interlocking units (Figures 2.6 and 2.7) can assemble wall as shown in Figure 2.8, but is restricted to half brick wall and to just stretcher bond.

### **2.2.7 AURAM SYSTEM FROM INDIA**

This type of interlocking brick has some similarities with Bamba and Thai types, but of a simpler shape with size 295 x 145 x 95mm. Figure 2.9 shows its family of bricks (intermediate, three quarter bat, half bat and channel) makes it relate more closely to the Thai system but with no grooves and reduced perforations.

**Figure 2.9 Auram Interlocking Brick**



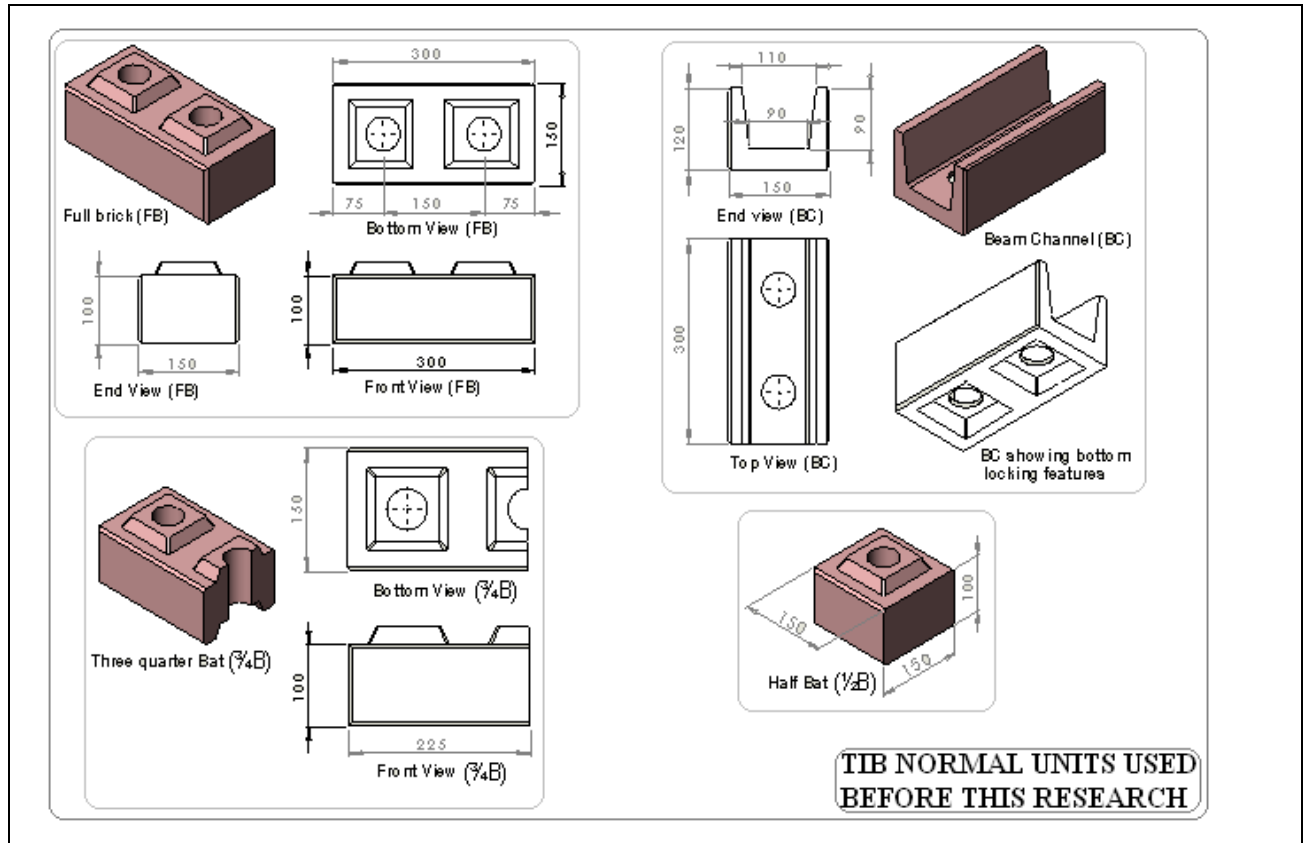
The Auram system reduces the number of three quarter bats required to just one due to shape similarity, compared to the two required with Bamba interlocking brick (Figure 2.7). In this type of interlock a three-quarter bat is used as a corner brick; this has flat ends, to avoid a semi-circle notch appearing at the external surface of the wall. The Auram brick is more solid and heavier at between 9Kg and 10Kg than the Thai and Bamba types at 7 to 8Kg. But the locking mechanism depends entirely upon the bosses and depressions; this will require experiments to examine the *optimum height* of male and *depth* of female features (<10mm) to *give enough wall punch-through strength*.

### **2.2.8 TANZANIAN INTERLOCK BRICK (TIB) SYSTEM**

The TIB system Figure 2.10 was designed by the author after observing the weaknesses in the Bamba system (Kintingu 2003). The new system (TIB), it was developed for appropriate technology applications; thus taking into considerations availability and affordability to the

users. The machine, which is locally made and manually operated, is a modification of CINVA-Ram press machine (VITA 1975, Weinhuber 1995).

**Figure 2.10 Tanzanian Interlocking Brick (TIB)**



The author made important modifications to improve the interlock brick to suit Tanzanian requirements. The size of the brick is 300 x 150 x 100mm, the same as that of Thai and Bamba types respectively. The locking knobs and depression are two as for the Auram type, but they are of pyramid shape with holes running through the centre of the knobs. The brick is chamfered to the front and back edges, providing pointed horizontal and vertical wall joints. This chamfer, gives a good key to the plaster if plastering is needed (the bricks from the machine are normally smooth enough to provide good finishing without plastering). The chamfer also reduces corner friction during brick production; thus reducing the ejection force required.



The number of different brick parts was reduced to four (Figure 2.10), from the six of Bamba (Figures 2.6 and 2.7) as follows: -

*Tanzanian type (TIB)* - Full brick, three quarter bat, half bat and beam channel.

*Bamba system* - Base brick, intermediate brick, left and right three quarter bats, half bat and channel.

TIB (Figure 2.10), apart from its good locking mechanism, needs investigation of the shear strength of its knobs and webs, to determine the optimum size that will provide sufficient wall stability during construction. Also it seems that the vertical joint is not secured well, as the brick ends meet at flat surfaces with no mechanical interlocking. It should have been provided with a groove of at least 2.5mm radius at both brick ends, to create a void for a minimum mortar to be placed (pumped) to fill the vertical gap. The TIB as other designs available on market fails to satisfy some of the demands from the building industry, such as the construction of:

- Various brick bonding joints,
- Piers (wider than half of brick length) attached into walls, which conventional (mortared) brickwork can easily perform,
- Thicker walls (thickness more than half of brick length) and
- Different wall configurations (circular, polygonal, etc.).

Correcting these deficiencies of mortarless technology is a further work of this research addressed in Chapter 4.

## **2.3 WALL PERFORMANCE FACTORS**

A wall is the base/background to roofing, ceiling, doors and windows, beams, plaster, painting and decorations, installation of electrical and water accessories, etc. According to

*Collins (1995)*, a wall is defined as a vertical structure made of stone, bricks or wood, with a length and height much greater than its thickness, used to enclose a building and divide it into cubes or rooms and support other elements/parts. The above-mentioned elements that are supported by the wall comprise more than 50% of the total cost of the building. The wall skeleton itself hardly accounts for 10% of the overall construction costs. We require the wall to be fit for purpose and durable in order to secure all the elements fixed to it for the entire life of the building. When we say a brick wall, we mean bricks arranged in certain pattern (*see bond as defined in Section 2.1*) and joined with whatever material or means. According to *Hendry et al. (1997)* the vertical compressive strength of a wall rises with only the square root of the nominal crushing strength of a brick, or with the fourth or cube root of the mortar cube strength. This is for walls that fail by crushing rather than by buckling. Also the relationship of the wall strength to the thickness of mortar, shows that the lower the thickness (down to one millimetre) the higher the wall strength. *Spence and Cook (1983)* show that mortar does not contribute much to the compressive strength of a wall, even if the mortar used is stronger in compression than brick. There is a need to find out if the mortar joint thickness can be limited to maximum of three millimetres (with the aim of filling the gaps after the bricks are laid). However wall strength does not only depend on the strength of the basic elements (brick/block and mortar) alone, but also on:

- The shape (*height, width, length and configuration*) of the wall
- Brick design
- The way bricks are laid (the bond/pattern employed) (*Hendry et al. 1997 and Spence & Cook 1983*)

## 2.4 CHARACTERISTICS OF MORTARLESS WALLING

The worldwide housing shortage has stimulated a search for appropriate, easy, fast and cost-effective ways of constructing walls. Among many technologies found to have promise is mortarless technology (MT) using dry-stack interlocking bricks/blocks.

Although MT is quite new, it is booming around the world with diverse use in the building industry, and it is now under study for space (extraterrestrial) applications. It comes in a variety of forms, shapes, configurations, and sizes (*Beall, 2000. Ramamurthy and Nambiar, 2004. Croft, 1993. Thanoon et al. 2004. Dyskin et al. 2005*). Interlocking bricks are often considered as 'specials' because of their need for unique moulds and their unsuitability for the extrusion technique widely employed in brick-making. Interlocking bricks' are normally produced using machines that guarantee good face texture (accurate and with appealing surfaces that are smooth and even), thus giving the bricks an attractive finish that requires little or no rendering, just joint sealing for protection from weather, achieving privacy and avoiding health hazards. The reduction or even omission of joint mortar and plastering saves construction time and materials.

The elimination of bedding mortar, although it reduces cost and accelerates the construction process *Ramamurthy and Nambiar, (2004)*, also induces structural weaknesses. Architectural inflexibility (*Chapter 4 subject matter*) and structural instability are caused by geometric imperfections in the brick-bed surfaces and any non-uniformity in the heights of adjacent bricks *Marzahn (1999)*. Moreover the complexity of some common ISSB configurations is a further barrier to design and construction flexibility. All these imperfections cause difficulty in keeping within maximum tolerable deviations from wall plumbness and straightness, and may prevent construction of particular wall configurations. This requires further investigations.

## 2.5 SELF-ALIGNMENT AND INTERLOCKING

There are two major objectives of any dry-stack interlocking brick system. The first objective is to be self-aligning (Gallegos 1988, Ramamurthy and Nambiar 2004, Thanoon et al. 2004, Beall 2000, Jaafar et al. 2006). Features required for self-aligning interlocking bricks includes:

- Fitting into each other without adjustments (cutting, shaving or shimming).
- Having distinct orientation features, so that if wrongly placed they will not fit and therefore require either reversing or replacement for rectification.
- Fulfilling modular coordination requirements (Gilroy and Goffi 2001, Thanoon et al. 2004)
- Having tight tolerances (Gallegos 1988, Marzahn 1999, and Jaafar et al. 2006)
- Having few elements, each with its simple and unique overall shape, to simplify the management during production and construction (i.e. unique shapes prevent confusion between one and another). The word ‘*element*’ here denotes a member of a brick set. For example a set might comprise three elements, namely full brick, half and three-quarter brick.

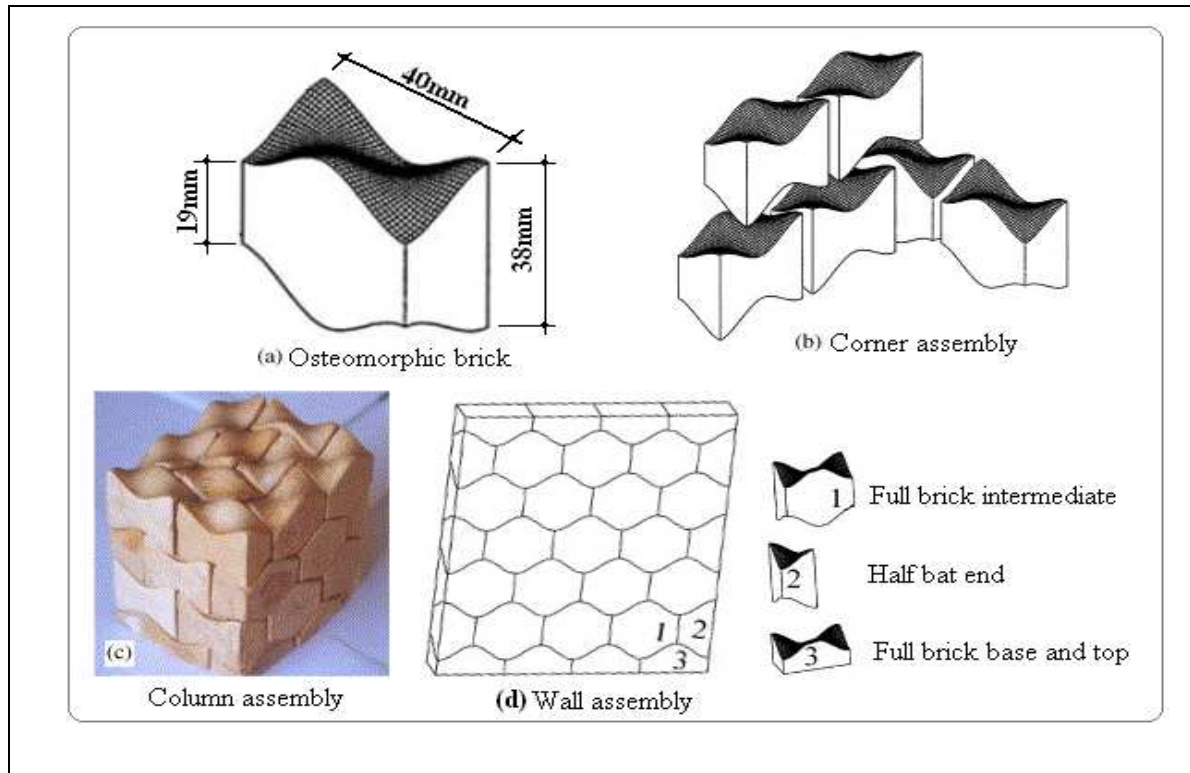
The self-aligning (automatic stacking) of bricks will reduce the need for skilled labour (Etherington, 1983. Gallegos, 1988), and enhance construction productivity.

Most interlocking bricks (Section 2.2) lock by either having protrusion and depressions or tongues and grooves, sometimes called male and female features. But the interlocking bricks discussed by (Dyskin et al. 2005, Dyskin et al. 2003 and Estrin et al. 2002), are based on topological non-planar contact. Such a brick is shown in Figure 2.11 and is called the *osteomorphic* brick.

Osteomorphic bricks interlock by matching the convex parts of the surface of one brick to the concave parts of the other Estrin et al. (2002). Under vertical loading (constraint) the bricks

are pressed together and achieve more surface contact. Such configurations restrict brick movements both perpendicular to the wall surface and along the wall, so osteomorphic brick fall under category A in Table 2.1 (Figure 2.11b).

**Figure 2.11 Osteomorphic bricks**

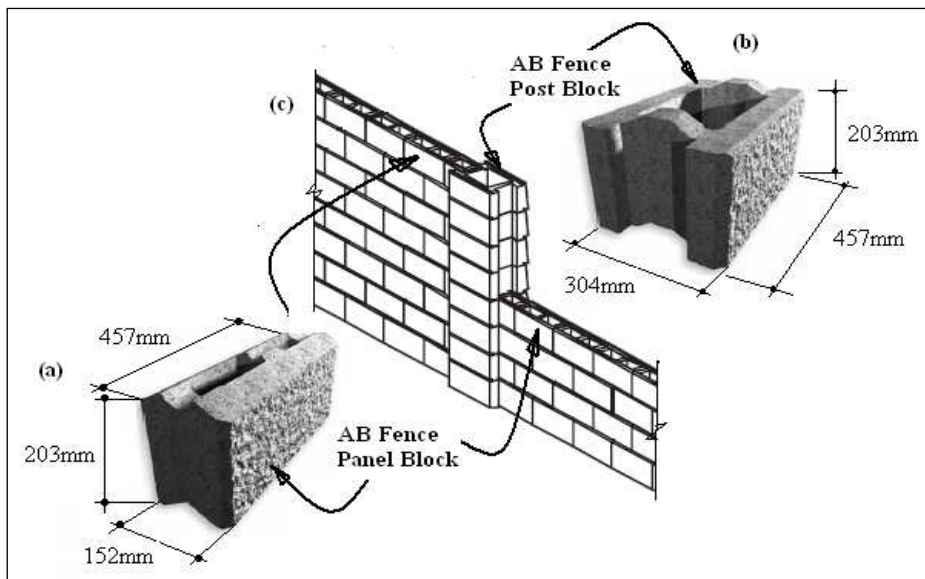


The topological interlocking with non-planar surfaces (if sufficiently smooth) reduces stress concentration. Being self-aligning and self-adjusting, osteomorphic bricks provide some relaxation of the accuracy requirements of both brick production and wall assembly. However the system being insensitive to the surface imperfection will lead to unevenness of wall surfaces (Dyskin, et al. 2005) and so require a thicker layer of render mortar. Therefore accuracy (smoothness and matching of the curvatures) requirements remain paramount as in other MT configurations.

Another brick shape with similar characteristics to the *osteomorphic* brick is the Allan Block (AB) see figure 2.12. It uses a “ball and socket joint”.

AB blocks were tested by Shrive et al. 2003 who showed they have good potential for tolerating both differential settlement and loading perpendicular to the wall surface (i.e. wind forces). The panel block Figure 12a restricts perpendicular movement but allows horizontal sliding during block-laying (category B Table 2.1).

**Figure 2.12 Alan Blocks**



However the mechanism of self-aligning just discussed (osteomorphic brick and Alan block) is not typical. Most of the MT systems that Least Developed Countries use (described in Section 2.2) employ T&G or P&D interlocks, which are the focus of this research.

The second objective of a dry-stack interlocking brick system is to have an *effective locking* means that allows dry-stacking to achieve straight, plumb and stable block-wall (Vasco Costa, 1993) that can withstand different forces (horizontal shear and vertical bearing) under loads applied (Gallegos 1988, Thanoon, et al. 2004) during and after construction. Table 2.1 divides the locking modes into two categories; one-way and two-way. Though each mode has advantages and disadvantages, this research is in favour of category A that restrict movements both perpendicular to the wall surface and horizontally along the wall. The protrusions and depressions provide interlocking and control of brick positioning that reduce

the use of levelling and aligning instruments *Gallegos (1988)*. The ability of IB to accurately locate brick positions improves the bonding value of mortarless technology. The precision of overlapping between courses improve masonry appearance and the distribution of loads *Nash (1991)*.

## **2.6 WALL ALIGNMENT ACCURACY**

An accurately aligned masonry wall should be vertical to plumb, with truly straight and horizontal (level) courses. The vertical joints (perpends) at alternating courses should be in line and truly vertical throughout the wall height. The masonry panel face should have a flat and true surface *Nash (1983)*. Conventional masonry gives an acceptable range of vertical deviation, which for a wall height up to 3m should not exceed 10mm (BS 5606:1990 Table 1 T.1.3).

All who have worked with interlocking bricks agree that in order to achieve good alignment, the bricks should be geometrically accurate (*Marzahn 1999, Beall 2000, Estrin et al. 2002, Jaafar et al. 2006*). However no critical analysis has been made of *wall alignment*. Research so far has only addressed the important issue of performance in direct *load-bearing* of interlocking dry-stacking systems.

*Beall (2000)* observed that the physical locking feature is a mechanism to improve the accuracy of dry stacked masonry; it makes it easier to align the wall vertical and straight and therefore speeds up construction *Jaafar et al. (2006)*. However the relationship between wall alignment accuracy and brick imperfection requires further research.

## 2.7 LOAD BEARING CAPACITY OF MORTARLESS WALL

A substantial amount of research has been performed to ascertain the behaviour of mortarless walls under applied loads (*Gazzola & Drysdale 1989, Drysdale & Gazzola 1991, Marzahn 1999, Marzahn and Konig 2002, Shrive et al. 2003, Jaafar et al. 2006,*) both in-plane and out-of-plane. Dry-stacked mortarless blocks have been tested under compressive, tensile and shear loads, and their performance related to that of conventional (mortared) brickwork, for which standards and codes for materials and structure quality are defined.

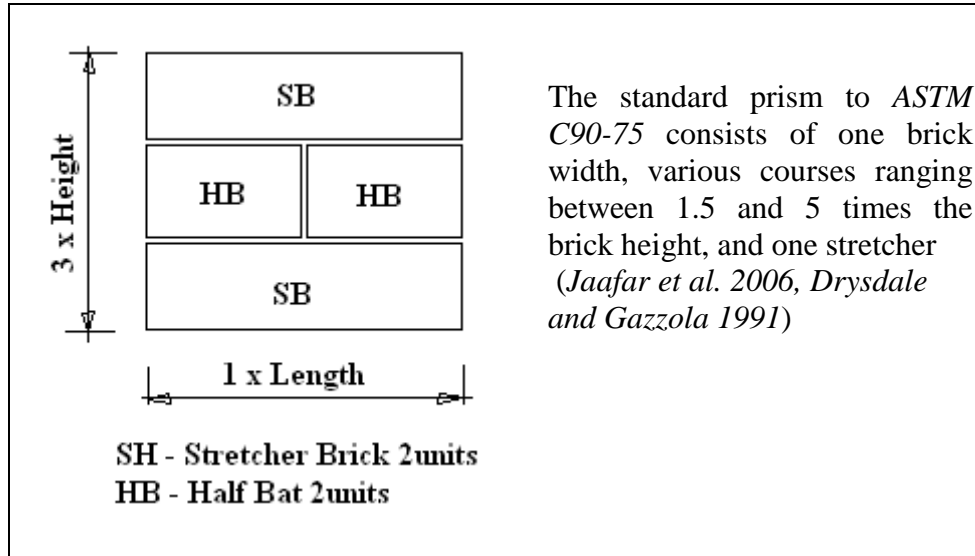
*Gazzola & Drysdale (1989)* tested dry-stacked interlocking hollow-block walls under compressive, tensile and shear forces. Their results suggest MT masonry construction is adequate for low rise buildings. Moreover any additional surface render enhances tensile and shear strengths and gives some improvement in compressive strength.

In further work, *Drysdale & Gazzola (1991)* studied the strength properties and load-bearing capacity of *grouted* dry-stacked mortarless hollow-block walls.

The blocks used to build test prisms had an average material compressive strength of 30.4 MPa. The test results of grouted prisms (Figure 2.13) attained an average flexural tensile strength of 1.7MPa. This is over six times the minimum value allowable in the North American building codes *ACI-ASCE (1988) and CAN3-S304-M84 (1984)*.



**Figure 2.13 Test brick prism**



The British Standards (*BS 5628-1:2005 Table 3*) require blocks with compressive strength above 17.5MPa, to be designed for a hollow-block wall to withstand average characteristic flexural strength of 0.25MPa. However the test result attained by Drysdale and Gazzola will produce a structure with a 6.8 factor of safety, which agrees with the North American Building Codes. This can be summarised as follows

Material classifications	Drysdale and Gazzola test results	British Standard (BS) requirements (for conventional wall)	
		Strength	Factor of safety
Block-compressive strength (MPa)	30.4	>17.5	1.7
Prism-flexural strength (MPa)	1.7	0.25 (hollow-block wall)	6.8

*Jaafar et al. (2006)* also tested interlocking mortarless hollow-block panels under compressive loads. He used blocks with an average compressive strength of 15.2MPa. The wall panels' compressive strength was 5.9MPa. The correlation between strength of individual blocks and wall panel was determined; the average compressive strength of a wall

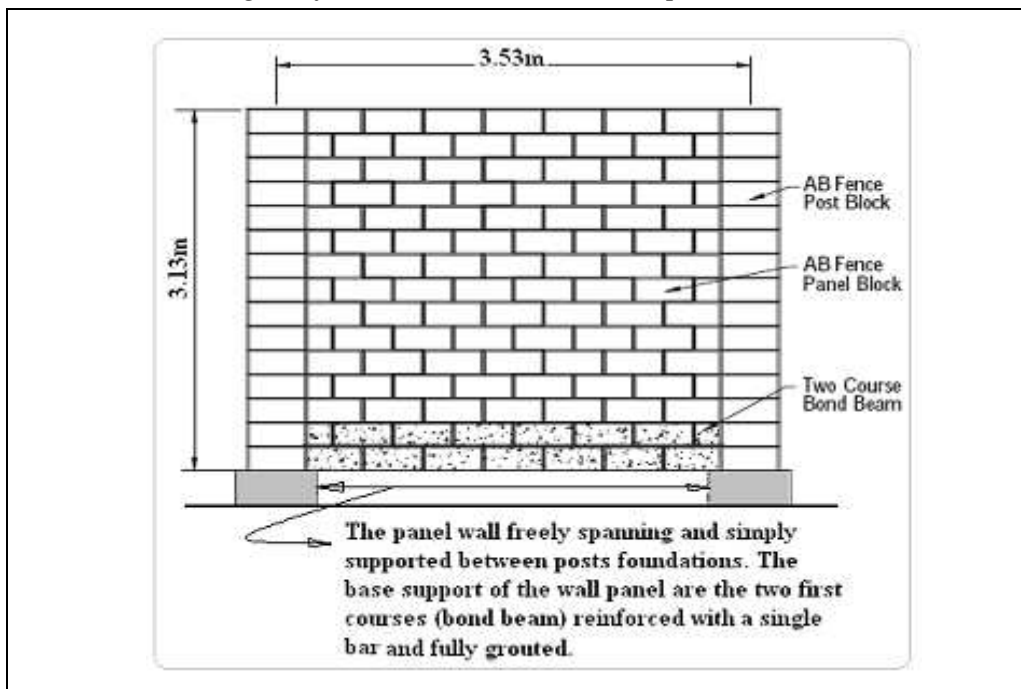
panel ( $f_{cw}$ ) was 0.39 of the compressive strength of the individual block ( $f_{cb}$ ): in equation form  $f_{cw} = 0.39f_{cb}$ .

*BS 5628-1:2005 Table 2c* yields, after interpolation, a value for panel compressive strength of 5.99MPa when brick strength equals 15.2MPa. The ratio ( $f_{cw}/f_{cb} = 0.39$ ) is in exact agreement with *Jaafar et al. (2006)* test results. It demonstrates the ability of mortarless block masonry to withstand loads as large as conventional (mortared) masonry does, being sufficient for low rise (up to two storeys) buildings. [Typical pressure on bottom of a 2-storey wall is 0.3MPa *Ophoven (1977)*, increasing to maximum of 0.6MPa if wall is leaning]

*Shrive et al. (2003)* studied the structural performance of dry-stack interlocking blocks using a ball and socket joint system (Figure 2.12). They found that the ball and socket joint rigidity increased with increased load. It was observed that the dry-stacked panel wall absorbed 30% of a load applied *perpendicular* to a wall and transmitted only 70% to the restrained end posts.

Using differential settlement tests on a simply supported panel Figure 2.14, they confirmed that mortarless ball and socket configuration of a panel wall and its interface with supporting columns spanning 3.53m centre to centre, were able to support the full weight of the panel assembly (7 x 15 AB panel blocks), while yielding less than 0.5mm deflection.

**Figure 2.14 simply supported panel tested for differential settlement**  
(Diagram from Shrive et al. (2003) report)



Marzahn (1999) investigated the “effects of the geometric imperfections in the bed joints to the structural behaviour of mortarless masonry under axial compression”. In order to undertake the tests, the brick bedding surfaces were specially machined to create different bedding conditions. Six bedding surfaces were created (Figure 2.15).

It was observed that for the brick units with uneven bed surfaces, they had to even-out before a uniform stress transfer was generated. Such uneven surfaces of dry-stacked masonry demonstrated extensive deformation/settlement during initial loading. Tensile and bending stresses occurred (Figures 2.16 and 2.17), that led to vertical cracks running through the bricks. This flexural cracking is a common feature of dry-stacked masonry;

**Figure 2.15 Brick surfaces of different imperfections**

*(From Marzahn 1999)*

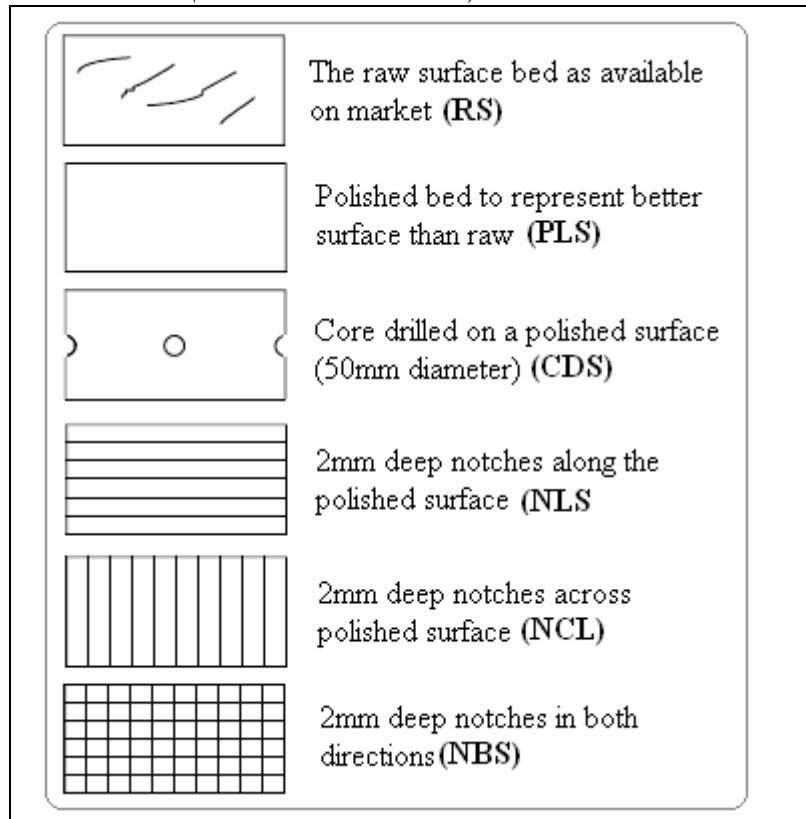
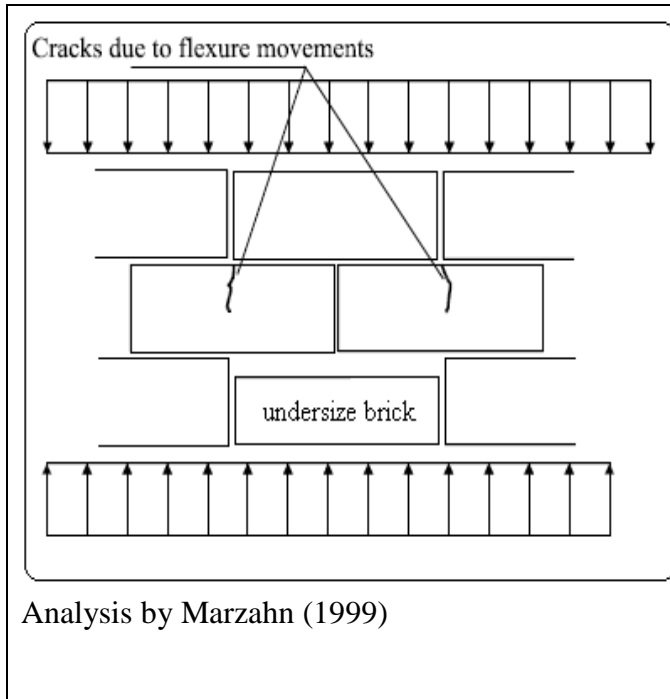


Figure 2.16 shows the effect of irregular brick heights in one course. In Figure 2.17 the bricks show cracking only from wall self weight (initial loading) even before they receive loading from roof structure, ceiling and other finishing materials.

The early cracking (Figure 2.17) of bricks indicates the low strength of material used. It can be minimised by the use of bricks with equal height in a course. Marzahn show that the quality of surfaces influenced the strength of brick units: the more uneven the bed planes the lower the strength because it causes initial deformation. However the initial deformation/settlement (joints evening-out) lowered load bearing capacity by only 5 to 15% compared to mortared masonry *Marzahn (1999)*.

**Figure 2.16 Cracks due to bending movements caused by unequal height of bricks in a course**



**Figure 2.17 brick early cracks caused by unevenness of brick surfaces**



Photo graph taken in 2006, at Mbezi-beach Dar es Salaam Tanzania by the author during site visit.

The settlement of dry-stacked masonry is influenced by the deformation of individual bricks and the unevenness of contact surfaces of the joint. However the movement of joints occurs only at the lower/initial stresses: they are directly influenced by the quality of bedded surfaces of units. It was revealed by Marzahn that the main objective of a wall structure is to have stiff joints, so that the internal movements are minimised to prevent masonry from experiencing tensile and bending stresses.

If the applied load/force (vertical or horizontal) is constant

$$\text{Vertical load (force) } F = \sigma_{nom}A_{nom} = \sigma_{ef}A_{ef}$$

$$\text{Horizontal shear force } S = \tau_{nom}A_{nom} = \tau_{ef}A_{ef}$$

Where suffix 'nom' indicates the nominal area (in plan) of the wall and suffix 'ef' indicates the effective contact area in plan.

$\sigma$  and  $\tau$  are respectively normal and shear stress at brick-to-brick contact surfaces.

$A_{nom}$  is the ideal area (overall plan Figure 2.18a) designed to bear the load applied on the block. For a block-laid on its bottom surface, the ideal area is 'length x width' if the brick surface is 100% in contact (this may be achieved under mortared condition).

In the case of dry-stacked bricks with imperfect surfaces, stacked or assembled without mortar, the ratio of effective ( $A_{ef}$ ) to nominal ( $A_{nom}$ ) contact areas (represented by symbol  $\eta_0$ ) is initially much less than one. As load increases, and small bumps are flattened, the ratio ( $\eta_0$ ) increases.

$$\eta_0 = \frac{A_{ef}}{A_{nom}} \quad \text{Where } 0 < \eta_0 \leq 1$$

The contact area ratio for interlocking bricks is less than one ( $\eta_0 < 1$ ) for two reasons:

- With interlocking and hollow bricks (Figure 2.18), often not all the interface area is meant to make contact. For example with the Tanzania interlock brick (Figure 2.10), only 47% makes contact, while for some hollow blocks this solidity or designed contact area may be under 30%.
- With bedding surfaces, imperfections (Figure 2.18c) reduce the contact area further, unless there is elastic deformation or bump crushing.

**Figure 2.18 Stages of contact area from overall solid block to mortarless to effective contact**

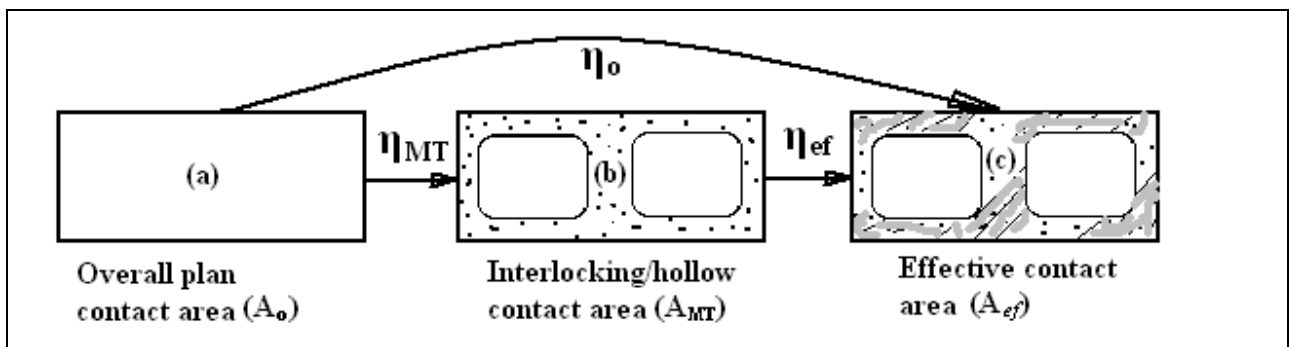


Figure 2.18 shows:

- (a) Overall plan area, of which a full contact area ( $A_{nom}$ ) may be achieved only under mortared condition.

(b) The designed interlocking or hollow contact area ( $A_{MT}$ ) is less than overall plan area ( $A_{nom}$ ). We can represent the ratio of mortarless brick area ( $A_{MT}$ ) to ( $A_{nom}$ ) by the symbol  $\eta_{MT}$  (effect of reduced contact area).

(c) Any deviation from flatness (irregularity of surface) reduces the surface in contact (Figure 2.18c) on loading to an effective area ( $A_{ef}$ ).  $A_{ef}$  that is less than  $A_{MT}$  and further less than  $A_{nom}$ . Thus  $\eta_o = A_{ef}/A_o = \eta_{MT} \times \eta_{ef}$

The combined effect of surface imperfection and hollowness is represented by a ‘surface utilisation factor’  $\eta_o$ , where  $\eta_o < 1$ , thereby increasing average stresses, to:

$$\sigma_{ef} = \sigma_{nom} \times \frac{A_{nom}}{A_{ef}} = \frac{\sigma_{nom}}{\eta_o}, \text{ and therefore } \sigma_{ef} = \frac{\sigma_{nom}}{\eta_{MT} \eta_{ef}}$$

*Marzahn (1999)* compared bricks with varying degrees of (artificially generated) surface roughness, taking as his datum (ideal) a brick with a machined and polished surface (PLS). He measured joint deformations ( $\epsilon_i$ ) under load for the six brick surfaces described in Figure

2.14 and from their deformations defined relative deformations ( $k_i$ ):  $k_i = \frac{\epsilon_i}{\epsilon_{PLS}}$  for  $i = RS,$

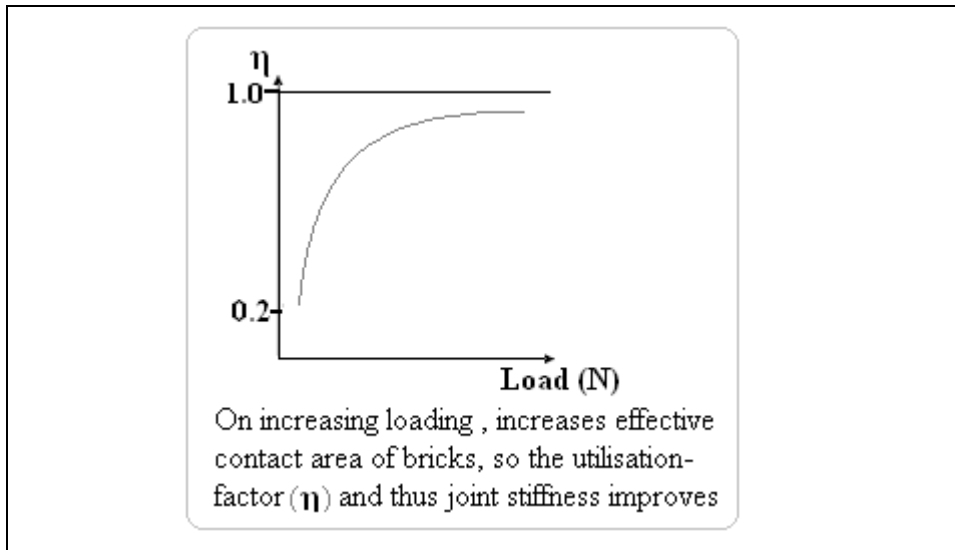
NLS, NCS...etc. (Figure 2.15), where  $\epsilon_{PLS}$  is a joint deformation for the PLS bricks.

From the computed relative joint deformations, and assuming that surface, utilisation-factor ( $\eta$ ) for the PLS is  $\eta_{PLS} = 0.97$ . Marzahn calculated surface efficiencies for the remaining five brick surfaces

(under full load), using the equation;  $\eta_i = \frac{\eta_{PLS}}{k_i}$ . He found that the values for  $\eta$  vary strongly with

load, generally in the form closer to one (Figure 2.19).

**Figure 2.19 Behaviour of dry-stacked brick joint under full loading**



The surface utilisation-factor  $\eta_0$  *under full load* are high enough ( $>0.2$ , with stress typically not exceeding  $5 \times 1 \text{MPa}$ ) that we need not to worry about brick crushing in 1 or 2-storey buildings. But gross brick height variations, large enough to result in total loss of contact for some bricks, will result in cracking (Figures 2.16 and 2.17) at far lower loads than those needed for brick crushing.

Further work by *Jaafar et al. (2006)* analysed the dry-joint behaviour of interlocking blocks under compression, taking into consideration their surface imperfections and variations between the block's thickness/height that influence joint deformation. This research showed that 75% of final joint deformation was realised from the first 57% of load, thereafter joint stiffened and the deformation rate decreased. These findings support early research done by *Marzahn and Konig (2002)* (long-term behaviour of dry-stacked masonry), in which realised a 70% of joint settlement/consolidation in the first 5 to 10 days of the total settlement achieved after a long-term loading for three and a half years. But when the block wall was grouted the deformation or movement started at 38% of the maximum loading, and continued



until splitting of block webs occurred. The stiffness of the joint is due to the bond between the grout and the surrounding block shells.

In their evaluation of test results both research groups assumed that the movement under loading was in the direction of applied force, effectively disregarding unevenness in the surface bumps, i.e. they assumed bumps of equal height. With this assumption, vertical loading has no effect on wall alignment: there can be no out-of-plane deviation caused by brick rolling or rocking perpendicular to the wall surface making the wall lean from plumb. So there remains a requirement for a study of the relationship between wall alignment and brick irregularity i.e. how surface bumps cause a wall to lean out of plumb. Any leaning results in a couple being superimposed on the direct inter-brick vertical loading, thereby increasing the peak inter-brick pressure by a factor up to 2. This in turn reduces the load bearing capacity of a wall.

## **2.8 PRODUCTION OF BRICKS/BLOCKS**

The production process for the basic elements of the wall i.e. brick/blocks and mortar, from soil (mud) involves either stabilisation (usually with cement) or firing. The process starts with soil identification and testing (at site and laboratory), followed by preparation (winning/excavations, pulverising and sieving), mixing and moulding (by hand, machine pressing or ramming between shutters). Finally, curing is needed for all elements containing cement or drying and burning for clay elements. These various processes are well covered by *Montgomery (2002)*, *Kerali (2001)*, *Norton (1997)*, *Craig (1997)*, *Houben and Guillaud (1994)*, *Gooding (1993)*, *Stulz and Mukerji (1993)* and *ILO (1987)*.

In this competitive world, the production process is the most important part of the building materials industry. It assures standardised quality and adequate quantity of materials to fulfil the needs of the market. In this thesis, we shall look at the production of Interlocking Bricks (IB), using soil as a main raw material, bearing in mind, that

*“The use of soil that is readily available, for construction, across the economic spectrum and across the various stages of social and technological development, makes available an appropriate and sustainable technology for the creation of the built environment” Morris and Booysen (2000).*

## **2.9 SELECTION OF SUITABLE SOIL FOR STABILISATION**

Low-quality stabilized bricks result from lack of control or monitoring of materials and of the whole production process. The field of soil-selection involves identification of the distribution of gravel, sand and fines (silt and clay) within a sample. To limit the size of gravel and remove other large particles, after being first pulverised, soil is passed through a standardised sieve with 4-6mm openings. An important factor in soil stabilization is the soil's cohesion that depends in its fines fraction. Soil selection is often conceived as a once-off process of testing to confirm the soil passes the criteria for stabilization and to determine the best ratio of soil to stabiliser. However to maintain soil consistency, it is necessary in practice to constantly monitor the soil's properties and compensate for any changes that occur.

The test procedure and the coherent test plan described by *Gooding (1993)*, for preliminary on-site testing is one of major steps of soil selection. Although the bottle/sedimentation and linear shrinkage tests were recommended as ‘laboratory tests’, The author is of the opinion that such tests could be used in the field and provide reliable guidance for determining mixing ratios for cement to soil (*Gooding 1993, Houben & Guillaud 1994, Norton 1997, Burroughs 2001*). The information reported in Table 2.2 suggest that a soil with a shrinkage

less than 2.5% or greater than 9% should be discarded for stabilization unless it can be modified to achieve adequate cohesion (clay content between 10% and 35% *BRU-B2 (1974)*). Any soil modified by blending should be tested repeatedly until the attained shrinkage is between 2.5 and 9%. Data in table 2.2 is a result of field experience in agreement with the calibrations after *VITA (1975)* for a low-pressure machine up to 2MPa, and higher-pressure machine of up to 10MPa after *Webb (1988)*. Linear shrinkage (LS) test results determine the ratio that allow calculation of the amount of stabilizer to be used as well as the compression needed. Also agreeing with *Webb and Lockwood (1987)* recommendations concerning choice of machine;

- Low shrinkage soils (high sand content) are better stabilized with Portland cement (PC) and compressed by high power (> 4MPa) machines, while
- High shrinkage soils (high clay content) are better-stabilized using lime and low power (to 2MPa) press machines.

**Table 2.2 Level of soil shrinkage with recommended compression pressure**

(Data using Alcock's shrink-box - 600x40x40 mm)

Source	Measured shrinkage (mm)	Shrinkage (%)	Recommended cement to soil ratio (C: S)	Cement (C %)	Remarks
Gooding (1993) Hauben & Gullaud (1994) ILO (1987). Norton (1997), UN (1992) VITA (1975) Webb & Lockwood (1987)	6 – 15	1 to 2.5	1:20	4.8	Only for heavy compression above 4MPa provided soil proves to have enough clay to reduce handling breakages
	15 – 25	2.5 to 4.17	1:18	5.3	Satisfactory for normal compression up to 4MPa
	25 – 35	4.17 to 5.83	1:16	5.9	Best soil for compression as low as 2MPa
	35 – 45	5.83 to 7.5	1:14	6.7	Satisfactory soil for compression as low as 2MPa
	45 – 55	7.5 to 9.17	1:12	7.7	Fair soil for compression even lower than 2MPa but of low production pace due to sticking Characteristics (high clay content).
	55 – 60	9.17 to 10	1:10	9.1	Poor soil; may need blending to reduce sticking or may need more Cement thus more expensive. Acceptable only when no alternative.

After measurement of fractional distribution of the soil, its linear shrinkage and selection of appropriate ratio (cement to soil – C: S), the final stage is to produce trial bricks; at least ten blocks from each soil batch. This is used to verify appropriateness of the soil for stabilisation using the proposed soil to cement and water to cement ratios (Table 2.3). The following observations to be made:

- The mixing process: if it is difficult, it indicates too high a clay content in the mix. The soil requires modification, either by the addition of extra cement or by blending with sandier soil.
- The rate of breakages on carrying the fresh bricks to their curing place. Too high (> 10%) a rate indicates there is too little clay in the mix.
- Crack developments, warping and any significant shrinkage during the first three days of curing. If this is too severe, indicates a too-high clay content that may require either sand blending or addition of extra cement.
- Testing the compressive strength at three, seven and fourteen days to check the effectiveness of stabiliser (minimum strength after 14 days >1MPa). The test depends on the availability of a suitably-equipped laboratory and demands of the project *Gooding (1993)*.  
The above quality control checks normally will continue for the whole period of production for every fresh soil batch even if the soil is from one source. Less checking is required if the soil is prepared all at one time.

### **2.9.1 SHRINKAGE BOX FOR SOIL TESTING**

The shrinkage box is a mould for linear shrinkage test. Linear shrinkage is defined as “*the change in length of a bar-sample of soil when dried from about its liquid limit, expressed as a percentage of the wet length*” (BS 1377-1:1990 clause 2.2.15). A wide variety of shrinkage

box dimensions (Table 2.3) are used in different parts of the world. The variation in the suggested initial moisture content of soil test samples between one researcher and publisher to another is also confusing, but we can clarify this by defining the two moisture conditions; Liquid Limit (LL) and Optimum Moisture Content (OMC).

**Table 2.3 Linear shrinkage moulds used in different parts of the world**

S/No	Source	Box shape	Box size in mm (Internal dimensions)	Initial Moisture Content (MC)	Where more Applicable
1	BS 1377 (1990)	Half round	140 x 25Ø	To LL Consistency	Laboratory
2	CML-TLM1999 (2000)	Half round	140 x 25Ø	Within 1% of LL	Laboratory
3	California Test 228 (2000)	Polygon	Tapered Top 127 x 19.05 x 19.05 Base 127 x 17.48 x 17.48	Wetter than LL	Laboratory
4	Burroughs (2001)  SAA (1977)	Half round	250 x 25Ø  a) 250 x 25Ø b) 135 x 25Ø it is used only with small soil sample	Near LL  At the LL	Laboratory
5	Keefe (2005)	Rectangular	600 x 50 x 50	OMC	Site
6	Gooding (1993) Houben & Guillaud (1994) Stulz & Mukerji (1993) Adam & Agib (2001)	Rectangular	Alcock shrink (box) mould 600 x 40 x 40	Near LL  OMC OMC OMC	Site
7	Norton (1997)	Rectangular	a) 600 x 40 x 40 b) 300 x 20 x 20	OMC (Controlled by drop test)	Site
8	Wolfskill at el. (1963)	Rectangular	127 x 19.05 x 19.05 (5" x ¾" x ¾")	Slightly wetter than LL	Site and Laboratory

**Liquid limit (LL)** is moisture content in a mix that allows the mix to start flowing i.e. a change of consistency from plastic to liquid state.

**Optimum Moisture Content (OMC)** is the moisture content in a cementitious mix that contains enough water for cement to complete its hydration reaction (normally is 0.25 of water to cement ratio) plus additional free water to fill pores improve mix workability.

Usually the extra water is just enough to enhance densification (Wolfskill *et al*, 1963) on compaction “*Optimum moisture content at which a specified amount of compaction will produce its maximum dry-density*” (BS 1924-1:1990 clause 2.23).

The free water can be specified and verified by trial mix because of its dependence on various soil characteristics;

- The type of aggregates (porous or impermeable)
- Shape of aggregates from round to sharp that affect workability of mix
- Type and amount of fines

From the definitions above, it is evident that LL and OMC are two different conditions for the moisture content in a mix, meant for different purposes. They therefore cannot be considered to be interchangeably, a wrong assumption used in the work of Keefe (2005), Houben & Guillaud (1994), Adam & Agib (2001), Norton (1997), Stulz and Mukerji (1993) (Table 2.2). OMC is a proper mix consistency for brick production (Hydraform Manual, 2004) that can be checked by simple field drop test; if the soil ball breaks into few (4-6) lumps then the water content is right (near to OMC).

However the author agree with BS 1377:1990, Burroughs (2001), Gooding (1993) and Wolfskill *et al*. (1963) that the moisture content (Table 2.2) at the start of a linear shrinkage test should be near the LL (“*This moisture content is not critical to within a few percent*” BS 1377-2: 1990 clause 6.5.4.2 NOTE), with the aim of checking the soil plasticity and getting a rough idea of how much stabiliser is required to modify the soil for safe use in severe conditions.

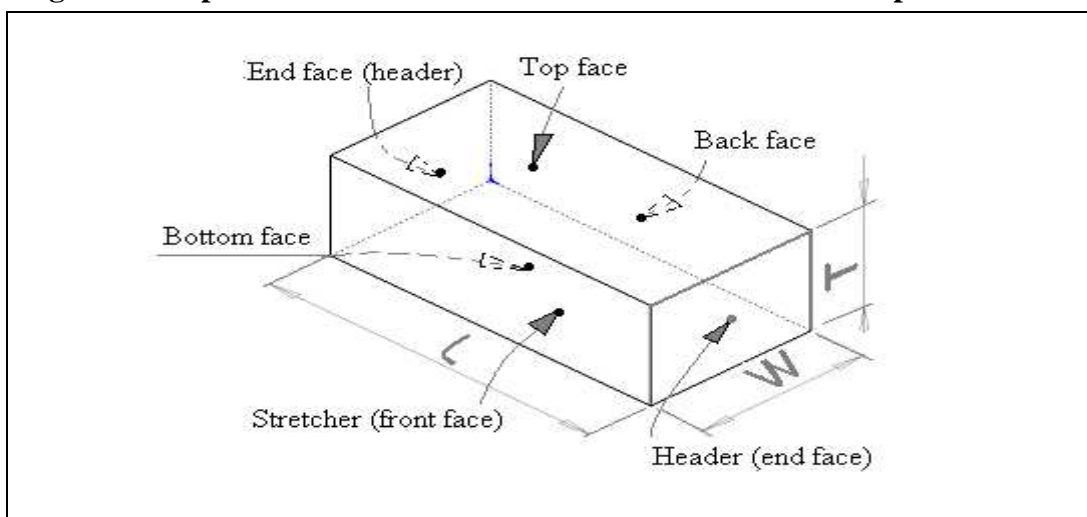
## 2.10 BRICK CURING

### 2.10.1 BRICK HANDLING

In traditional concrete block production, the block is ejected together with a pallet from a machine and placed at the curing area until next day. However during production of stabilized-soil bricks, it is common practice for each brick to be removed from the machine manually without a pallet to support it. The brick is then placed on the curing floor either on its end-face or on its front/back-face (Figure 2.20). The faces likely to be affected by warping and a flexure are the top and bottom (Figure 2.20). Such distortion is likely to happen if both these two faces are left free during curing, so one of these faces should be placed on a hard, straight and level base for the first two to three days.

The reason why bricks are traditionally not placed on their bottom or top faces is to avoid these faces torching the dirty and uneven surfaces of poorly prepared curing floors. We recommend with flat floors, place bricks on their bottom and with poor prepared floors place them on their sides or ends.

**Figure 2.20 Specification of bricks' sides as used on block-work position**



The controlling factors for deciding how and where the brick are placed on the curing surface are as follows: -

- As handling is a significant component of labour input, it should be made as fast and comfortable as possible, for example by mounting the press at ergonomic height (waist-high) table into which bricks will be place until they harden.
- The quality of the curing floor; if the floor is not well prepared (is not level, or has loose sand or aggregates that may stick on the surface) it may cause the bricks to have a curved face. Many professionals recommend that a plastic sheet should cover the floor. This does not change the floor surface level, but it does prevent loose material from sticking on to the brick surface. Any irregularity of the floor will still however be stamped on the brick surface, giving it a shape distorted from that desired.

## **2.10.2 CURING CONDITION**

Hardening of any concrete products requires the continued presence of water in the brick to enable cement to complete hydration process (*Kerali, 2001*). The strength of the concrete components made from Ordinary Portland Cement (OPC) increase gradually with time (*ILO, 1987*). The purpose of curing is to maintain moisture in the concrete component for the whole period required of hydration process. To achieve proper curing, it is necessary to control curing duration and site conditions (*Kerali 2001*). Curing duration is dictated by the type of binder used, for OPC as per *BS 12, (1971) and ILO, (1987)* 28days is recommend. In brick-making this would be expensive to maintain, and 7 days is probably a better compromise between maximizing strength and minimizing curing cost. The curing conditions depend on environment (wet, dry, temperature, wind etc.) the component is placed (*Kerali, 2001*). For Interlocking bricks meant for dry stacking, there are additional important conditions that



affect surface tolerance, such as poorly prepared curing floors, curing in open air and without cover.

A poorly prepared curing floor (not level, permeable, with loose sand or aggregates) is most damaging to brick quality, because in such condition the green (fresh) brick is denied the ability to retain sufficient moisture, therefore inhibiting the cement hydration process. This can result into a low strength brick (*Kerali 2001, and Odul, 1984*), warped, curved and with severe shrinkage.

Therefore curing requires proper support and good moisture control, shading, covering and frequent watering to maximize the cured strength. However placement of bricks on flat, clean, firm and impermeable surfaces for the first four hours prevents bricks from warping and curving. So poor curing is one of the major sources of poor quality (inaccurate and unstable) of dry-stacked (mortarless) walls because it inculcates irregularity of bricks.

## **2.11 SUBJECTS WORTHY OF FURTHER ANALYSIS**

From the literature review, seven topics/issues were identified as deserving further research and are very briefly analysed below. However only the last two of these topics are taken forward for fuller analysis in the ensuing chapters: the others require the attention of other researchers.

### **1. The relationship between the shape of IBs and the proportion of stabilizer required for the production mix.**

There is a direct relationship between brick configuration and the quantity of stabilizer/cement needed to strengthen the soil. The simpler the shape of the interlocking brick (i.e. solid or with minimum perforations) the less the stabiliser fraction needed to meet

strength requirements. More complicated shapes, with thin features (protrusions or tongues), require stronger materials. Therefore there is a need to develop or choose the most favourable shape of interlocking bricks to give best results, by using the minimum stabiliser and simple moulding machine to attaining the required wall stability and strength.

## **2. Optimising the size of brick grooves and chamfers acting as key to plaster mortar.**

The grooves made in bricks, for example of the Thai type (Figure 2.2) appear on the wall face. Also the chamfers on the free edges of the brick form grooves where bricks meet. These grooves differ in magnitude, and because of their volume may increase the render mortar required, or they may reduce it because of the better “key” which they provide (allowing thinner mortar). For best plaster and wall strength, the minimum size of groove consistent with good keying should be identified. If un-plastered, big grooves are better as they save material in brick. If plastered, small grooves are better because plaster is more expensive than brick.

## **3. Constant-volume versus constant-pressure production of IBs**

Blocks made in press moulding machines, i.e. where a defined pressure is applied, will vary in size for several reasons. There are:

- (i) Incorrect amounts of soil
- (ii) Inconsistency of soil
- (iii) Different moisture contents of soil
- (iv) Incorrect pressure applied

By contrast, bricks made in machines with a fixed mould size (constant volume) will vary in density due to reason (i) to (iii) above and hence have variable strength. The preferable

method is the constant-volume, which can easily control brick dimensions, which is more important than achieving constant density in IBs. The first test is to check the density of fresh brick from the press. If it resists the handling pressure to move brick from machine, it is believed that both the volume of material and the moulding pressure are satisfactory. The second test proposed by *Montgomery (2002)*, is the “Indentation testing for green brick”. It’s application therefore requires further experiment. This test defines the weight of a ‘rod punch’, the height it is to be dropped from and the maximum allowable indentation it produces. The indentation test may be easily tracked throughout curing duration.

#### **4. Choice of direction of compacting/pressing bricks and dimensional error consequences on bricklaying**

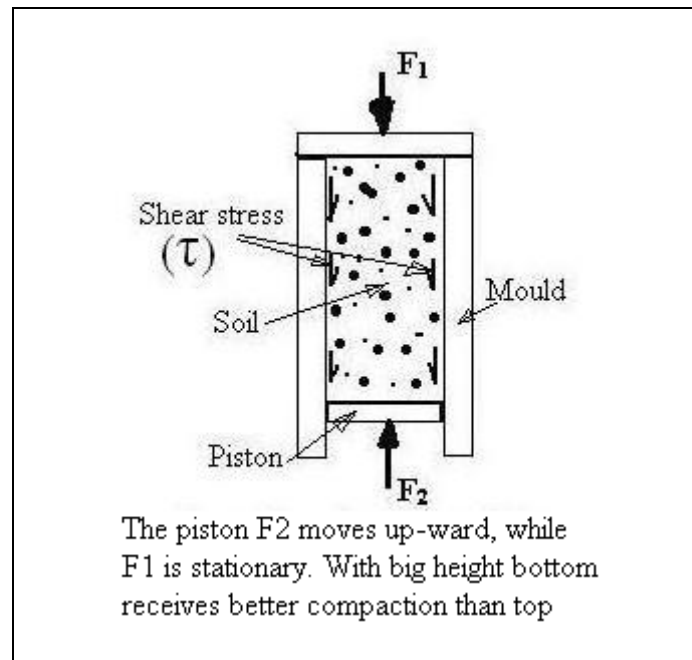
When moulding bricks, the compacted/compressed side in normal cases is the top or bottom. The conventional method of pressing bricks with a piston and a moulding rectangular will closely control two of the three-dimensions of the brick and less closely the third dimension. The poorly controlled dimension is that in the direction of the piston stroke (Figure 2.21), for example the brick height is impinges on the top of the brick. Moreover which the mould walls will be parallel, the piston may not be exactly parallel with the base: thus the pressed face may be at a slight angle to the opposite face. Depending on the type of locking features the compaction force can be applied perpendicular to the end, top or front-back faces of the brick.

- (i) **Compaction force is applied perpendicular to brick end faces** (as for the Solbric and Hydraform blocks)

For any given compaction pressure this will minimise the force that has to be applied since the area of the brick end is small. Minimising force allows the press linkages to be made less

strong. As shown Figure 2.21 the pressures inside the brick during moulding are likely to be more variable, as which the piston-end ( $F_2$ ) of the brick experiences full pressure ( $P$ ).

**Figure 2.21 Press machine operations schema**



$$P_{\text{piston}} = F_2/A_{\text{end-face}}$$

The opposite end of the brick experience a lower pressure

$$P_{\text{mould}} = (F_1 - \tau)/A_{\text{end-face}}$$

Where,  $\tau$  is the shear-force between the soil and the sides of the mould. For a length to width ratio of 2:1,  $P_{\text{mould}}$  may be as little as  $P_{\text{piston}}/2$  (Gooding 1993). Variability in pressure along a brick implies variability of density on ejection from the mould.  $F_1 = F_2$ , but while all of  $F_2$  is transmitted to soil, only some of  $F_1$  is.

If the brick is controlled in its height and width, so a wall built using these bricks will have level courses with minimum gaps between courses. Also wall will have even internal and external surfaces, which leads to minimum thickness of plaster. However to allow for variable brick length requires larger gaps at perpend (per-course).

- (ii) **Forces applied perpendicular to the brick's top/bottom faces** (*as in Thai, Bamba, Auram and Tanzanian types*).

This mode of pressing is essential if the top and/or bottom face are of complex shape. It will control brick width and length; so that, both internal and external wall surfaces will be flat because of uniform brick width. From the accuracy of brick length it is easy to maintain equal and constant overlaps for alternating courses, and therefore simplifies the process of estimating the brick quantity required in the construction. It also facilitates the standardisation of house measurements to multiples of brick length or width. Although for constant-volume pressing all dimensions are fixed, only certain surfaces are 'wiped' during moulding and ejection, which does not affect dimensions. However variation in brick dimensions made in a fixed-volume press might be caused by:

- Air trapped at piston or at mould-end
- Expansion on release of pressure (in the direction of retreating piston)
- Distortion during de-moulding
- Rocking of the piston, so the pressed face is not perpendicular to other faces.

- (iii) **Force applied perpendicular to brick front/back faces**

It will control the height and length of the brick, which will allow the wall to have one uneven (internal) surface. To make the surface straight and even will lead to a small increase in thickness of plaster.

Table 2.4 summarises the effects of brick pressing to each of the three dimensional directions, the strength and weaknesses are given for each compaction scenario and the errors expected and how they affect the wall alignments.

**Table 2.4 Advantages and disadvantages of compaction scenarios**

S/No	Compaction Stroke Direction	Loading Direction	Advantages	Disadvantages	Remarks
(i)	Along the brick length i.e. force applied to end faces	Perpendicular to compaction	a). Easy to lay (level and plumb) bricks of controlled thickness and width. b). Straight and flat wall surfaces resulting in min. thickness of plaster. c). Low force for a given pressure as end area is small.	a). Unequal brick overlaps in alternating courses. Give unpleasant appearance. b). In a given wall length may lead to brick cutting at site, which will increase - construction time, labour cost, also material waste. c). Likely to have a high variation in density 4(i). d). Only compatible with sliding interlock.	Brick load bearing strength not known if compaction and loading are on different direction and surfaces.
(ii)	Parallel with brick height i.e. onto top or bottom face	Normal to the surface of compaction	a). Min. thickness of plaster. b). Automatic laying equal and constant brick overlap (half brick). c). Simplifies house measurement, (standardisation to multiples of brick length or width). d). Easy and accurate estimate of brick quantity.	Levelling of brick courses may delay the construction speed with dimensional differences in brick thickness.	a). A small amount of mortar will be needed to compensate or level the wall courses. b). Scraping to reduce excess brick thickness delays construction, and hence increases labour cost.
(iii)	Parallel with brick width i.e. pressed front-to-back	Perpendicular to compaction direction	a). Easy to lay bricks. b). Equal and constant overlaps automatically formed. c). Simplifies standardisation. d). It is easy and accurate to estimate number of bricks.	Require thicker plaster on uneven wall surface to make it straight and flat. Not compatible with any interlock.	Unknown strength of brick as direction and surface of compaction during production different to those of loading.

**5. The effect of the brick locking mechanism on wall stability.**

Wall alignment (stability) in mortarless construction depends entirely on the locking mechanism, whereas in a conventional wall stability depends on mortar joints. Control is needed over both the height and the length of a wall. To keep the dry bonded wall straight horizontally and vertically may need an effective locking system that requires particular shapes of bricks. Large rooms with walls which do not contain a major opening but exceeds 2.5m height and not more than 3m in length *BS 8103-2:2005* other straightening mechanisms such as *shimming or mortaring, piers* and *beams* will be required.

Piers are inbuilt columns, protruding from the wall surface by a half brick or more. They are built at intervals depending on the distance from one support to the next and on the height of the wall. By building the piers, ribbed wall panels are formed. With piers less or equal to 3m apart, the wall may be built up to three metres high without need for horizontal strengthening. Increasing the distance between centres of piers up to 4.5m will require the wall to be strengthened horizontally (*Weinhuber, 1995*) by beams at both cill level and lintel or below the roof at ring beam level. Strengthening methods need to be assessed for economic comparison for their comparative cost.

## **6. Brick tolerances**

### **Dimensions**

The dimensions of the brick are the measurement of length ( $l$ ), width ( $b$ ) and height ( $T$ ) as shown in Figure 2.20.

In a mortarless technology, the bricks are to be laid one over the other with their top and bottom surfaces in direct contact, so the dimensions of each brick needs to be to a tolerance of  $\pm 1$  millimetres. This will make the wall formed by these bricks to be flat (depending on the constancy of the width of the bricks) on its surfaces, and the overlaps (depending on the length) of the bricks will be equal or of a certain interval required. The horizontal and straight rows will be affected by the uniformity of height of the bricks.

## **Surfaces**

A brick (Figure 2.20) has three pairs of parallel outside faces (two ends, front and back, top and bottom). The flatness of the surfaces of these faces is paramount in mortarless brick technology because of the absence of mortar.

In particular, the top and bottom surfaces of the bricks need to be flat, parallel and without any deformations, which in practice is very difficult to achieve. That's why, in conventional masonry, mortar is used to compensate and take care of gaps caused by brick inaccuracy. In some cases the material needs to be flexible, so that when loaded will automatically adjust to fit in whatever the tolerance will be. Usually we put conditions of tolerance in accordance with allowable standard deviations that for interlocking brick have yet to be established. The limits of allowable brick inaccuracy should be known for production quality control, standardization, and wall construction accuracy performance.

## **Accuracy of alignment**

Mortarless technology will not work if the bricks, to be assembled do not fit and *lock* to each other. This locking mechanism, allows the units be arranged (bonded) one over the other to form stable wall in a designed height and width, to a certain accuracy of verticality and horizontality. The locking features (knobs and depressions) should provide enough tolerance ( $\pm 1$  mm along the brick) to allow flexibility and  $\pm 1/4$  mm transversally for a minimal allowance between male and female in arranging the bricks. This need to be done so, because the material is brittle (stabilised soil can be easily broken if forced to fit).

## **7. Construction flexibility**

The interlocking bricks and part bricks available to date allow only one pattern of brick assembly that abides to the rules of bricklaying good practice (*The BDA Guide 2000. Nash*



1991. Nash 1983). All interlocking bricks support stretcher bond only (Figures 2.1, 2.2, 2.3, 2.5, 2.8, 2.11 and 2.12), and so have limited construction flexibility compared to conventional/mortared bricks. Therefore we need to investigate alternatives and possibilities of increasing mortarless-wall construction flexibility.

## **2.12 CONCLUSION TO LITERATURE REVIEW**

Of the seven subjects discussed above, the critical ones for mortarless technology are *construction flexibility* and *brick accuracy*.

Interlock-bricks configurations restrict the builder to only constructing stretcher bond, half-brick-thick walls and right-angled quoins. Thorough analysis of brick configurations, parts, bonding or patterns and joining techniques is needed to remove this weakness and so rescue the technology from being rejected by architects for not providing enough construction flexibility (*Chapter 4*).

The wall straightness, plumbness, stability and stiffness will not be attained if the bricks are not made with good tolerance or are distorted in shape. There is a need to find the main reasons for the irregularities found in current brick systems that hinder the ease and accuracy of wall construction by mortarless technology. It is time to identify the maximum brick deviations that MT can tolerate yet achieve acceptable wall accuracy. This research focuses on the causes of brick irregularities, how to minimise them (*Chapter 5*) and the implications of different degrees of irregularity. Also the investigation describes brick uniformity tolerance in relation with mortarless wall alignment (*Chapter 6 and Chapter 7*).

# CHAPTER 3

## 3.0 RESOURCE USE IMPLICATIONS OF EMPLOYING MORTARLESS TECHNOLOGY

### 3.1 INTRODUCTION

The construction of walls makes use of natural resources, including labour, which has significant cost consequences. Interlocking stabilised-soil bricks (ISSB), whose use is known as Mortarless Technology (MT), are produced from the following physical resources: cement, soil, water, equipment and energy. Any new technology will be attractive (*Co-Create 2004, Stewart 1987, Moustafa 1990*) if, in comparison with what is currently used (conventional), it: -

- Reduces use of limited (natural) resources
- Reduces cost
- Reduces constraints, by being more accommodating
- Better matches the context of use, and
- Increases performance (appearance, durability, productivity etc.)

In this chapter we compare the cost of MT walls using two variants of dry-stacked ISSB (Hydraform – ISSB-SA Figure 2.4 & Tanzanian – ISSB-T Figure 2.10), with walls constructed using Conventional (mortared solid-sand-cement) Blocks CB, currently the most popular modern form of wall construction in Tanzania. With CBs we can build a 150mm thick wall by laying bricks (CB-1) as stretchers on their front face, or a 230mm thick wall by laying CB-2 as stretchers on their bottom face (see Figure 2.20). The descriptions of the bricks/blocks used for the walls compared are summarised in Table 3.1. In each case we assume one square metre of walling is to be produced by a competent brick/block maker and

a skilled mason. We might have compared MT with hollow CBs instead of solid ones, but field experience shows that hollow blocks are not cheaper than solid as they require richer mixes and during construction waste a lot of mortar, which is more expensive than block. Also hollow blocks allows fewer courses be laid in a day than solid blocks as for stability purposes the mortar needs more time to strengthen.

**Table 3.1 Characteristics of walls compared**

S/No	System	Brick type	Brick volume (litres)	Mortared wall	Un-mortared wall	Wall-thickness mm	No. of bricks per m <sup>2</sup>
1	Mortarless Technology (MT)	Perforated ISSB-T* 300x150x100mm	4.5		Optionally grouted	150	33
2	MT	Solid ISSB-SA** 230x220x115mm	5.8	¼ of courses are mortared	¾ of courses un-mortared	230	40
3	Conventional Block one CB-1	Solid CB-1 450x230x150mm	15.5	Laid on its front face		150	9
4	Conventional Block two CB-2	Solid CB-2 450x230x150mm	15.5	Laid on its bottom face		230	14

**NOTE:** \* Interlocking Stabilised-Soil Brick Tanzanian type

\*\* Interlocking Stabilised-Soil Block South African type (Hydraform system)

In general MT is less flexible than mortared block, because there is no option of cutting bricks on site. However Chapter 4 shows as an outcome of this research, that the Tanzanian MT-set meets most architectural requirements (Table 4.1), so the flexibility objective is met but only at the level of ‘not less flexible than’ conventional technology.

## **3.2 NATURAL RESOURCE USE**

Most building materials are created by labor from naturally occurring substances, such as clay, sand, wood and rock. The production of bricks is the system of processing the raw material supplied by the earth. This section describes the three main constituents of stabilised-soil brick production:

- Cement, which require the resource of land from where raw material are obtained, plus much energy for manufacture, usually from fossil fuel
- Soil (sand and clay), which require land for quarrying
- Water

The comparison is made of how much each technology (ISSB and CB) utilises cement, whose production is the major generator of greenhouse gases in the building industry. Therefore any measure to reduce cement use will help preserve the environment.

A simple method for determining how much water is needed for production is also shown.

### **3.2.1 CEMENT**

Cement is a vital component for soil-stabilized bricks, enhancing both strength and durability. Cement, an expensive element, can be kept down to the range of 3 to 10 % of the mix without compromising performance (Section 2.9). From Tanzanian experience, a ratio of 1:16 (cement to soil) can produce an average of 100 stabilised-soil bricks (ISSB-T) from one 50kg bag of cement Table 3.1. This is equivalent to 450 litres of wall volume. By contrast CB with cement-to-sand ratio of typically 1:8 can only produce 20 blocks per 50kg bag of cement (equivalent to 310 litres of wall volume). Therefore ISSB yields 31% more wall volume than CB.

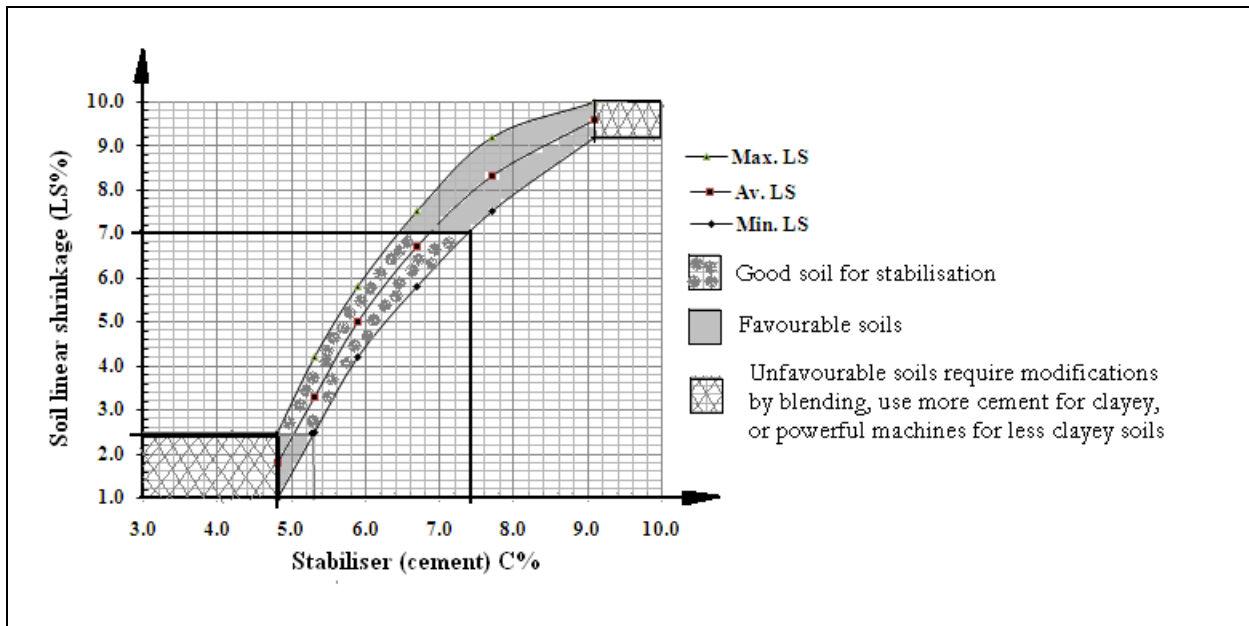
To make a fair comparison of cement consumption between the two systems of production and construction, we first need to explain the reason for the difference in cement content between the two systems.

Soil stabilization as shown in Table 2.2 (presented in diagram form Figure 3.1) has the characteristic that the less the clay (less shrinkage) the less the cement required in the mix, but the more powerful the press (more than 4MPa) that is needed. With a higher clay fraction (higher shrinkage) the more the cement required but a low pressure (up to 2MPa) press is satisfactory. CB traditionally employs only 'clean sand'; in consequence CB requires extra cement to compensate for the sand's lack of cohesion and to fulfil the high early strength required for remoulding from pallets after twenty four hours.

With ISSB it is normal to use soils with some clay in them (Table 2.2 and Figure 3.1). This clay gives a number of advantages in production:

- No pallets are required,
- The technology is tolerant of a wide range of soils, and
- Less cement is required, which may further be of benefit to the environment as discussed below.

**Figure 3.1 Limit of soils for stabilisation that reduce cement use in the brick production**



### 3.2.2 CEMENT REDUCTION

Interlocking stabilised-soil bricks (ISSB) can save cement in both brick production and bricklaying compared to Conventional blocks (CB), as shown in Table 3.2, where a one story house of three bed-rooms built using ISSB-T is compared to one built with CB. The house wall area is 182m<sup>2</sup>, requiring 6000 ISSB or 1638 bricks for CB-1 and 2548 blocks for CB-2 respectively (Table 3.1 show number of bricks in one square metre for each type of brick). In section 3.2.1 we compared the number of brick produced from one bag of cement. The quantity of cement per unit volume (litre) computed as follows:

$$\text{ISSB-T consumes } \frac{50_{\text{kg}}}{100_{\text{bricks}} \times 4.5_{\text{litres}}} = 0.111 \text{ kg of cement per volume (litre) of brick-mix,}$$

with the same formulae we get CB-1 consumes 0.161kg cement per litre block-mix.

In conventional walling mortar is compulsory. The density of OP cement mortar is  $2162 \text{ kg/m}^3 = 2.162 \text{ kg/litre}$ . If the mortar ratio is 1:4 (cement to sand) the cement content will be  $(1/5 = 0.2)$  of the total volume. In practice volume batching is normally used, which increases the weight of cement because cement has a higher density than sand. And due to the fact that mortar require more workability and hence more water, a cement content of up to 0.5kg per litre mortar may be employed (increased from  $2.162 \times 0.2 = 0.4324\text{kg/litre}$ ).

One CB-1 plus its joint mortar occupies  $460 \times 240\text{mm}$  of a wall surface area, of which the block occupies 94% and mortar joint (10mm) occupies 6%. The total cement consumption for block and mortar will be:

94% is block @ 0.161kg cement per unit volume (litre) of block

6% is mortar @ 0.5kg cement per litre of mortar,

Giving:

$$(0.94 \times 0.161) + (0.06 \times 0.5) = 0.151 + 0.03 = 0.181 \text{ kg/litre of wall}$$

Therefore  $\{(0.181 - 0.111)/0.181 = 0.39\}$  CB-1 consumes 39% more cement than ISSB in a wall unit volume.

### **3.2.3 CEMENT & GREENHOUSE GASES**

The threat of climate change has pushed the reduction in emission of greenhouse gases high on the world political agenda. This has motivated professionals to find new ways of designing buildings to create zero-carbon development *Eco-towns (2008)*. Cement is fundamental to building; it is a key component of concrete, essential for building and civil engineering i.e. houses, bridges, airport runways, modern reservoirs, underground stations, etc. *BCA (2007)*. However cement is fast growing to be a major barrier on the world's route to the low-carbon economy, since as the production of cement grows, so too do greenhouse gas emissions (*The Guardian 2006*).

The reduction of cement use shows benefit to the environment as there is an equivalent of 900 kg carbon emission per ton of produced cement (*Ruth et al. 2000, VanderBorgh and Brodmann (2001), Kruse (2004)*). Table 3.2 shows how the use of cement-soil stabilisation in house construction can reduce cement consumption, resulting into a reduction of CO<sub>2</sub> emission from cement manufacture.

**Table 3.2 Reduction of carbon emission by minimum use of cement**

Brick/Block type	Quantity pcs in 182m <sup>2</sup>	Cement for Production t	Cement for Mortaring t	Total Cement t	Carbon (CO <sub>2</sub> ) t	% Carbon Saved by using ISSB-T
ISSB-T*	6000	3.0	-	3.0	2.7	-
CB-1**	1638	4.1	0.9	5.0	4.5	40%
CB-2***	2548	6.4	1.8	8.2	7.4	64%

**NOTE:** \* Interlocking Stabilised-Soil Bricks Tanzanian, 150mm wall thickness  
 \*\* Conventional Block One, 150mm wall  
 \*\*\* Conventional Block Two, 230mm wall

The manufacture of cement contributes to greenhouse gases both directly and indirectly. Directly is because when calcium carbonate is heated, it produces lime and carbon dioxide. Indirectly, because the energy used is usually sourced from fossil fuels. It is estimated that the cement industry produces 5% of the global man-made CO<sub>2</sub> emission, of which 2.5% is from the chemical process itself, 2% from burning fuel and 0.5% from electric power plus transport (*IGPCC 2001., Marchal, 2001*). The positive part of cement in the CO<sub>2</sub> emission and climate change is that concrete buildings are adaptable to future climate as they have the ability to absorb and release heat, which in some climates means less energy, is needed for heating and cooling over their lifetime. The current available data indicates that concrete could reabsorb by carbonation, during its life, around 19% of carbon emitted in its manufacture *BCA (2007)*.

Apart from carbon emission, cement manufacture causes environmental impacts in all stages of its production including emission of airborne pollution in the form of dust and gas, noise and vibrations, damage to countryside from quarrying.



### **3.2.4 SOIL**

Although site planning is a well-known subject in the building industry, the full utilization of available resources at the individual sites (plots) is rarely achieved. Every site produces enough soil for brick production from three sources: the foundation trenches, the septic tank and the soak-away pit. Tanzanian experience shows that the soil from the three sources mentioned above can produce more than six thousand perforated interlocking bricks, which are enough to build a medium-size single-story house. What is required here is to test the soil available on site first before going anywhere else. Proper soil selection for stabilization is, as argued in Chapter 2, a well covered theme. Soil is a major raw material for stabilized brick; it requires only labour for its preparation and therefore in a low-wage country is the cheapest material for brick production.

### **3.2.5 WATER**

The importance of water in construction and in building material production is well known, but the quantity needed is normally not clearly assessed, nor its availability checked nor did its significant cost realise. It is assumed to be readily available and cheaply obtained when needed. In developing countries (African ones in particular) lack of clean water is among things that hinder health and development in general.

The cost of water for brick-making is sometimes higher than the cost of soil when the latter is obtained in the vicinity of the site. Many African rural districts, villages, and even suburbs of towns have no permanent source of water (pipe water) and thus the quality is not guaranteed. Water cost varies from one location to another depending on source and labour. Here we meet a major obstacle of least developed countries; scarcity of quality water that makes such water expensive. However the production of ISSB doesn't have requirements for water quality differing from other concrete works as recommended by (*BS EN 206-1:2000 and BS*

8500-2:2006). Water suitable for making concrete should be free from impurities and harmful ingredients (chlorides and sulfates, alkalis, organic and suspended solids). It is generalised that water fit for drinking is the suitable one (*BS 5328-1:1997 and BS 5628-3:2005*).

Water requirements depend on the following factors:

- Production – water consumption depends on water-to-cement and soil-to-cement ratios
- Curing – depends on duration in days (minimum 7days). The potential strength of any Ordinary Portland Cement (OPC) product will be maximised by curing under moist conditions. The highest rate of reaction (hydration) between cement and water takes place in the first three to seven days, which therefore require proper curing/attention (*BS 5328-1:1997 and BS 5628-3:2005*).
- Cleaning – depends on number of labourers and tools

The following is a simple example of estimating the volume of water for production and curing, based on author's practical experience with stabilised-soil brick production in Tanzania (summary Table 3.3). Knowing the average ratio of cement to soil (1:16) and assuming a water/cement ratio of 0.5:1, one bag of cement (50kg) requires on average three buckets of water (60 litres) to produce 100 bricks. With one brick press, three labourers can comfortably produce 500 bricks a day, namely a batch, and to cure one batch we require two buckets (40 litres of water) per day for 7 days. Washing of three labourers and tools requires five buckets of water (100 litres) per batch.

**Table 3.3 Water quantity for production and curing**

Brick Quantity	Water requirements in litres			Cost (Tsh <sup>*</sup> )
	Production include cleaning	Curing for 7days	Total for Production & curing	One litre = Tsh. 12.5
One brick	0.8	0.56	1.36	17.0
One batch -500 pieces (day production)	400	280	680	8,500
* Tanzanian shillings, in 2008 £1 = Tsh. 2500				

This water cost, if omitted from the project costing, may give a significant negative impact on any project development. As the value of one brick is 250 Tsh, the cost of water is about 7% of sale price (yet normal profit margin is typically only 7.5% of the brick value) that means if water cost is excluded from expenditure the profit margin cover no more than 0.5%. Such under-estimation of water requirement in brick production can prevent further development of projects, because to minimise production cost bricks are often not cured properly.

### **3.3 MT PERFORMANCE AND COST REDUCTION**

#### **3.3.1 ELEMENTS OF COST REDUCTION**

A major objective for an efficient and effective new technology is to make a saving in *material and/or labour time*. Early in Section 2.5 it was shown that for Mortarless Technology (MT) to operate properly bricks, need to be self-aligning and provide an effective locking. The use of MT in bricklaying reduces or even removes a number of operations: mortaring joints, aligning operations (levelling and straightening), and rendering. From reduced construction operations, MT results in a reduction of construction duration of up to 60% *Whelan (1985), Hines (1993), Anand and Ramamurthy (2003)*. Due to the simplicity of the construction process of MT, it can be easily managed by semiskilled labour and therefore

cuts the labour cost up to 80% *Harris et al. (1992), Hines (1993) and VanderWerf (1999)*. Changing to MT also can enhance the labour productivity of wall construction by more than 80% *Whelan (1985), Anand and Ramamurthy (2003)*.

Table 3.4 Compares the costs for the construction of one square meter masonry walls using respectively: (1) solid Hydraform Stabilized-Soil Interlocking Blocks (*ISSB-SA, Figure 2.4, South African type – 230mm thick wall*), (2) perforated Interlocking Stabilized-Soil Bricks (*ISSB-T, Figure 2.10, Tanzanian type – 150mm thick wall*), (3 and 4) walls constructed from Solid Conventional Blocks (*CB-1 and CB-2, with 150mm and 230mm thick walls respectively*). Although the wall thicknesses of the four options are not the same, this can be allowed for. All costs of materials, transport, labour and the construction processes are for Tanzania in 2005/2006. Materials costs include site delivery.

### **3.3.2 WALL CONSTRUCTION STAGES**

The wall construction process includes the cost of materials and only four stages are considered (Table 3.4): Bricklaying (BL), Pointing/jointing (P/J), Rendering/plastering (R/P), and Wall-strengthening (WS). Painting and decoration is not included, assumed to be the same as the wall surfaces are well prepared.

The interlocking bricks are assumed perfectly produced and in good condition, likewise the sand-cement blocks. The bricks are built in the following wall construction stages: -

1. Bricklaying [costs per piece include materials (brick) and bricklaying labour per piece].
2. Jointing (cost is based on cement, sand and water per cubic meter ( $m^3$ ) of mortar).
3. Pointing of interlocking bricks (externally only); (unit cost includes mortar and labour per  $m^2$ ).

4. Rendering/Plastering (a standardized construction cost per square meter (m<sup>2</sup>), that includes mortar and labour). Some saving could be realized here by rendering soil-stabilized walls with a stabilised-soil plaster that matches the lean mix used for the bricks themselves; such lean plaster cannot be used on conventional blocks because it will not adhere properly. This option is not generally considered, but it should be in practice. Because of the machined MT brick quality, their external surfaces do not require rendering; only pointing to prevent insects breeding and moisture penetration. By contrast CB is usually given an external render to improve their appearance.
5. Strengthening interlocking brick walls by pouring grout through vertical holes. Hollow/Perforated interlocking brick walls *optionally* require strengthening by pouring grout (soil/sand-cement slurry) into the vertical holes through the wall *Kintingu (2003)*, forming 50mm diameter cores at 300mm centres throughout the wall.

This task (grouting) is normally done after completion of wall erection, while preparing the wall to receive a ring beam. Before doing so, we insert all conduit pipes in the required positions and any reinforcement if required. Placement of grout can be accomplished in one lift for single-story walls less than 8.5 ft (2.60 m) high. Grout lifts must be consolidated with an internal vibrator with a head size less than 25 mm *NCMA TEK 14-22 (2003)*.

The Hydraform solid interlocking block wall is by contrast strengthened by laying the first two to three courses and the four last/top courses with mortar like a conventional wall *Hydraform Manual (1988)*. Thus about a quarter of all courses are mortared and the remaining three-quarter is un-mortared (Table 3.2).

Other costs not included in the calculations are: -

- Supervision by:

- High-level expert (Engineers or Architects), which may be done on call (temporary) or on permanent basis.
  - The foreman, on a daily routine.
- Material wastage
  - Security of the site.

The above three listed items (supervision, material wastage and security) are normally categorised under ‘sundries’ and assumed to cost not more than 5% of the above four main wall construction stages.

**Table 3.4 Cost comparison of one square metre wall in Tanzanian Shillings (Tsh.)**

S/No	Stages of wall construction (cost for material and labour)	Wall Type			
		Interlocking Soil-Stabilized Bricks (ISSB)		Conventional Sand Cement Blocks (CB)	
		Tanzanian ISSB-T 150mm	Hydraform ISSB-SA 230mm	Solid CB-1 150mm	Solid CB-2 230mm
1	Bricklaying (BL)	7755	11600	14400	22400
2	Jointing/Pointing (J/P)	1	3	1196	1589
3	Rendering/Plastering (R/P)	3675	3675	7350	7350
4	Wall Strengthening (WS) (filling vertical holes with mortar)	482	0	0	0.0
<b>Total cost for each type of wall including 5% sundries</b>		12509	16042	24093	32906
<b>150 mm wall equivalence</b>		12509	10462	24093	21460
<b>Normalised to ISSB-T costs</b>		<b>1</b>	<b>0.84</b>	<b>1.93</b>	<b>1.72</b>
<b>Average for each wall type</b>		<b>11485</b>		<b>22776</b>	

### 3.3.3 COST ANALYSIS

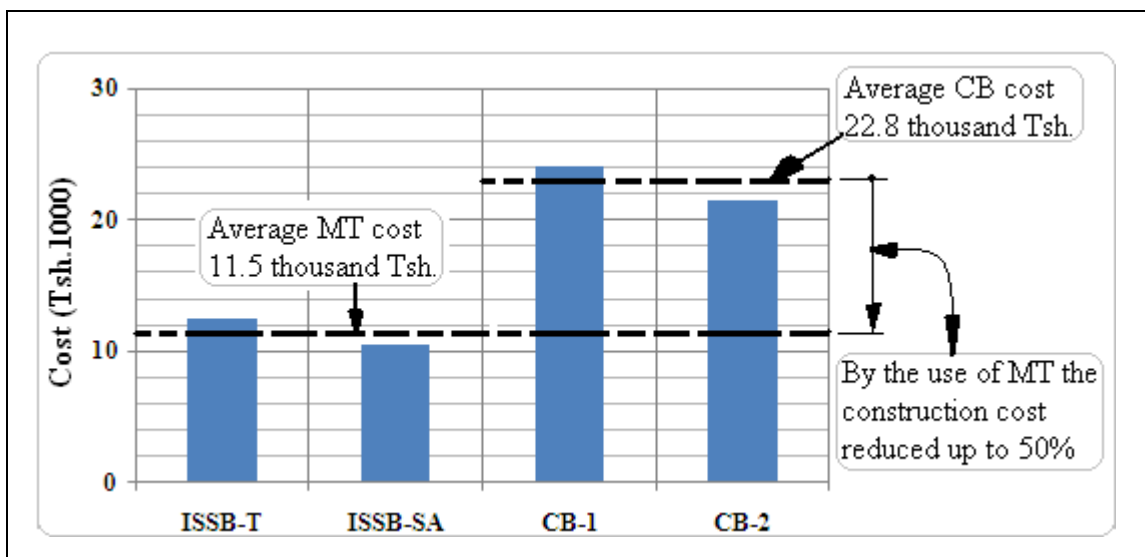
Table 3.4, which combines labour-costs with material costs, compares the average 150mm-equivalent costs (Tsh.11485 and 22776) of MT and CB is summarised in Figure 3.2. It shows that using mortarless technology we can reduce construction cost by 50% (i.e.  $MT/CB = 11485/22776 = 0.50$ ) due to the use of cheaper material and elimination of some of the construction operations.

An alternative approach (Table 3.5) is to look at materials costs and labour separately in the following order:

- (a) The CB material cost to labour cost ratio is assumed as 70:30 *UN (1965)*.
- (b) Estimates of MT/CB cost ratios for material ( $R_m$ ) and labour ( $R_L$ ) are respectively made
- (c) Finally the data is combined to obtain MT/CB overall cost ratio.

For the value of  $R_m$ , the material cost ratio, we adopt the approximate value  $MT/CB = 0.5$  from Figure 3.2 the extraction of Table 3.4.

**Figure 3.2 Comparison of construction cost between MT and CB**



The value of  $R_L$ , the labour cost ratio, was estimated after a number of considerations were made. Interlocking bricklaying is three to five times faster than conventional bricklaying *Whelan (1985), Anand and Ramamurthy (2003)*. This can be best compared in terms of wall area covered per day rather than number of bricks laid per day. Taking an average laying rate of 1150 pieces per day of interlocking bricks *Hines (1993), VanderWarf (1999)*, and knowing 33 pieces of ISSB-T cover one square meter (Table 3.1), gives that 35m<sup>2</sup> of wall can be completed in a day by one mason and one helper. With conventional blocks and the same wall thickness (CB-1) the same masons can lay an average of 225 pieces (each weighing over 30 kg), equivalent to only 25m<sup>2</sup> of wall per day. Here we can see that the labour productivity has been increased by 40% if we use the CB-1 as the datum for comparison. (Taking CB-2 this increases to 120 %.). We can support the above arguments by the summarised efforts towards improving construction productivities reported by Anand and Ramamurthy (2003) Table 3.5.

**Table 3.5 Productivity enhancement as a means of labour cost reduction**

S/No.	Source	Type of interlocking block	Productivity % increase	Labour cost ratio ( $R_L$ )
1.	Whelan (1985)	WHB hollow block	79	0.50
2.	Adamus and Spevak (1986)	TSZ hollow block		0.35
3.	Hines (1993)	Haener hollow block	60	
4.	VanderWerf (1999)	Haener hollow block	80	0.35
	VanderWerf (1999)	Sparlock hollow block	80	0.33
	VanderWerf (1999)	Azar hollow block	50	0.33
5.	Anand and Ramamurthy (2003)	SILBLOCK/HILBLOCK	80	
	<b>Average</b>		<b>71.5</b>	<b>0.37</b>

According to *Harris et al. (1992) and Hines (1993)* with the combined effect of less skilled labour and increased output, MT is estimated to reduce labour cost by as much as 80%. From this estimate; we determine that  $R_L \geq 0.2$ .

We may adapt a value of  $R_L = 0.3$  (interpolating between 0.37 from Table 3.5, and 0.2 from Harris and Hines. Table 3.6 thus results into:



**Table 3.6 Costs of materials and labour separated**

<b>Bricklaying system</b>	<b>Material Cost</b>	<b>Labour Cost</b>	<b>Total Cost</b>
<b>CB*</b>	70%	30%	100%
<b>Ratio of MT/CB</b>	0.5	0.3	-
<b>MT**</b>	35%	9%	44%

**NOTE:** \* Conventional Blocks.

\*\* Mortarless Technology, partial costs expressed as % of CB Total Cost for given wall area.

MT/BC - assumed ratio of (MT to CB) costs for each input.

The value of MT labour cost being 9% of the conventional total cost, and therefore making MT total cost equals 44%. However MT realises 56% cost saving compared to CB.

### 3.4 SUMMARY

Building industry can make a step forward to protect the environment by making the revolutionary choice of using alternative walling materials (dry-stacked stabilised-soil bricks) to replace conventional (sand-cement-blocks) that consumes more cement. The use of dry-stacked stabilised-soil bricks realised more than 50% cement saving, thus a reduction of up to 40% of CO<sub>2</sub> released by cement production.

The study identified the importance of water in the quality control of material using cement, showing a simple method for estimating the water quantity needed for production and curing.

It estimated that water cost equalled 7% of brick value (selling price), equivalent to the normal net profit margin. So omitting water costs in estimating production expenditure can result in losses and ultimately the death of brick-production projects.

Finally the chapter compared the cost of wall construction using mortarless and conventional technologies. MT shows a potential saving of more than 50%, this may make a substantial contribution to making housing affordability to the low income people.

# CHAPTER 4

## 4.0 INTERLOCK-BRICK WALLING FLEXIBILITY

### 4.1 INTRODUCTION

The difficulties of getting interlocking brick systems to adapt to a variety of conventional wall construction configurations and shapes, joints and thicknesses, led to the study of how to enhance the flexibility of dry-stack interlock-brick walling.

Chapter 2 described six types of interlocking stabilised-soil bricks/blocks (ISSB), the low-cost building material for wall construction. The existing range of interlock brick designs in the market as reported by *Thanoon et al. (2004)* is an indicator of popularity of Mortarless Technology (MT) in the world; the ISSB technology is gaining more popularity in Developing Countries. The author developed the Tanzanian Interlocking Brick (TIB) Figure 2.10, after studying the deficiencies of the Bamba interlocking brick system (Figures 2.6, 2.7 and 2.8) *Kintingu (2003)*. This Chapter describes new developments of TIB under this PhD program in response to building industry demands, from which interlocking bricks (IBs) have demonstrated weakness compared to hitherto, i.e. MT using IBs has been incapable of constructing:

- (a) Various brick-bonding joints
- (b) Piers attached into walls
- (c) Thicker walls (thickness more than half brick length)
- (d) Circular and polygonal wall configurations

There are terminologies used in the previous Chapters requires further description for better elaboration of dry-stacked interlock-brick walling technology.

<b>Technology flexibility</b>	is the ability to perform variable tasks
<b>Common element</b>	is a regularly or normally used element, and can be produced with a normal or standard machine.
<b>Conventional technology</b>	is the existing standard (i.e. mortared brick) technology

#### 4.1.1 BACKGROUND

The efforts to improve construction performance of interlocking bricks in Tanzania starts back in year 2000 when the author faced one of the fundamental requirements of the building construction using Bamba interlocking brick (Figures 2.6 and 2.7), namely: to provide means of joining interlock brick walls when they meet to form tee joints or cross joints Figure 2.8. The solution was to produce a three-quarter bat, *Kintingu (2003)*, which raised the performance of mortarless technology by 2 scores (tasks 3 and 4 in Table 4.1). Before the development of Three-quarter bat the general performance of interlocking bricks was only 2 scores (tasks 1 and 2 in Table 4.1). In 2003, the further improvement of Bamba system resulted into the formation of TIB Figure 2.10, which we can take as the starting point for this PhD programme. We now compare the MT (Interlocking Bricks-IB) vis-à-vis Conventional Technology (CT).

The wall construction flexibility of CT and the IB before this PhD programme is compared in Table 4.1. The number of tasks the technology performs shows how flexible the technology is. The existing or conventional (mortared) bricks used here as a base line. We can see that IB in 2000 could not solve some common wall-construction tasks and therefore require more effort to improve them.

**Table 4.1 Wall construction flexibility of CT and IBs (year 2000 technology)**

S/No.	Construction Operations	Types of Interlocking brick/block (IB)							Conventional Technology (CT)*
		Canadian & USA		Indian	South African			Thai	
		Haener interlock system	Sparlock interlock system	Auram	Bamba	Hydraform	Solbric		
1	Setting a right angled corner for a ½B wall	✓	✓	✓	✓	✓	✓	✓	✓
2	Bricklaying in stretcher bond	✓	✓	✓	✓	✓	✓	✓	✓
3	Construction of cross and tee joints of ½B walls	X	X	X	X	Special preparations	X	Site cutting	✓
4	Attachment of ½B wide piers to ½B thick wall	X	X	X	X	By shaving	X	Site cutting	✓
5	Attachment of piers wider than ½B to ½B wall	X	X	X	X	X	X	X	✓
6	Construction of isolated piers wider than 1½B	X	X	X	X	X	X	X	✓
7	Construction of 1-Brick thick wall	X	X	X	X	X	X	X	✓
8	Attachment of piers to 1-Brick thick wall	X	X	X	X	X	X	X	✓
9	Construction of curved wall	X	X	X	X	X	X	X	✓
10	Construction of polygonal wall	X	X	X	X	Cutting and shaving	X	X	✓
<b>Flexibility score</b>		<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>10</b>
<b>Brick-parts (elements)*</b>		<b>3</b>	<b>3</b>	<b>3</b>	<b>2</b>	<b>2*</b>	<b>4</b>	<b>1*</b>	<b>1*</b>

\* - Typically a full brick (FB), distinct elements are created by cutting on site (half bat - ½B, three-quarter bat - ¾B and closer – CL)

From this table we can see that, in the stage of development reached by IB systems in 2000, none had a flexibility score exceeding 2 points of 10 unless some cutting or shaving on site is employed. Such site work removes the fundamental advantages of IB.

Before we address the outstanding problems, which are the subject matter of this Chapter (listed in Section 4.1), it is important to get enlightened to brickwork patterns, brick shapes, wall configurations and the importance of brick-parts for brickwork bonding.

### **4.1.3 BRICKWORK PATTERNS**

The construction of masonry wall is an arrangement of brickwork into a defined pattern known as bonding. These patterns are formed into consecutive courses (horizontal layers) with uniform and constant overlaps of individual bricks laid one over the other. The vertical joints (perpends) in alternate courses should be in line and truly vertical throughout the height of the wall, however there should be no continuity in the perpend-lines from any course to the course immediately above it. And the courses should be level (*The BDA Guide 2000, Nash 1991*). For constructing one-brick (230mm thick) walls, many types of bonding pattern have been used for centuries: the most popular ones are Stretcher and Header, English, Flemish and Garden bonds. For half-brick walls only the Stretcher bond is feasible. English, Flemish and Garden bonds are combinations of stretcher and header bonds. In English bonding the stretcher and header patterns alternate in consecutive courses, while in Flemish bonding the stretchers and headers alternate in the same course. The Garden bond is a variation of English and Flemish bonding with increased number of stretcher courses (3 or 5) for every one-header course in English bond, and for Flemish bonding headers are inserted after every 3 or 5 stretchers of the same course.

None of the above patterns are perfect or correct without the addition of part-bricks to fulfil the objectives of true and proper bonding of a masonry wall. Therefore part-bricks are important units to enhance bonding accuracy, effectiveness and flexibility. Also if the part-bricks are ready-made, not cut at site, it will save time, labour and material (*Knight, 1997*).

### **4.1.4 BRICK SHAPE**

Different brick-set designs vary in configurations/shapes. But at the same time from one design it is possible to form several shapes (*Figure 2.10*) by cutting the brick into parts as demanded by the pattern. In conventional bricklaying, such cutting is a normal process, used

to achieve the desired pattern during construction. However, it is difficult to cut accurately without high-standard equipment and skills, the process requires labour-time and wastes substantial amount of material. Mortarless technology (MT) assumes production of all part-bricks right from the mould/machine as standard, instead of cutting at site: this gives precision and economic advantages.

#### **4.1.5 WALL CONFIGURATIONS**

The simplest wall configuration is a straight and right-angled wall that forms a rectangular room or yard boundary. Whenever we require more complex wall configurations, then we should think about special patterns (bonds), and the cutting of bricks to different shapes (*BS 4729: 2005*) to fit the proposed wall configuration and therefore allow stacking to a particular pattern. The main purpose of building different wall configurations in a house is to break the monotony of wall appearance and thus increase the building's aesthetic appeal. One major constraint on using interlocking bricks is the difficulty of employing them in the construction of curved and polygonal walls. Although there are special bricks for such wall configurations, in remote areas (especially of developing countries) it is not easy to get them.

Curved and polygonal walls are however normal architectural features and designers will not appreciate any new technology not providing such flexibility. Interlocking brick by its shape is restricted to a particular pattern of half brick overlaps. Due to geometric rigidity, for most interlocking bricks it is considered not possible to build curved and polygonal walls unless special bricks are made. In this chapter the author analyses and describes a few alternative ways to resolve the problem.

## 4.2 BRICK-SET DESIGN TO ENHANCE THE FLEXIBILITY OF INTERLOCK WALLING

In chapter 2, Figure 2.10, introduced the particular interlock system “Tanzanian” on which all subsequent PhD work would be based.

### 4.2.1 COMMON PART-BRICKS

“Common element” was defined in Section 4.1 as a part-brick, which is regularly used and can be produced using a standard machine. We can summarise the common part-bricks available made by cutting on site, used in CT and counter check its availability and use in the IB<sub>2003</sub> (Table 4.2).

**Table 4.2 Common brick elements**

<b>Part- bricks</b>	<b>CT</b>	<b>IB<sub>2003</sub></b>
Full brick	✓	✓
Three-quarter bat	✓	✓
Half bat	✓	✓
Closer (quarter bat)	✓	X

With part-bricks we change the length of the brick in order to enable the overlaps (*half or quarter brick*) between two consecutive courses to abide to the rules of the chosen bond type. Common part-bricks used for decades (defined in Section 2.2.1) are the half bat, three-quarter bat and the closer *Nash (1991), The BDA Guide (2004)* Table 4.2.

Using the common part-bricks shown in Figure 2.10, Mortarless Technology (MT) can construct in stretcher bond only a half-brick thick wall Figure 4.1. The common bond (stretcher) is used in MT because of the configurations and locking features provided. The locking features make the difference between the two technologies (MT and conventional).

## 4.2.2 HALF-BRICK WALL

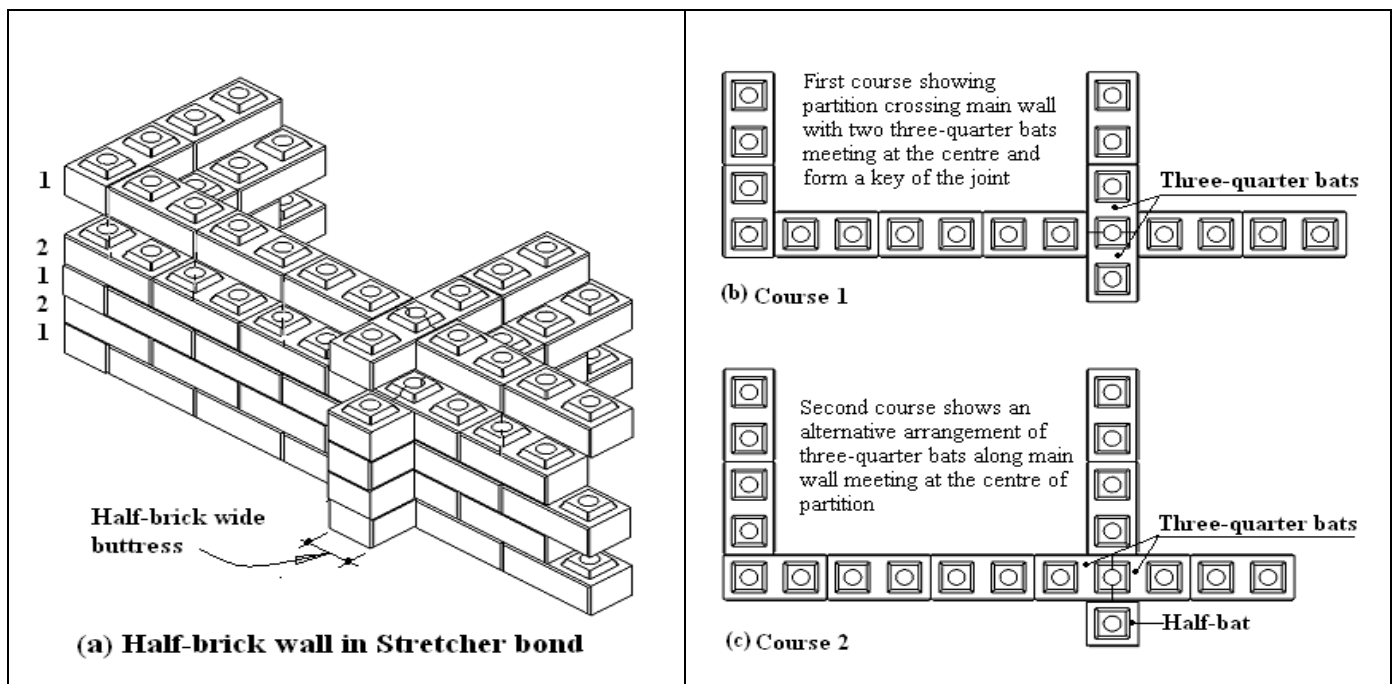
The assembly method for interlocking bricks in 2003 was a stretcher bond (Harris et al. 1992) making a half-brick thick wall, using bricks with their width equal to half of their length. Using three-quarter bricks it was possible to form tees, pier or cross joints (*Kintingu (2003)* as shown in Figures 2.8 and 4.1.

Figure 4.1(a) shows an isometric view of a half-brick quoin and junction wall adjoining a half-brick main wall in Stretcher bond. The top course is raised to show the bonding arrangement in alternate courses and how the  $\frac{3}{4}B$  facilitate formation of the cross joint.

Figures 4.2b and 4.2c demonstrate the first and second courses of this bonding in plan view.

The main task of this PhD programme was to improve the ability of interlocking system to make more types of wall joint, and configurations whose absence up to 2003 was a key market weakness of MT.

**Figure 4.1 Common bond for interlocking bricks (2003 technology)**

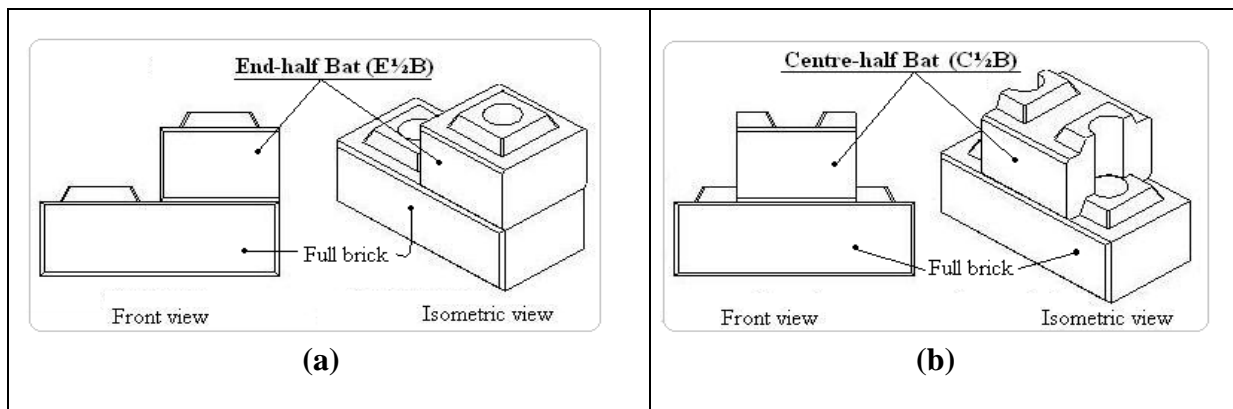




### 4.2.3 DEVELOPMENT OF A NEW PART-BRICK

In CT we have a half bat i.e. an element usually cut on site, which is half the length of the brick. Once made, this element can be placed in line with one end of the brick below or in line with the centre of the brick below. In the case of IB, half-size bricks have so far been designed to align with the end of the brick below Figures 2.7 and 2.10, and strictly we might call them ‘end-half bats’ ( $E\frac{1}{2}B$ ) Figure 4.2(a). We now wish to introduce a second type of half brick for location above the centre of the brick below, which we will call ‘centre-half bat’ ( $C\frac{1}{2}B$ ) Figure 4.2(b). Unlike CT, in IB construction, due to interlocking requirements the  $C\frac{1}{2}B$  and  $E\frac{1}{2}B$  are not the same: they are different elements.

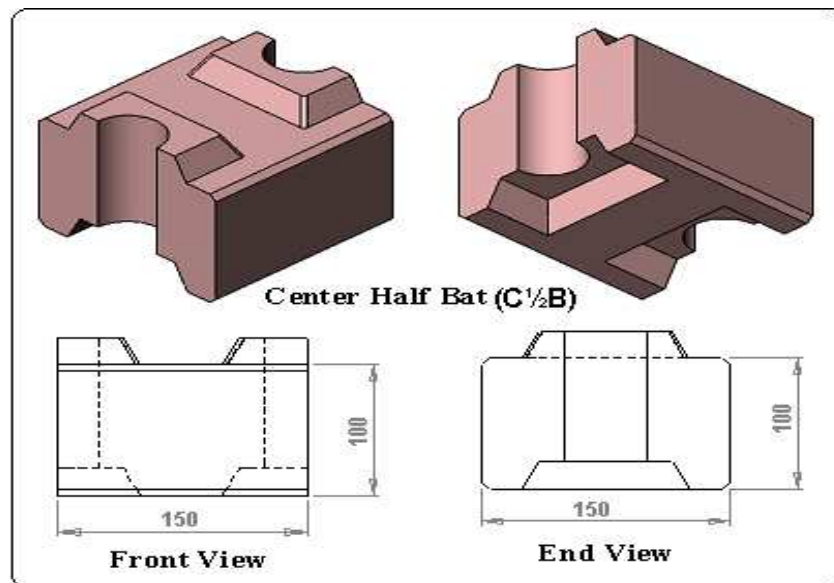
**Figure 4.2 Two  $\frac{1}{2}$ -bricks for the Tanzanian interlocking brick (TIB) system**



This PhD program started with the brick-set available shown in figure 2.10, which includes  $E\frac{1}{2}B$  Figure 4.2(a). Many trials of laying half-brick and one-brick walls attached to different sizes of piers (*brick columns of 1-Brick,  $1\frac{1}{2}$ -Brick and 2-Bricks*), confirmed the potential of a new part-brick (Centre-half bat -  $C\frac{1}{2}B$ ) shown in Figures 4.2(b) and 4.3. The  $C\frac{1}{2}B$  is a brick modified to exclude the two end quarters and remain with the centre half portion.

Bricklaying using the  $C\frac{1}{2}B$  does not follow the well-known bond types, but it conforms to the basic rule of bonding, namely the prevention of continuous straight joints (*vertical and cross*) running through consecutive courses.

**Figure 4.3 Details of a Centre-half bat (C½B)**



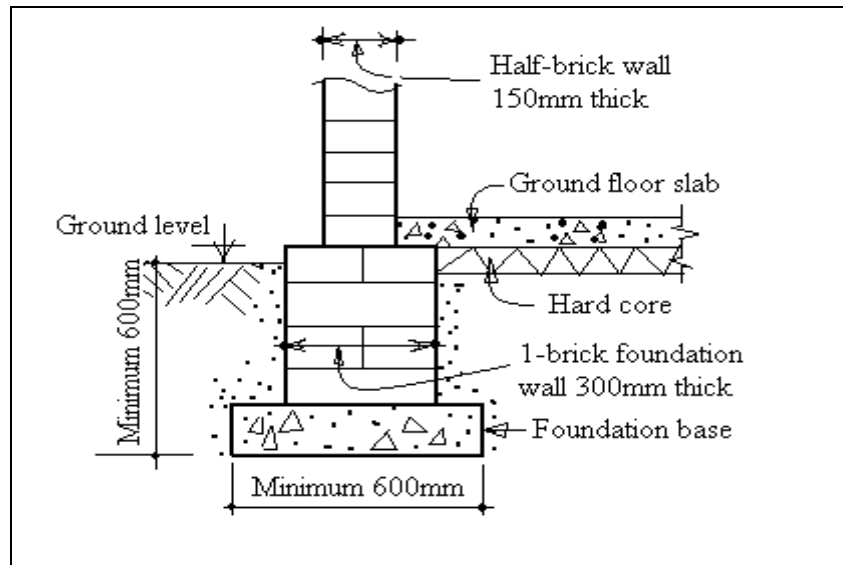
The major contribution of C½B is in enabling:

- the attachment of buttresses wider than ½-brick to walls
- the construction of isolated piers wider than 1½-brick
- the formation of two new bonds (*Shokse and Lijuja Figures 4.9 and 4.14*)

The common thickness for solid walls has been taken as 150mm. Foundation walls are normally twice the width (300mm) of solid walls. Figure 4.4 show a ½-brick wall built on a 1-brick foundation wall, a typical foundation used for single story buildings.

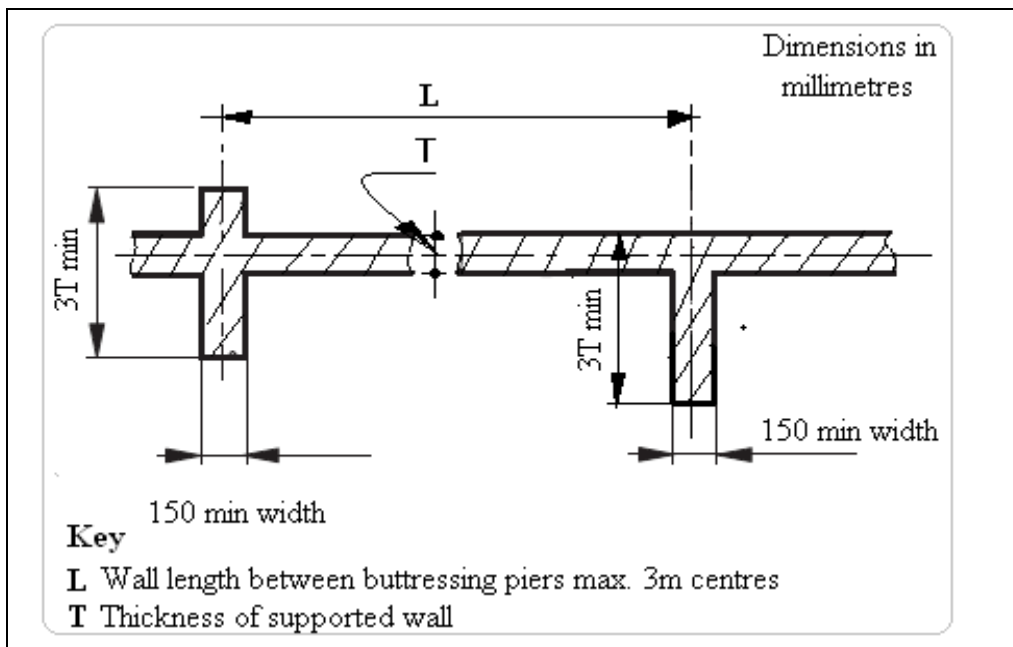
This research has therefore adopted 150mm thickness as standard for solid walls and 300mm as a maximum thickness for foundation walls (Figure 4.4).

**Figure 4.4 Typical single story brick wall foundation**



The minimum width for a buttressing pier is  $\frac{1}{2}$ -brick (150mm) Figure 4.5, and a maximum width for a buttressing pier and of an isolated solid brick pier has been taken to be 2-bricks (600mm).

**Figure 4.5 Piers providing restraint to wall**



## **4.3 USES OF C½B'S IN THE ASSEMBLY OF INTERLOCKING BRICK - WALL**

Because there is no mortar to bind them, dry-stacked bricks are vulnerable to shaking during construction. They require strengthening to achieve tolerable plumbness and straightness in walls over 3m long (Figure 4.5) or over 2.5m high. In Tanzania, cheap farmers' stores are built using concrete partial frames with a centre-to-centre distance of 4.5m to 6.0m and height more than 3.5m. To build a masonry wall to infill the spaces, requires the formation of buttressing piers wider than ½-brick. The invention of C½B allows construction of piers of different widths (1-brick, 1½-brick, 2-brick etc.) attached to wall at their ends, corners, middle and at junctions. The following subsections illustrate both attached piers to ½-brick thick walls (buttressing) and isolated piers.

### **4.3.1 PIERS**

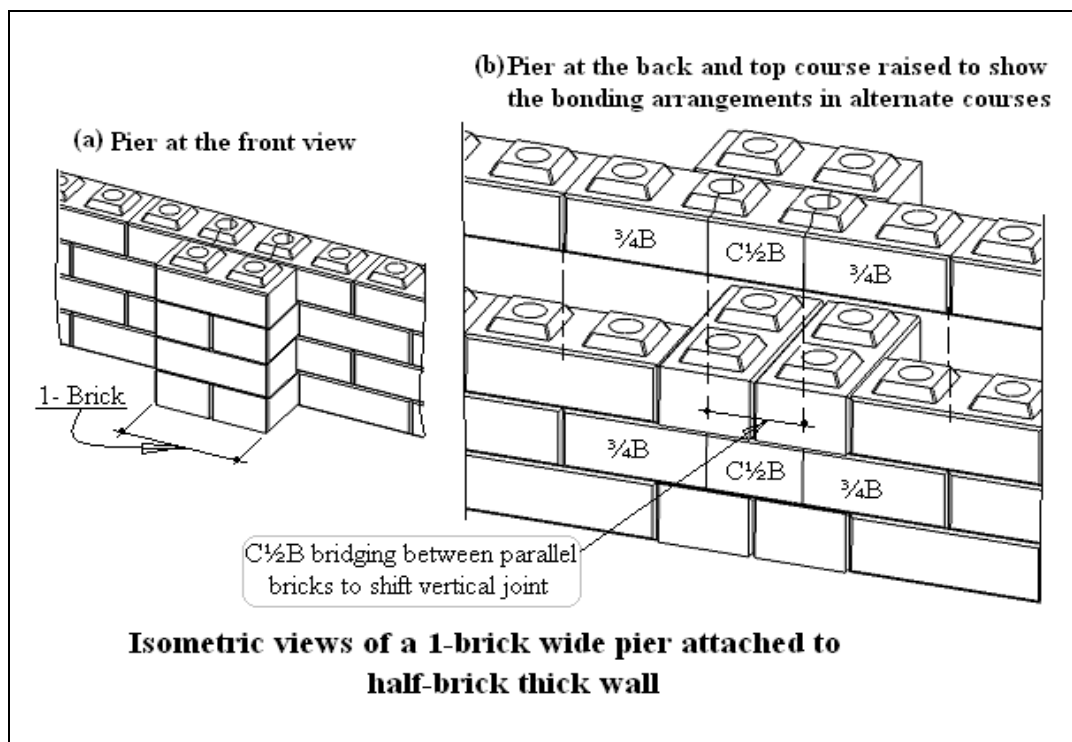
A pier is a localised wall thickening, designed to increase a wall's vertical and horizontal stability and lateral strength. Piers may be isolated from, or attached to, the wall. Isolated piers are simple brick columns. Attached piers are combined or joined to the wall and form protrusions of ½-brick or 1-brick depth or even more. Accordance to *BS 8103-2:2005*, the minimum length of buttressing pier is three-wall thicknesses Figure 4.5. Using the new brick shapes it is possible to construct sizes of isolated piers and attached piers (*at wall quoin, junctions and along the walls*). These piers can be reinforced if required. Let's look at a few examples of how to bond the joints formed by attaching piers to walls.

### 4.3.2 ATTACHED PIERS

The use of  $C\frac{1}{2}B$  is illustrated in Figure 4.6 showing a pier attached along a wall of half-brick thickness. In the top course Figure 4.6(b) shows how to alternate the joints from first course by the use of  $C\frac{1}{2}B$ , it is bridging between the two parallel bricks of the pier and shift perpendicular (vertical joint) to the centre of the two bricks.

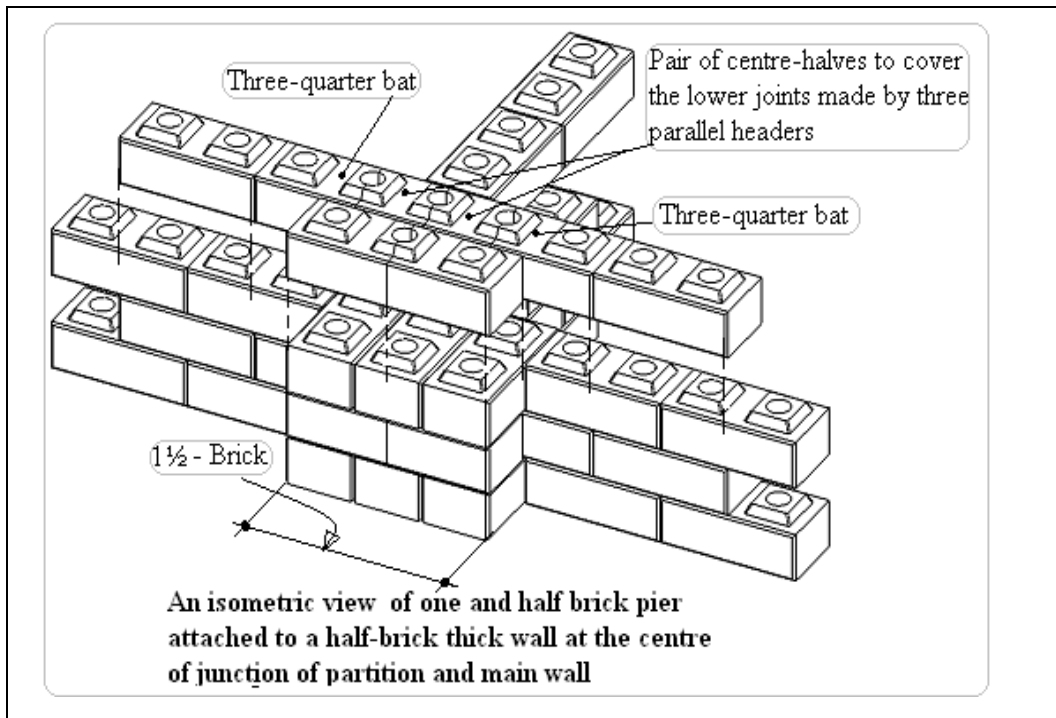
The ends of the  $C\frac{1}{2}B$  are joined or closed by the  $\frac{3}{4}B$ s at both sides to regulate the normal overlaps to half brick for the proceeding brickwork.

**Figure 4.6 Construction of attached piers enhanced by centre-half bats**



The same pattern appears in Figure 4.7, where even courses employ three parallel headers and the odd courses employ a mix of  $C\frac{1}{2}B$  and  $\frac{3}{4}B$  parts.

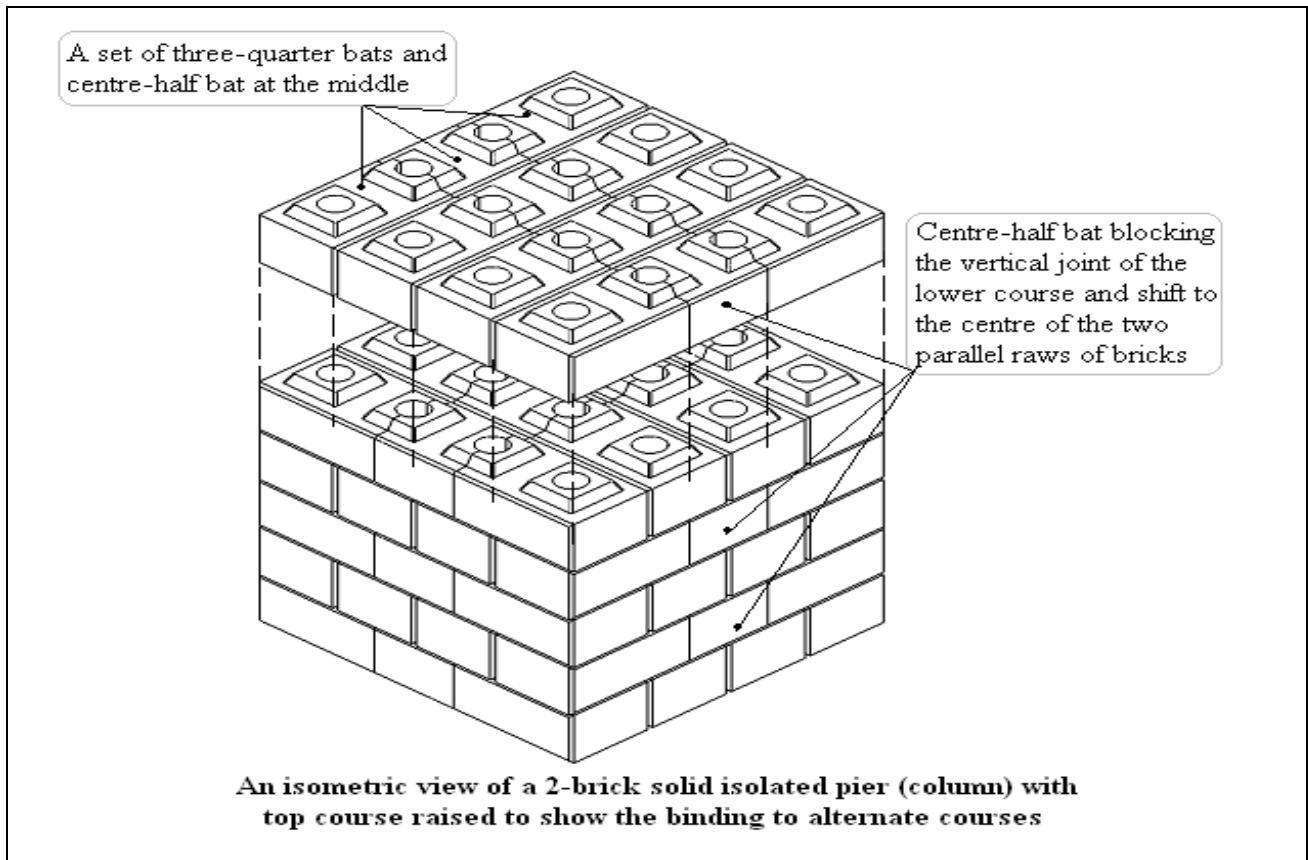
**Figure 4.7 Attached one and a half-brick wide pier**



### **4.3.3 ISOLATED PIERS**

Figure 4.8 show the only possible brick pattern for a square column with side length of two-brick lengths. It uses sets of two  $\frac{3}{4}$ Bs bats and one  $C\frac{1}{2}B$  alternating directions in consecutive courses. The normal size of isolated piers are one-brick (1 x 1), 1 x 1½, or 1½ x 1½ because they require few variety of part-bricks, therefore they are simple to assemble, save construction time and hence labour cost (because labour is normally paid per piece of brick laid).

**Figure 4.8 An isolated solid two-brick square column**



#### **4.4 FORMATION OF NEW BOND**

The new bond is needed, as the classical bonds cannot be formed from previously available interlock brick elements (FB,  $E\frac{1}{2}B$  and  $\frac{3}{4}B$ ). The development of a new interlocking element ( $C\frac{1}{2}B$ , Figure 4.3) facilitated the formation of two new bricklaying patterns (Shokse bond - Figure 4.9 and Lijuja bond - Figure 4.14) similar to English and Flemish bonds. The bases of new bonds start with Flemish bond. They differ in the second course, where the Shokse bond is similar to English bond and the Lijuja bond requires closers in a regular pattern, as other brick elements. This is contrary to conventional bonding, which allows use of closers only after quoin header. The new bonds make possible the construction of walls thicker than half-brick, which is a new practice to mortarless technology. The author

considers one-brick thick (300mm) wall to be a maximum thickness for conventional load bearing walls (Figure 4.4) and retaining walls, because of the cost implications of going any thicker. Compared with half-brick walls, such walls will double the requirements of material and labour work, which will add cost on both brick production and construction.

#### **4.4.1 SHOKSE BOND**

The bond developed to enable full-brick wall construction has been named ‘Shokse Bond’ – the word shokse is the author’s nick-name. Figures 4.9, 4.10 and 4.11 show consecutive courses for Shokse bond alternating as follows: the odd numbered (1) courses encompass stretchers (S) and headers (H) alternating in the same course Figure 4.10, the following even numbered (2) courses starts with a header followed by  $\frac{3}{4}$ -stretchers (Figure 4.9) meeting at the centre of the headers of the odd numbered courses. This makes a continuous and repeatedly pattern of *one and a half brick-length units*. At the tee junction of the second course Figures 4.9 and 4.10, the header is replaced by two C $\frac{1}{2}$ B units laid as stretchers in the even courses, bridging the two headers, side by side, in the odd courses.



**Figure 4.9 One-Brick thick wall in Shokse bond**

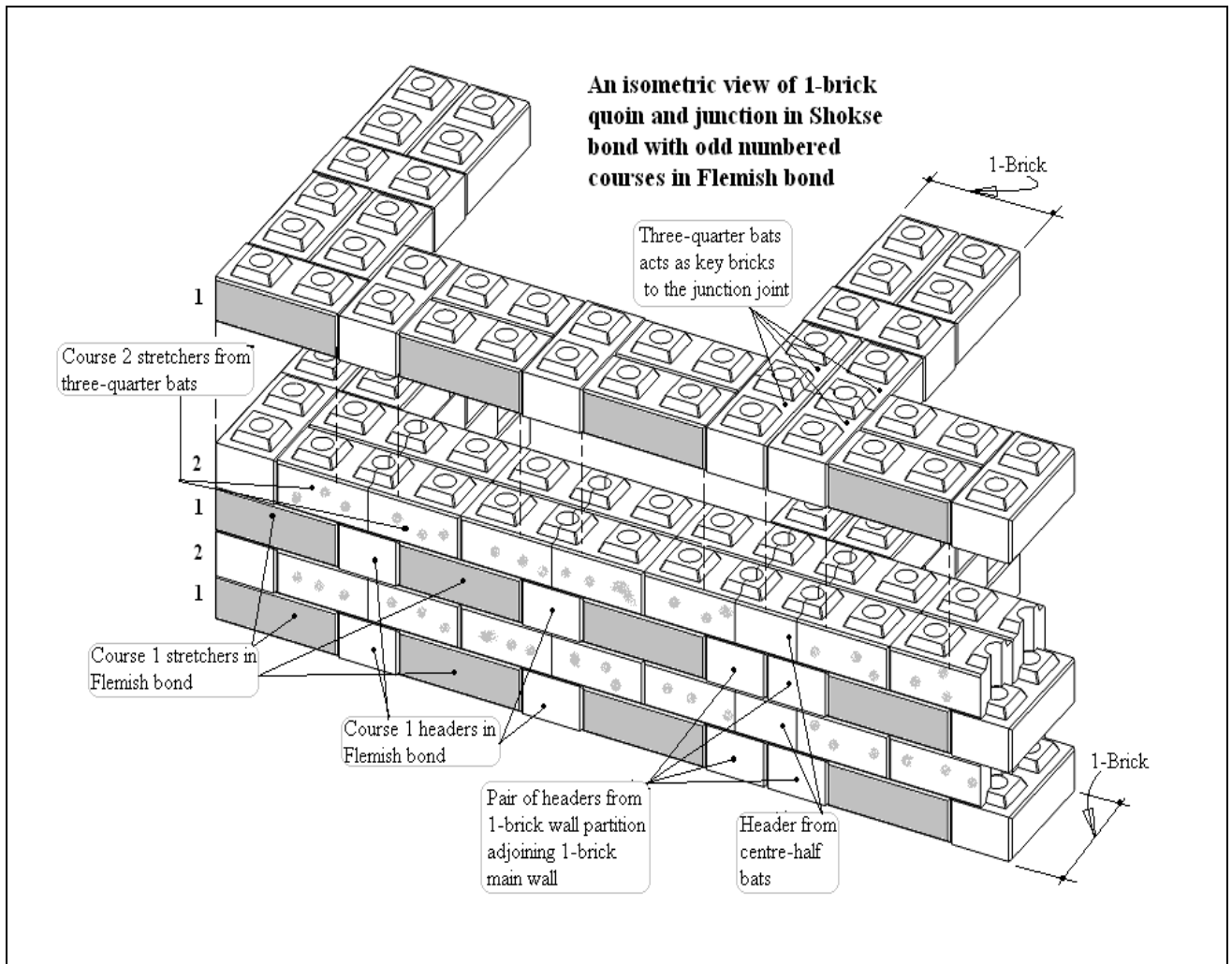
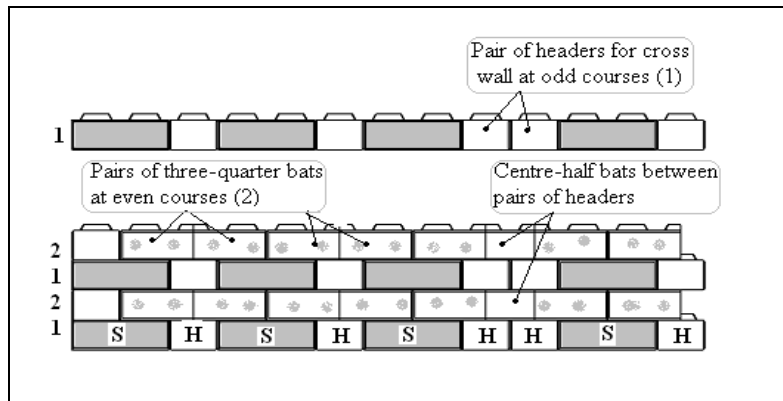
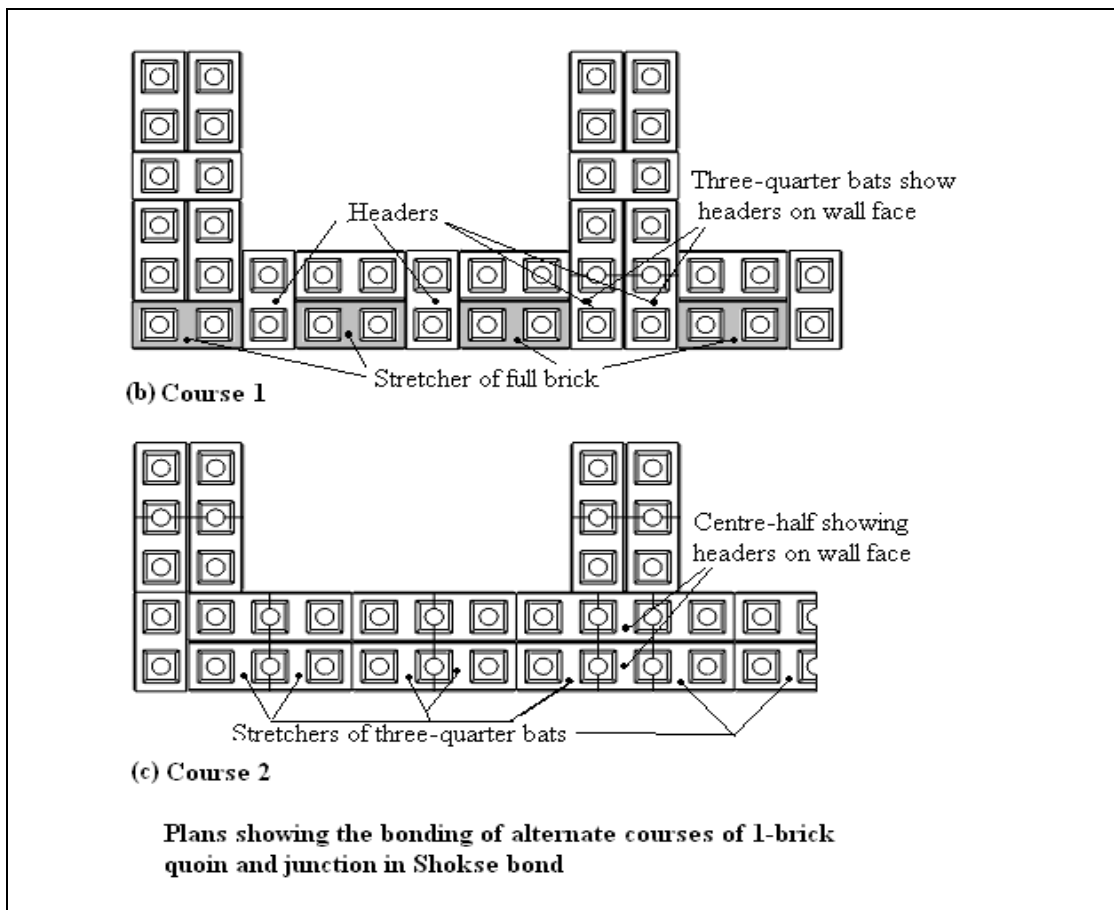


Figure 4.11 show plans of the two alternate courses in a one-brick quoin and junction wall in Shokse bond. Odd-number courses (1) are in Flemish bond, alternating stretchers and headers on the wall face, except at the tee junction. Even-number (2) courses start with a quoin header continues with  $\frac{3}{4}$  bats.

**Figure 4.10 Front elevation of a wall in Shokse bond**



**Figure 4.11 Plan views of course 1 and 2 of 1-brick thick wall in Shokse bond**

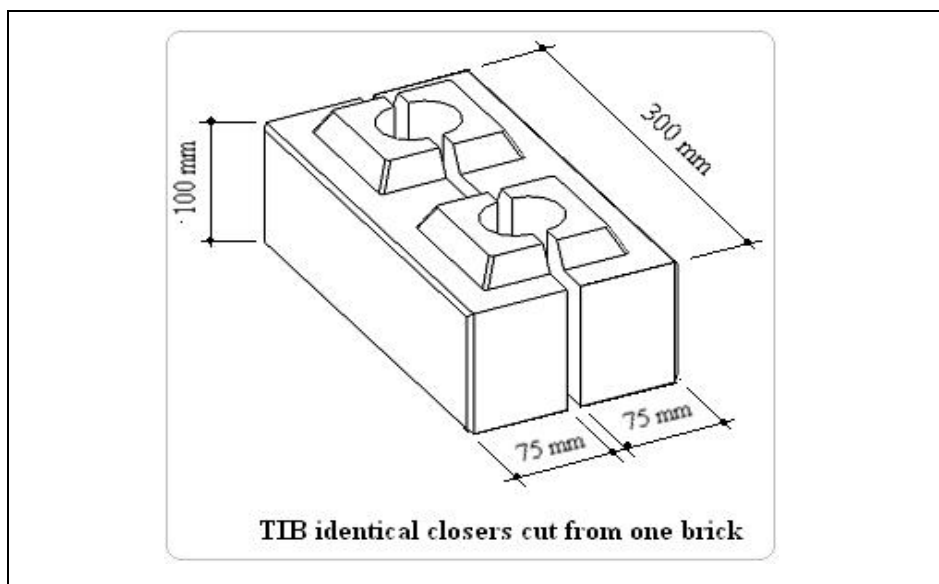


Walls constructed using Shokse bond are shown in Figures 4.9 and 4.10, It can be observed that except at the tee junction, there is a continuous joint between the inner and outer leafs making up even courses. Moreover a similar joint exists along  $\frac{2}{3}$  of each odd course. This

internal joint running throughout the wall height requires some means of blocking or locking. A solution was found by the use of a closer (CL). This solution effectively defines another new pattern (Lijuja bond) Figures 4.14 and 4.15. Lijuja bond is thus stronger but requires an extra component in the brick set.

CL is a common part-brick in conventional brickwork (Table 4.2); TIB closer Figures 4.12 and 4.13 was incorporated for the first time in interlocking bricks under this research program.

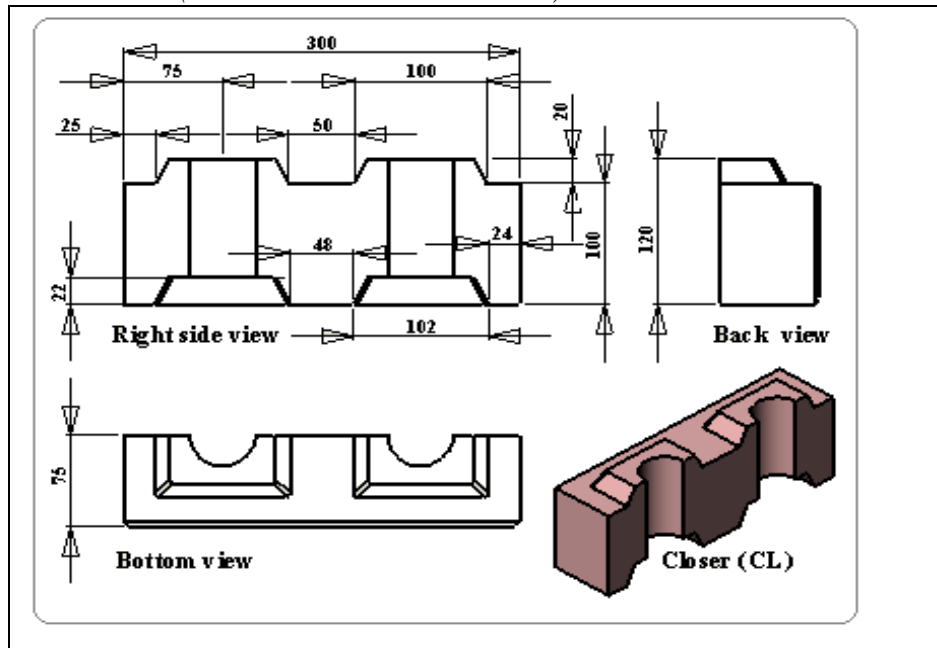
**Figure 4.12 TIB closer is a half-brick cut perpendicular to end face**



The traditional CL is a quarter-brick and according to The BDA Guide (2004) is named 'quarter bat'. By contrast, the TIB CL is twice the length of conventional CL. The TIB closer has the measurements (300 x 75 x 100mm); it is in effect a half-brick (see Figure 4.12 how is cut from a brick).

**Figure 4.13 Tanzanian Interlock Brick (TIB) Closer**

*(all measurements are in mm)*

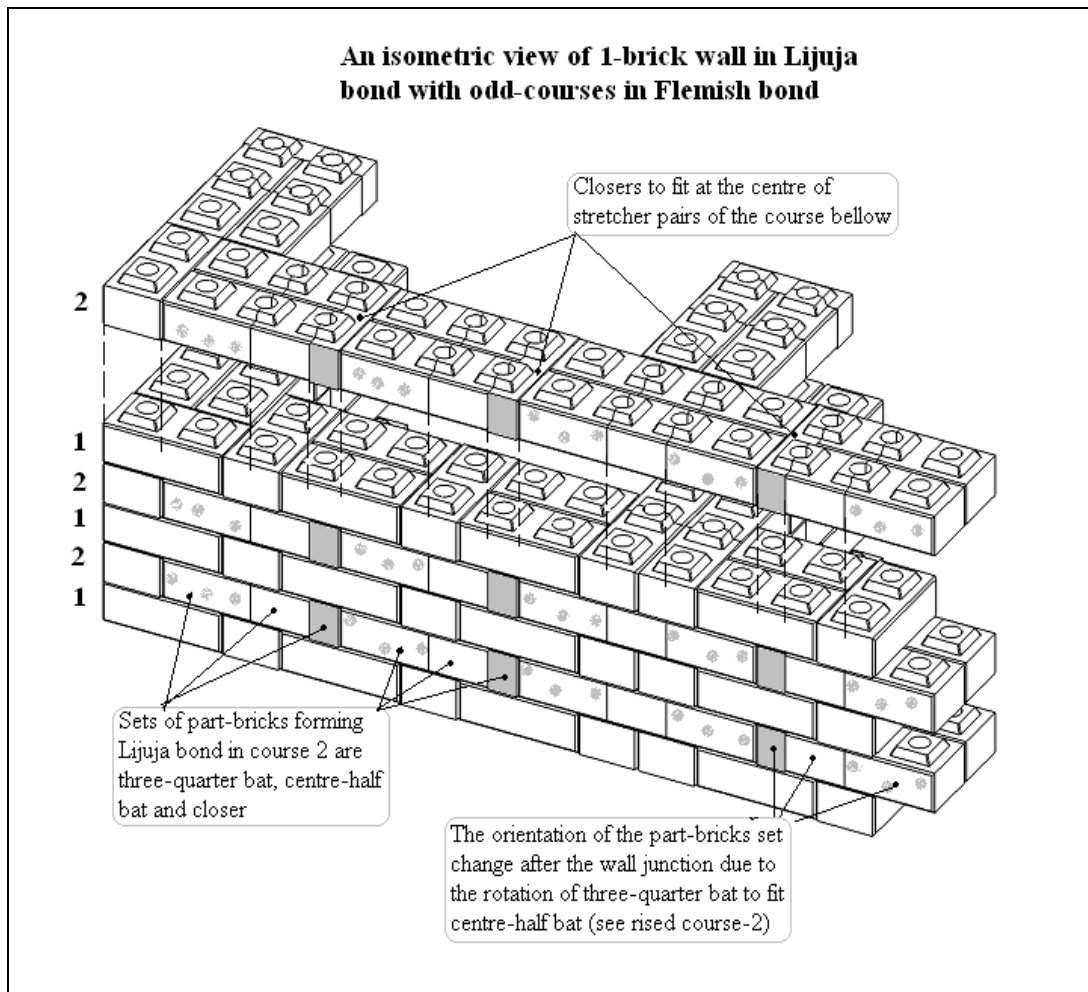


#### **4.4.2 LIJUJA BOND**

Lijuja bond incorporate CLs for the first time in the history of MT. Lijuja bond starts with the first course in Flemish bond as the Shokse bond (Figures 4.11). In the second course, after the quoin header, are found sets comprising one  $\frac{3}{4}B$ , one  $C\frac{1}{2}B$  and one CL repeated throughout the course. See Figures 4.14 and 4.15.

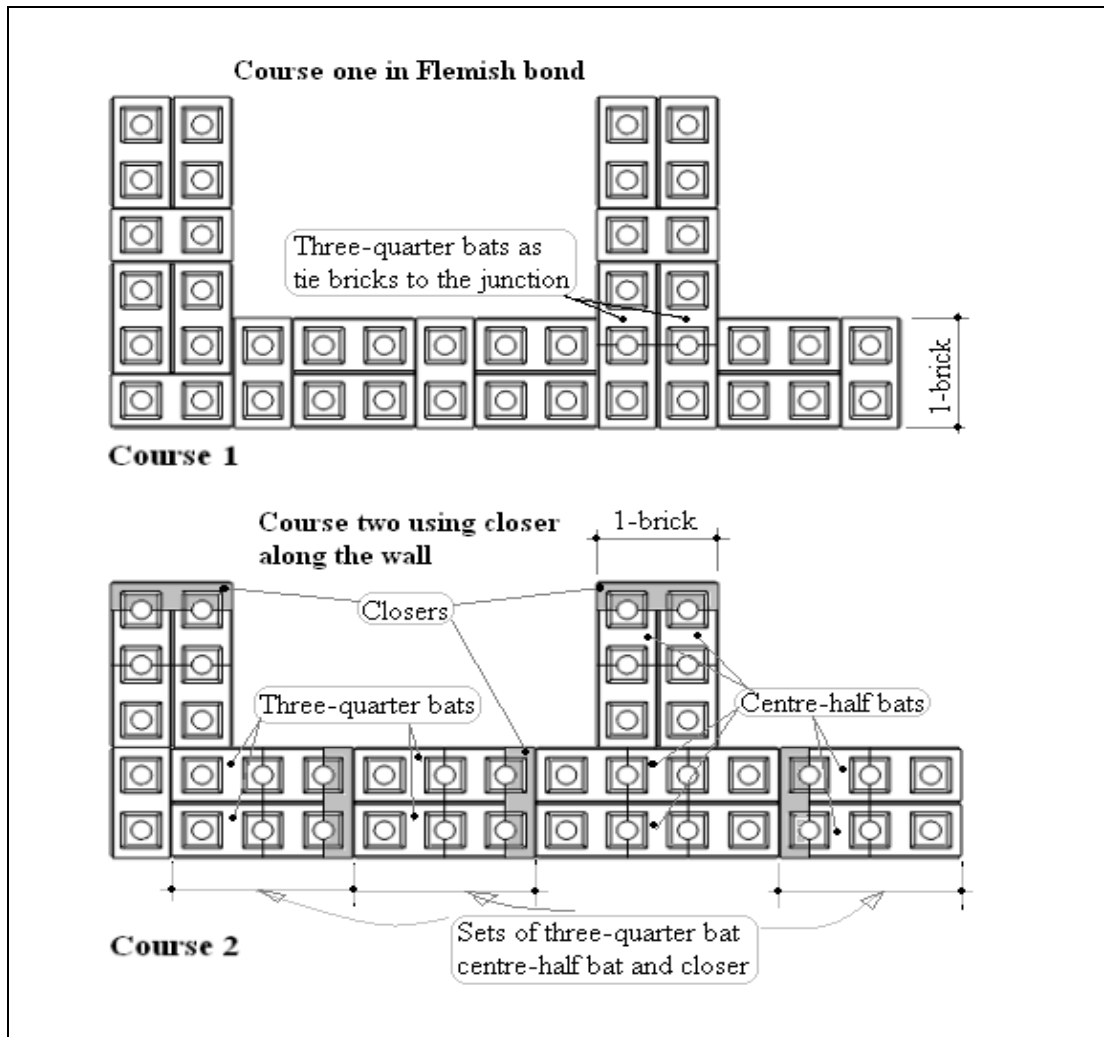
Most literature on brickwork does not recommend the use of CLs in the face of wall except next to the quoin header. However the Masonry Code of Practice (*BS 5628-3:2005 clause 5.11.1.1*) recommends that “*the horizontal distance between cross-joints in successive courses of brickwork should normally be not less than one-quarter of the masonry unit length, in no case less than 50mm for bricks and 75mm for blocks*”. This condition is observed in Lijuja bond, as the minimum horizontal distance of the cross-joints between the consecutive courses in Lijuja bond is equal to a quarter-brick length (75mm).

**Figure 4.14 One brick thick wall in Lijuja bond**



The purpose of adding CLs (see Figure 4.14 course 2) throughout the course is to reduce the *inherent continuous vertical joints* (Knight, 1997) and to tie stretcher bricks at their middle, preventing them from opening up.

**Figure 4.15 Plans of alternate courses of 1-brick quoin and junction wall in Lijuja bond**



The range of application of C $\frac{1}{2}$ Bs was thoroughly evaluated by trial and error. It was found that some other peculiar joints that were not possible to arrange even using C $\frac{1}{2}$ B. After many attempts at masonry joint construction, it was observed that perpendicular wall junctions forming tee joints, centrally attached to piers of 1-brick width Figure 4.16 require a special brick, the 'Tee Brick'(TB) shown in Figure 4.16. This is 'special' not because it requires a different shape of mould box (it doesn't), but because it can not be produced with cores in their normal positions.

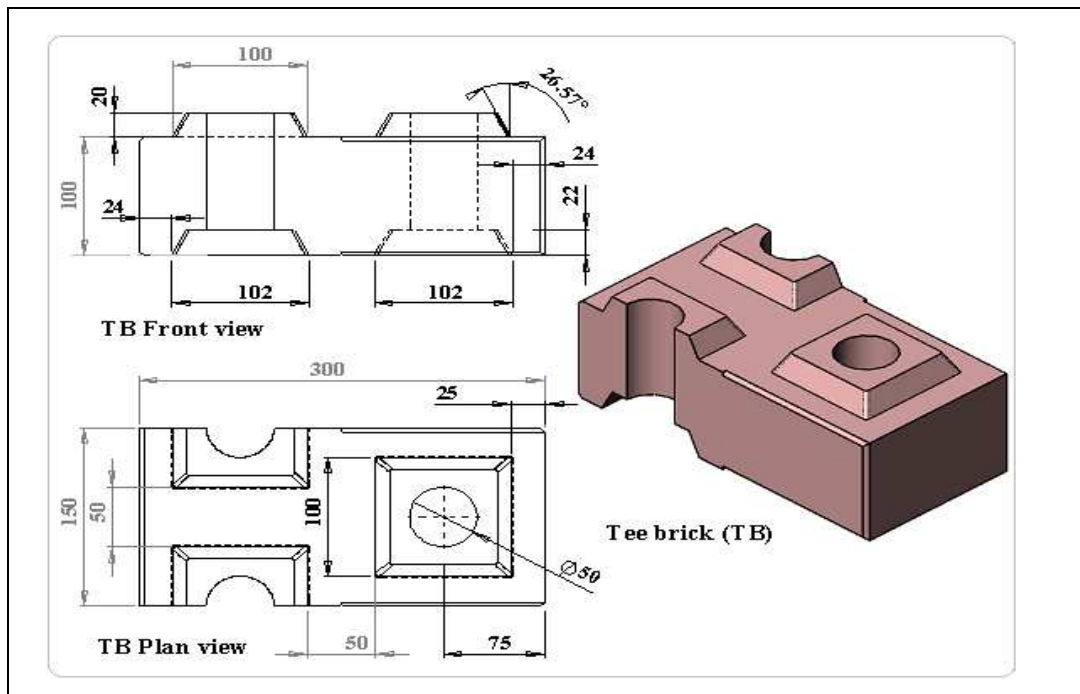
## 4.5 SPECIAL BRICKS

A special brick is one that can not be produced using a normal brick-moulding box. This research briefly examines special bricks. It shows that with interlocking bricks it is also possible to produce and use special bricks (*angle and tee*) to cater for the demands of special structure configurations.

### 4.5.1 TEE BRICK (TB)

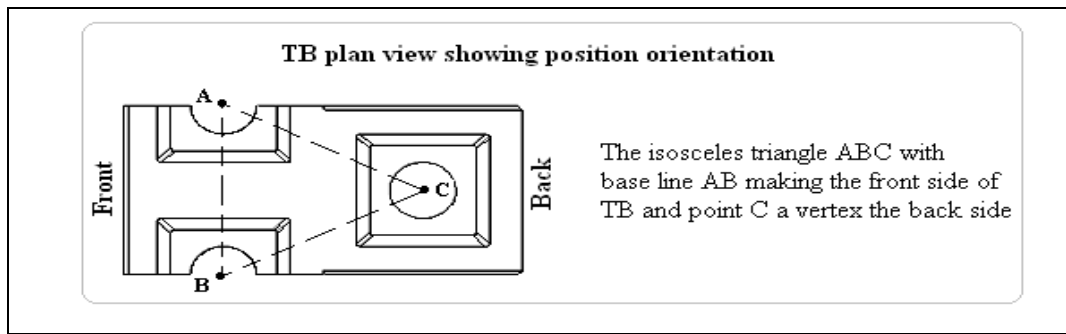
The TB was developed to construct particular (but uncommon) joints that were not possible using existing common brick elements (i.e. FB, E $\frac{1}{2}$ B and  $\frac{3}{4}$ B of Figure 2.10, C $\frac{1}{2}$ B of Figure 4.3 and the CL of Figure 4.13). This TB is shown in Figure 4.16; its use is illustrated by the wall construction example in Figure 4.18.

**Figure 4.16 Tee brick (TB)** (*all measurements are in millimetres*)



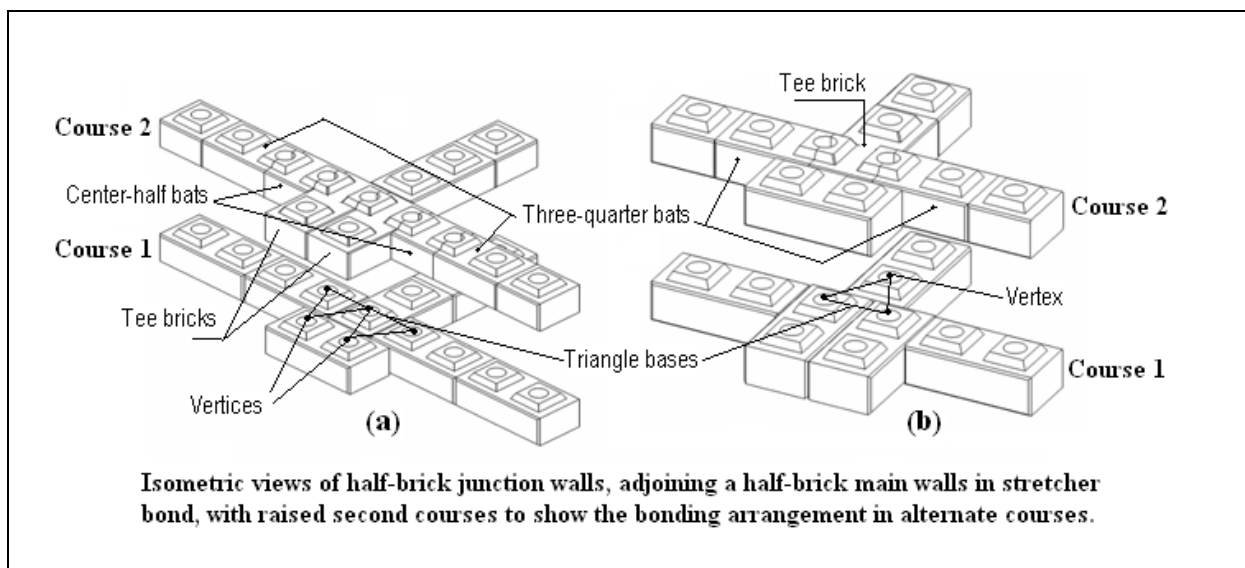
TB has a specific orientation; as illustrated in Figure 4.17 showing the front and back sides, which should be observed during the construction of joints (Figure 4.18).

**Figure 4.17 TB specific positional orientation**



In Figure 4.18 the triangles mark where and how we must position a TB in a joint. The TB should be always positioned in such a way that the front (see Figure 4.17) is hidden in the wall. This is shown in Figure 4.18(a) for the joint between buttress and main wall, and in Figure 4.18(b) for the joint between the two parallel bricks forming a pier attached to the main wall.

**Figure 4.18 One-brick wide pier attached to wall junction assembled using TB**



The joints illustrated in Figure 4.18 are those identified in this research that makes use of the special (TB) brick.

There may be alternative configurations that avoid the occurrence of this type of joint, which therefore do not require TB. For example we could alter the room sizes or change the



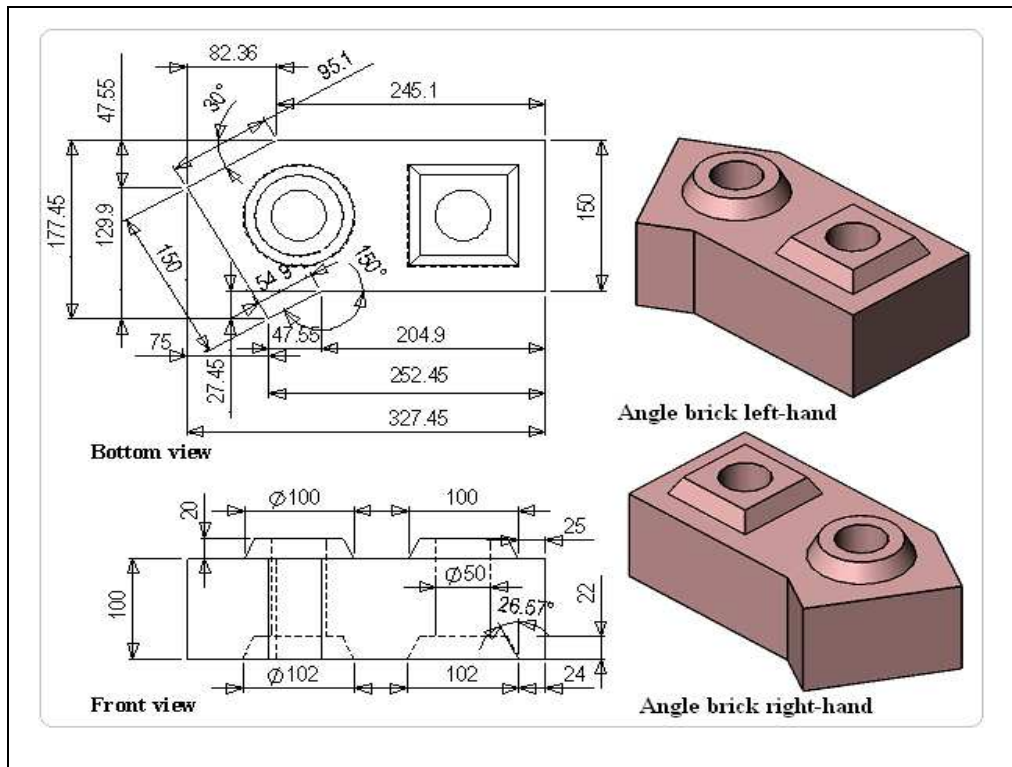
buttressing pier positions (i.e. in Figure 4.18(a) we may move position of the attached pier by half brick to either side, and in figure 4.18(b) we may move the position of the partition by half a brick).

But the configurations using the TB is the most appropriate because it will preserve the original design and maintain the positions of load bearing structures from the foundation to the roof for better performance. The alterations may require additional repetitions to make it appear as an original design and not happened accidentally to maintain similarity and good appearance, these are the additional works and hence additional costs not planned for. This requires thorough examination of design to identify the occurrence of such joints before setting of the brickwork and make corrections.

#### **4.5.2 ANGLE BRICKS**

In accordance with the BS 4729:1990 there are three standard angles used for angle bricks (30, 45 and 60 degrees). The author developed the 30 and 60 degrees angle interlocking bricks, with one side three quarter length and the other side quarter length (Figure 4.19). The ideal angle brick for interlock walling is one that turns the corner and maintains a half-brick overlap without requiring closers or three-quarter bats (*The BDA Guide, 2000*).

**Figure 4.19 Angle bricks**



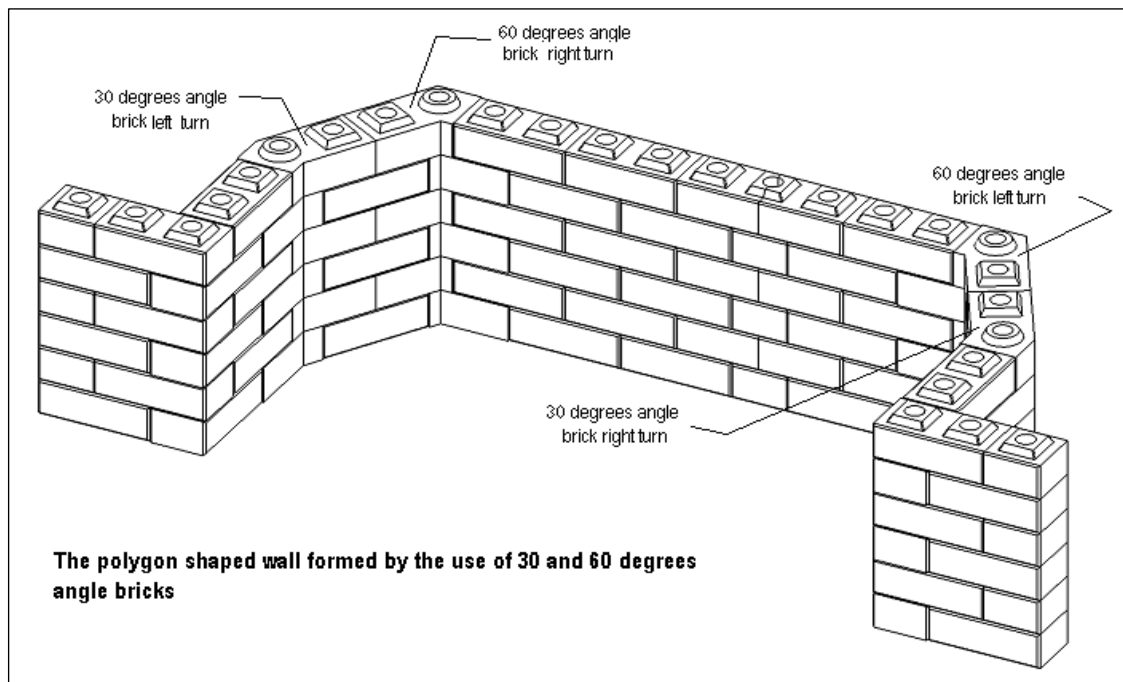
IB angle bricks differ from conventional angle bricks because they have locking features. This requires that IB consecutive courses alternate with left-hand (LH) and right-hand (RH) bricks (Figure 4.19). By contrast in conventional bricklaying only a single angle brick is required, since LH can be converted to RH by inverting the brick.

Note that the shape of locking feature at the centre of the short side of the angle bricks has been changed from square to round to ease the production. The alternative would be to use a hexagonal-shaped protrusion. However such a hexagonal-shaped locking feature would increase roughness and make the mix stick into the mould during production, which would slow the pace of production resulting into low productivity.

The polygonal shaped wall in Figure 4.20 demonstrates a common use of special *angle* bricks. Such bays are employed in the front elevations of many UK houses *Lynch (1994)*. The wall is normally offsetting from the main wall of the building for decorative purposes, an

alternative way of room expansion or internal decoration of spaces for fire places, bath rooms and built in cupboards etc. This configuration requires four ‘specials’ (LH and RH from 30° and 60° bricks) whereas restricting angle to 45° would need only two specials.

**Figure 4.20 Common polygonal wall assembled using angle brick**



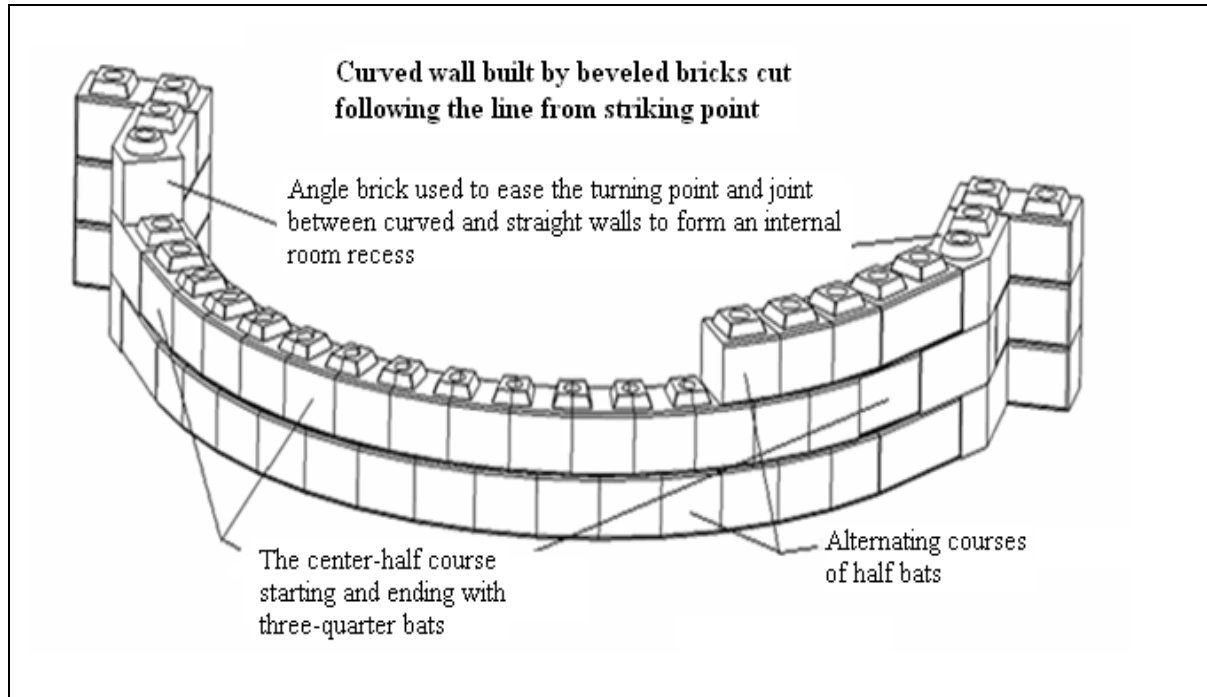
### 4.5.3 CURVED WALLS

Round and polygon-shaped structures are commonly used in the building industry. Corner plots whose configurations are of irregular shapes often require structures to be of the same shape, built with the help of special bricks. Bricks of special shapes and sizes are made ‘to create shapes in brickwork which would be impossible, unsatisfactory or expensive using only standard bricks’ (*The BDA Guide, 2000., BS 4729:1990*).

The development of special bricks is an interesting theme to deal with but very wide. Details of the modifications to angle bricks to fit interlock walls are beyond the scope of this research. Figure 4.21 shows the use of a combination of angle bricks, end-half bats, centre-

half bats, three-quarter bats and normal bricks to construct a curved wall, as an example of future development of interlocking bricks (MT).

**Figure 4.21 Isometric view of curved wall**



Modification to the interlocking  $E\frac{1}{2}Bs$  and  $C\frac{1}{2}Bs$  will allow the construction of curved or circular structures. Bricks and part-bricks are cut with a bevel to give perfect joints and curve (Figure 4.21). The bevel shape can be cut on site, using the simple gauge and hand saw to the designed curve following line from striking point (*The BDA Guide, 2000*). However if we maintain the policy of no site-cutting, then we must mould special bevelled  $C\frac{1}{2}Bs$  and  $E\frac{1}{2}Bs$ . Moreover the portion of locking features of  $C\frac{1}{2}Bs$  may need to be angled too (by half the bevel angle) to achieve proper interlock. Alternatively, as discussed early in section 4.5.3, square interlocks can be replaced by circular ones.

## 4.6 IMPROVEMENT IN FLEXIBILITY ACHIEVED

Finally we can compare the performance of TIB to other interlock systems Table 4.3, after the development of new TIB part-bricks (C½B Figure 4.3, CL Figure 4.13, TB Figure 4.16 and angle bricks Figure 4.19), and formation of new patterns (Figures 4.9 and 4.14). Ten construction operations compared between three development stages of interlocking systems.

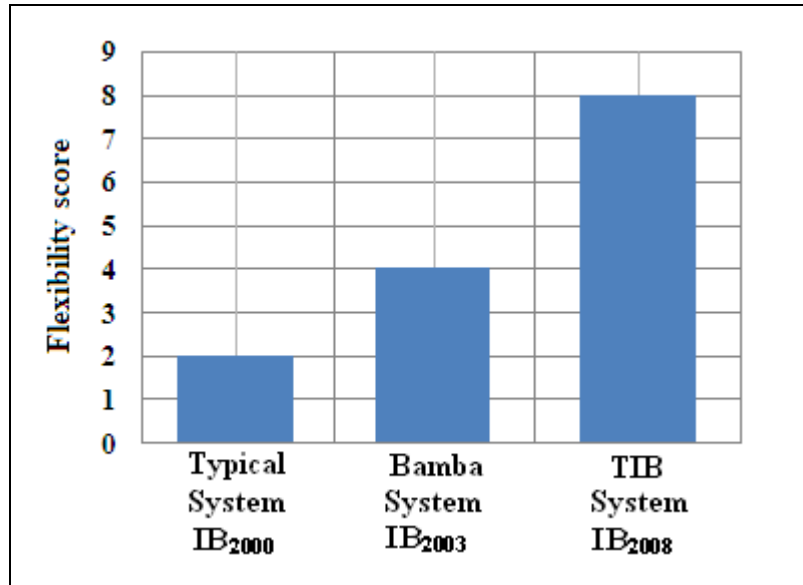
**Table 4.3 Wall construction flexibility achieved by TIB**

S/No.	Tasks (construction operations)	Development stages of interlocking bricks (IB)		
		Typical IB system (IB <sub>2000</sub> )	Bamba System (IB <sub>2003</sub> )	TIB system (IB <sub>2008</sub> )
1	Setting a right angled corner for a ½B wall	✓	✓	✓
2	Bricklaying in stretcher bond	✓	✓	✓
3	Construction of cross and tee joints of ½B walls	X	✓	✓
4	Attachment of ½B wide piers to ½B thick wall	X	✓	✓
5	Attachment of piers wider than ½B to ½B wall	X	X	✓
6	Construction of isolated piers wider than 1½B	X	X	✓
7	Construction of 1-Brick thick wall	X	X	✓
8	Attachment of piers to 1-Brick thick wall	X	X	✓
9	Construction of curved wall	X	X	*
10	Construction of polygonal wall	X	X	**
<b>Flexibility score</b>		<b>2</b>	<b>4</b>	<b>8</b>
<b>Brick-parts (elements)</b>		<b>2</b>	<b>6</b>	<b>5</b>
* - Formation of bevelled brick by cutting at site				
** - The use of special bricks				
<b>Note:</b> Mortarless strictly don't allow cutting or shaving at site for best performance				

The bar chart Figure 4.22 summarises score data of Table 4.3, it shows the development of new part-bricks improved the TIB system performance by 4 points above IB<sub>2003</sub>. TIB with five brick elements (FB, ¾B, E½B, C½B and CL) scores eight points. The addition of specials (angle and TB), which didn't require cutting scores one point more, making a total

of nine out of ten. With an advantage of not cutting at site will improve construction productivity and saving more construction time and labour.

**Figure 4.22 Performance improvement level of TIB**



## 4.6 SUMMARY

The development of the new part-bricks ( $C\frac{1}{2}B$  & CL), initially only for the Tanzanian interlocking brick set, which could also benefit other interlocking bricks in the same category Table 2.1. These part-bricks enable the construction of most masonry wall joints. From Table 4.3 it is evident that the TIB system offers higher flexibility in the wall construction.

In this chapter we have demonstrated the increase in flexibility obtained by using a new part-brick ( $C\frac{1}{2}B$ ) and identified interlock specials (*tee and angle bricks*) with the potential to further increase the flexibility of interlock bricklaying. The contribution of the  $C\frac{1}{2}B$  and CL to MT includes the formation of two new bonds (*Shokse and Lijuja*). With these two bonds, it is now possible to build one-brick thick (e.g. 300mm) walls that can be used for foundations and other load-bearing structures like retaining walls. It is also possible to attach different

sizes (*from 1-brick to 2-brick*) of piers to walls and build-isolated piers more than 1½-brick wide, which was not possible before. The uses of the two new brick shapes C½B and CL will improve the craftsmanship quality of masons and simplify interlock bricklaying for most masonry joints. However the accuracy requirements of interlocking brick for smooth bricklaying will need more attention during production and curing. Tee and angle bricks will remain special bricks to be produced to order as in conventional practice, because they require special moulds and attention that adds more cost per unit. Professionals designing and specifying materials should be aware of the cost implications of such bricks.

The task ahead for this research (*Chapters 5 and 6*) is to analyse the alignment accuracy of MT construction (plumbness, straightness, and course levels) during construction (*per BS 8000-3:2001 – Table 2*), and establish the limits of wall length and height to be allowed before the need of strengthening.

# **CHAPTER 5**

## **5.0 BRICK IRREGULARITIES AND THEIR IMPLICATIONS FOR WALL QUALITY**

In chapter 2 we discussed the tolerance requirements of interlocking bricks for mortarless technology. It was pointed out how brick irregularity affects the accuracy of dry-stack interlock-bricklaying alignment. In this chapter we are going to describe types of brick irregularity, their causes, the implications of these irregularities and the measures to be taken to minimise them. In the following two Chapters one of the major implication of brick irregularities, namely poor wall alignment is examined in detail.

### **5.1 BRICK IRREGULARITIES**

For a brick to be irregular, one of the following imperfection (types of brick irregularity) is present: variation in size (due to variable shrinkage), warping or curvature, taper and surface roughness. These are considered in turn in the following sections, where the causes, consequences and avoidance of each are discussed.

#### **5.1.1 VARIABLE SIZE**

These are variations in the size of bricks within or between mix/batches, which cause the bricks not to lock or fit with each other.



**a) Causes of variable shrinkage**

Brick shrinkage occurs because of moisture evaporation during the drying process. However this is of small impact unless the soil used contains a high fraction of clay that is prone to excess shrinkage. If there were constant shrinkage within or between the batches there wouldn't be any problem. Non-uniform shrinkage may be caused by one or more of the following: -

- Excess water in the mix,
- Poor mixing,
- Changes in soil properties,
- Differential compacting pressure caused by poor batching (uneven amount of mix placed in a mould for each compacting cycle)
- Poor curing (described in more detail in section 5.2)

**b) Implication of variable shrinkage on wall alignment**

The poor matching (in height, length are easily visible) of bricks during wall assembly delay construction and cause additional activities (selection, shaving, shimming and replacement of rejects) that increase construction cost.

**c) Remedial measures to control shrinkage**

To minimize the outcome of excess shrinkage will require systematic monitoring and close supervision of all processes to brick production, which include: -

- Treating soil with the correct type and amount of stabilizer (proper designed ratio of cement to soil)
- Mixing with proper water/moisture content (proper water/cement ratio)
- Proper soil preparation: -

- Pulverizing to remove hard particles
- Sieving to a required size/limits
- Mixing to a standard consistency (by sight)
- Use of adequate compacting pressure during moulding
- Proper curing conditions: -
  - Under a roof and on a level floor or
  - In the open air with proper flooring and covering materials (plastic sheets, grass, sawdust etc.)

However the occurrences of variations in brick size due to shrinkage are in general practice minimised and not eliminated. The remedial measures taken are to prepare and correct them to be fit for use, as described in Section 5.2.

### **5.1.2 WARP (CURVED OR TWISTED BRICKS)**

These are the changes in brick shape not in right form (twisted), which at the same time may change the size of the brick.

#### **a) Causes of warped, curved or twisted bricks**

In soil stabilization, warping and twisting may occur mainly due to two causes (both considered in 5.2 below): -

One is rapid drying of bricks cured at the open air without cover. This practice has been inherited from the production of mud bricks, which normally are left in the open air to dry. Apart from causing warping, rapid drying will result in low strength because of incomplete cement hydration.

Secondly using poorly prepared curing-floor surfaces is a major cause of brick curving. Poorly prepared curing floors are especially common and damaging in (hot) developing

countries. For these two reasons bricks are often of poor quality having irregular shapes (warped, curved and with severe shrinkage).

**b) Implications of warped, curved or twisted bricks for wall alignment**

The implications of warped and curved bricks to the wall alignment are more severe than shrinkage alone, because shrinkage is a linear change to all sides, so to deal with it is simpler, but warping forms surfaces with ditches and humps. Warped and curved bricks when dry-stacked make contact at specific points (bumps). If these points are scattered over the surface, during assembly the contact of the two brick faces will induce rocking, rolling and pitching until a stable position is found. Moreover placing another brick above may change the lower brick's balanced position. This may result in the phenomenon of 'lateral softness' that causes difficulties in maintaining good vertical wall alignment. To stabilise, the structure will require strengthening i.e. shimming, addition of buttresses etc.

Due to having low contact surface areas between them, bricks develop load concentrations at their contact points. This concentrated loading easily surpasses the crushing strength of bricks and therefore resulting in cracking or failure of individual bricks. To prevent cracking in the case of severe warping, bricks may require a lot of shimming as in traditional bricklaying, which of course mortarless technology is trying to avoid.

**c) Remedial measures to reduce warping, curving and twisting of bricks**

Warping, curving and twisting for stabilised bricks can be reduced by proper curing i.e. under a roof and or under the covering of plastic sheets, grass or any other material to reduce exposure to air and sun and thus prevent quick evaporation of moisture. The other remedial measure is making curing-floor surfaces level and hard to reduce moisture percolation into the ground from the fresh bricks. We can conclude that poor curing regime is the major cause

of brick irregularities; so curing require proper control and close monitoring for effective performance. Warping and curving can be much minimised on fulfilling the above-recommended remedial measures. But shrinkage, which is associated with the soil properties, will remain a task to be addressed by proper soil selection and proper design of the ratios of cement to soil and water to cement.

### **5.1.3 BRICK SURFACE ROUGHNESS**

The rough-surfaces (random localised bumpiness) of the brick's faces designed to form contact, normally are the top and bottom faces that the mortarless technology should direct more attention. The causes and consequences don't differ much with those described in Section 5.1.2, so, do the remedial measures. The emphasize should be on the quality of curing places and the stacking practice, to keep floor always clean, flat and smooth will protect brick faces from roughness.

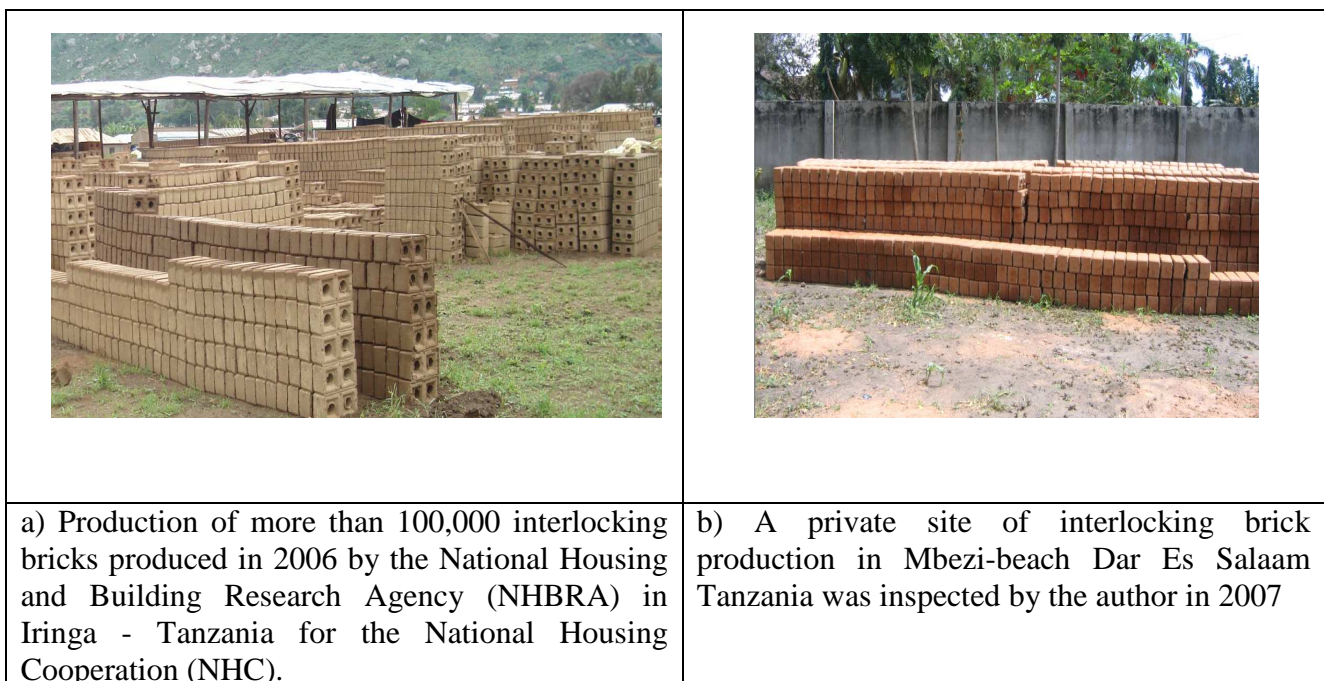
### **5.1.4 TAPER**

These are uneven brick shape changes due to general wear and tear of the press, changes in mould box dimensions due to bulging or twisting to one side and rocking of movable plate of press. We leave aside intentional vertical taper introduced to make demoulding easier, although with wear this may grow to exceed the allowable tolerances. Close monitoring and control of any source of taper (i.e. having non-parallel top and bottom faces) will give a warning of brick biases forming. Consistent bias can be corrected by reversing alternate courses. But when having bricks with variable bias, it will be difficult to control wall leaning.

## 5.2 SOIL-CEMENT BRICK CURING PRACTICE

Mortarless technology makes use of pressing as a normal brick production method, and requires that proper soil-selection and soil-preparation are practiced. The major stumbling block causing block irregularity is poor curing practice. From a survey in 2006 and 2007 for this research and the general Tanzanian experience of stabilized cement-soil blocks, it was found that most of all production sites have no curing-shade, no proper floors (flat, hard and impermeable), and bricks are uncovered during curing as shown in Figure 5.1.

**Figure 5.1 Typical poor curing conditions in low-cost building-material production sites**

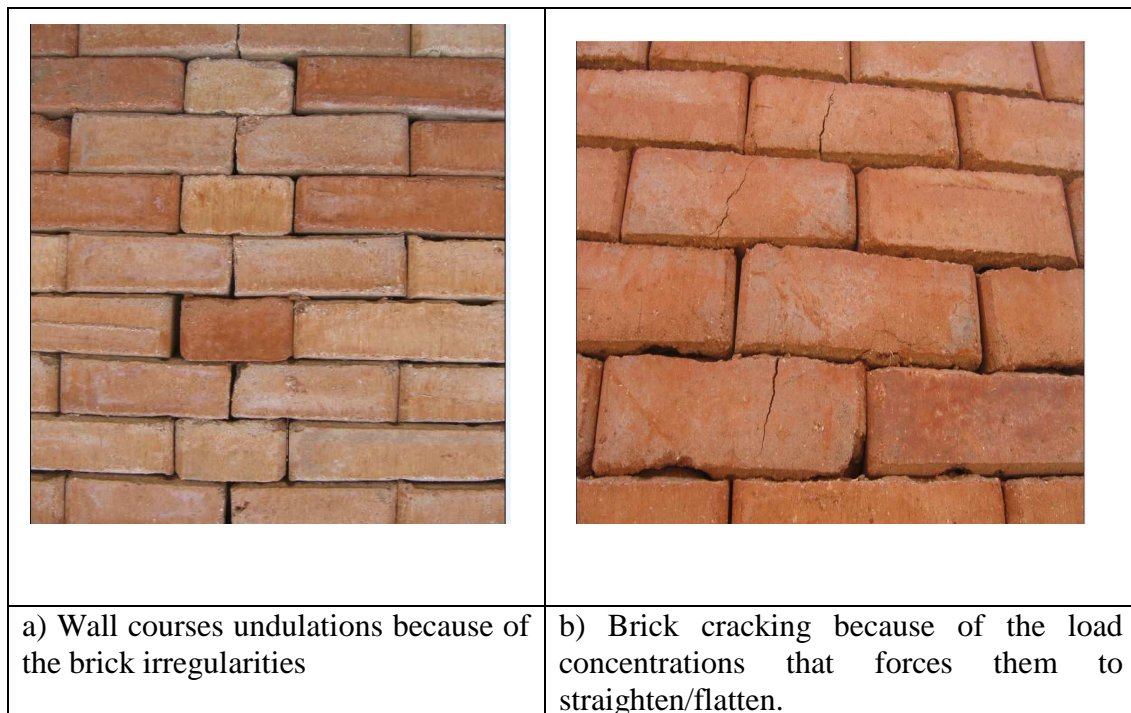


The outcome of using such poor curing conditions (Figure 5.1) is the formation of irregular bricks. The photos in Figures 5.2(a) and 5.2(b) show the construction problems caused by using such bricks in wall construction. With irregular bricks it is difficult to attain level courses or to avoid forming load concentrations at the points of contact. As the load increases the brick are forced to flatten and the enclosed stress field can lead to tension cracking (Marzahn 1999).

If differences in size occur during brick production, then the following are the additional efforts required to select or correct them for use:

- Selection and grouping of bricks of approximately equal height.
- Reduce those too big to size by shaving or grinding them to match with the most common.
- Those appear to be too small will need shimming during construction to match with the rest. Alternatively an entire thin course will be laid, if there are in enough quantity to complete one course.

**Figure 5.2 Implications of brick irregularities on wall assembly**



These adjustments will create rejects or breakages that require additional production for replacement. The extra time spent for preparation, extra material to be used for shimming and any extra production, are thus *consequences* of brick *irregularity*. They cause delays in construction and increase the construction cost, which jeopardize the good image of mortarless technology. That is why a further analysis of brick irregularity is necessary.

### 5.3 SUMMARY

Brick irregularities impact negatively on wall alignment and weaken the performance of the wall. Mortarless walling by its nature is vulnerable to shaking due to brick units being stacked dry; it therefore requires careful handling before any strengthening stage. Irregular bricks increase wall instability' as the bricks are difficult to place in their proper position. The more the wall grows in height and length, the more flexible and unstable it becomes. Irregularity of bricks can be graded by how difficult or easy it is building an accurate wall with them, and attain straight and level courses that are vertical to plumb, and sustain an accurate position during construction. Of the various imperfections in brick-shape, the most serious are:

- Variation in height – causing cracking,
- Warping or extreme roughness – causing both instability and cracking
- Variable lateral taper - 'roll taper' – causing loss of verticality

Poor curing and stacking practice are the main cause of these brick imperfections. The effect of irregular bricks on mortarless wall alignment is analysed in *Chapters 6 and 7*.

# CHAPTER 6

## 6.0 THE RELATIONSHIP BETWEEN WALL ALIGNMENT AND BRICK GEOMETRIC IMPERFECTION

### 6.1 INTRODUCTION

The elimination of mortar layers between the courses of interlocking brick wall is the main characteristic of mortarless technology (MT) compared to conventional masonry. The mortar joint is replaced by physical locking features to enable the wall to withstand lateral and flexural loads *Gazzola & Drysdale (1989), Marzahn (1998), Drysdale & Gazzola (1991), Marzahn (1999), Shrive et al. (2003) and Jaafar et al. (2006)*.

A mortar layer that traditionally separates brick courses performs a number of functions. Well-pointed mortar may add to a wall's aesthetic appeal – though the crudely smeared mortaring commonly found in villages of Least-Developed (African) Countries certainly does not. In 'gluing' the bricks together, mortar increases resistance to localised forces, such as those that might punch an individual brick through a wall; however interlocking can also perform this particular function (*Shrive et al. 2003*). Mortar may help the wall to act as a beam spanning across soft spots in its foundation or across openings. It seals the wall against wind and noise penetration, whereas a mortarless wall has to be (internally) rendered to achieve this and other purposes. Mortar removes stress concentrations due to point contact between bricks in successive courses and it may reduce 'binary' deviations (one brick rocking between two rival seats on the brick below). In MT, greater brick accuracy is required since the mechanism of levelling each course using mortar is no longer available.



As the key function of conventional mortar is to allow good wall alignment to be achieved despite irregularities in the individual bricks, the research here reported was undertaken to assess how accurately bricks need to be made if in *mortarless* assembly they are to give satisfactory overall alignment. The wall parameters of most interest are course straightness (deviation from horizontal) and wall-lean (displacement of the top brick's front face from a plumb line touching the bottom brick's front face). It is the accuracy of the top and bottom faces of the individual bricks whose interaction determines these two measures.

### **6.1.1 THE EXPERIMENTAL OBJECTIVES**

Mortarless technology (MT) replaces mortar by making mating brick surfaces (top and bottom) more accurate. The main objective of the following experiments is to identify what accuracy (of flatness and parallelism of top and bottom brick surfaces) is needed to ensure wall alignment lean is within the limits prescribed by *BS 8000-3:2001 and BS5628-3:2005*, namely that the straightness deviation in any 5m length wall does not exceed  $\pm 5\text{mm}$ , and verticality lean up to 3m wall height is within  $\pm 10\text{mm}$ . Although these permissible wall deviations are meant for mortared technology, they will be used here as benchmark data. The other important objective for these experiments is to contribute to the formation of production quality control measures and IB walling standards.

In the absence of mortar in a brick wall we would expect;

- a) The wall alignment to be poorer than when connecting course mortar is used to maintain vertical, level and uniform course spacing i.e. mortar corrects geometric imperfections. Dry-stacking bricks produces cumulative imperfections, which the bricklayer has little mechanism for correcting.

- b) The wall to be less stable when subjected to (small) horizontal forces because at some of the brick-to-brick interfaces rocking is possible (if the contact points are few and too close to the brick's centreline) ; also there is increased chance of wall wobbling under vertical forces.
- c) The contact forces to be localised rather than spread over the whole brick top/bottom surfaces, leading to brick failure (by cracking) to occurring at lower vertical loading than it would in a mortared wall *Marzahn (1999), Jaafar et al. (2006)*.

Each of these weaknesses of dry-stack bricks are caused by brick surface (top and bottom) imperfections that were analysed and tested for. The two measures developed to ameliorate problem (a) and (b) above were: (i) modifications to brick shape and (ii) special bricklaying procedures. These were tested for effectiveness as described in Chapter 4.

Because bricks imperfections are essentially random (though with measurable statistics), very many experiments are required to obtain a single performance measure. For example to assess within  $\pm 10\%$  with 90% confidence the standard deviation in straightness of a specified course in a column would need the construction and measurement of over 100 columns. Because such large-scale physical experimentation is too costly of time, more limited experiments were performed whose primary purpose was to calibrate and confirm the performance of theoretical formulae and computer simulations.

## **6.2 PRIMARY PREPARATION FOR EXPERIMENT**

The experiments involve the assembling of columns and walls, which require preparation of brick components. The brick components to be produced are the TIB described in Chapter 4.

The following activities were deemed necessary for the primary preparations:

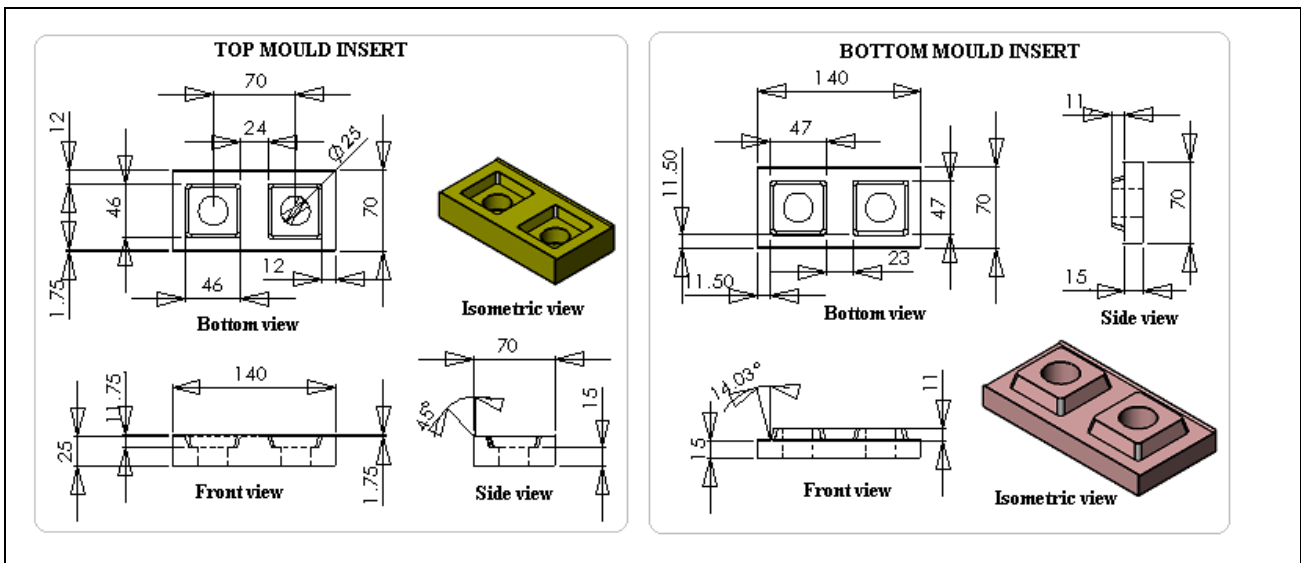
- Design and fabrication of ISSB component moulding inserts to enable production of (FB,  $\frac{3}{4}$ B,  $E\frac{1}{2}$ B,  $C\frac{1}{2}$ B and TB) brick types.
- Production of bricks for experiment
- Determination of brick characteristics
  - Dimensions
  - Flatness and parallelism of top and bottom faces
  - Statistical analysis of brick characteristics for a substantial measured sample

### **6.2.1 MOULD DESIGN AND FABRICATIONS**

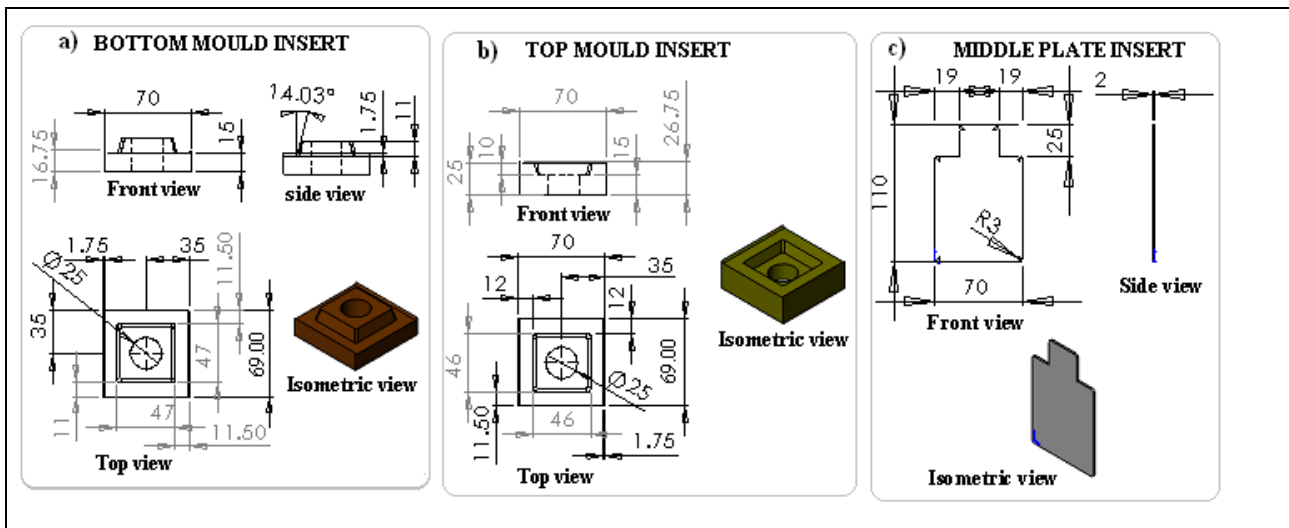
The available brick press (MultiBloc Figure 6.8c) in the Engineering laboratory of the University of Warwick, is a CINVA Ram type (*VITA 1975, UN 1992, Weinhuber 1995*), which can produce solid bricks of size 290 x 140 x 90mm. The interlock brick design and its elements in Chapter 4, required design of mould inserts to permit production of the interlock brick components. The study required about 500 bricks, which is a fairly big number. To save production time, material and the limited space in the laboratory, a half-scale was adopted. The available press mould box was sub-divided into three equal compartments to produce, in each pressing cycle, three bricks of size 140 x 70 x 50mm. Mould inserts were designed by the author and fabricated in the Engineering mechanical workshop, for the following components: full brick (FB) shown in Figure 6.1 and end-half bat ( $E\frac{1}{2}$ B) shown in Figure 6.2. Each unit need separate top and bottom inserts. In one compartment of the three a plate was inserted (Figure 6.2c) to produce two  $E\frac{1}{2}$ Bs. Three-quarter bats ( $\frac{3}{4}$ B) Figure 6.3, and centre-half bats ( $C\frac{1}{2}$ B) Figure 6.4, as well their top and bottom moulding inserts, required a

quarter block (Figure 6.4c) to cut off one end to make the  $\frac{3}{4}B$  and two such blocks to make the  $C\frac{1}{2}B$ . The assembly of inserts in press mould are shown in Figures 6.8a and 6.8b. The tee brick (TB) moulding inserts were also fabricated: details shown in Figure 6.5. All moulding inserts are used with spacer blocks (Figure 6.6a) to divide the press moulding box into three equal spaces (see assembly Figure 6.8). To form the large vertical perforations, steel rods were used (Figure 6.6b). The design incorporated tolerances on interlock features of 1mm clearance between protrusion and depression and the edge chamfers are 1.75 x 1.75mm, all halved from the original design (*A Tanzanian interlocking brick (TIB) with – tolerance = 2mm and chamfer = 3.5 x 3.5mm Figure 2.10*). The materials specified for pattern making were aluminium and mild steel. A new press cover (Figure 6.7) was designed to allow production of interlock brick because the original solid cover was not fit for the purpose.

**Figure 6.1 Full brick (FB) moulding inserts** (*measurements in millimetres*)

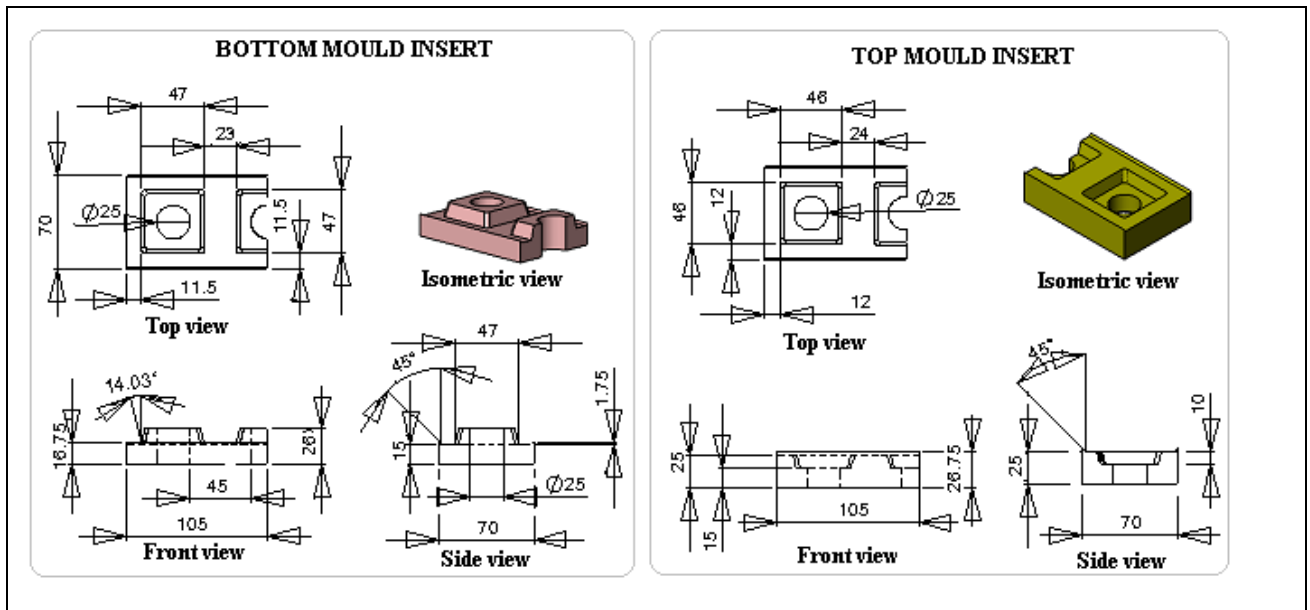


**Figure 6.2 End-half bat (E<sup>1</sup>/<sub>2</sub>B) moulding inserts** (*dimensions in millimetres*)

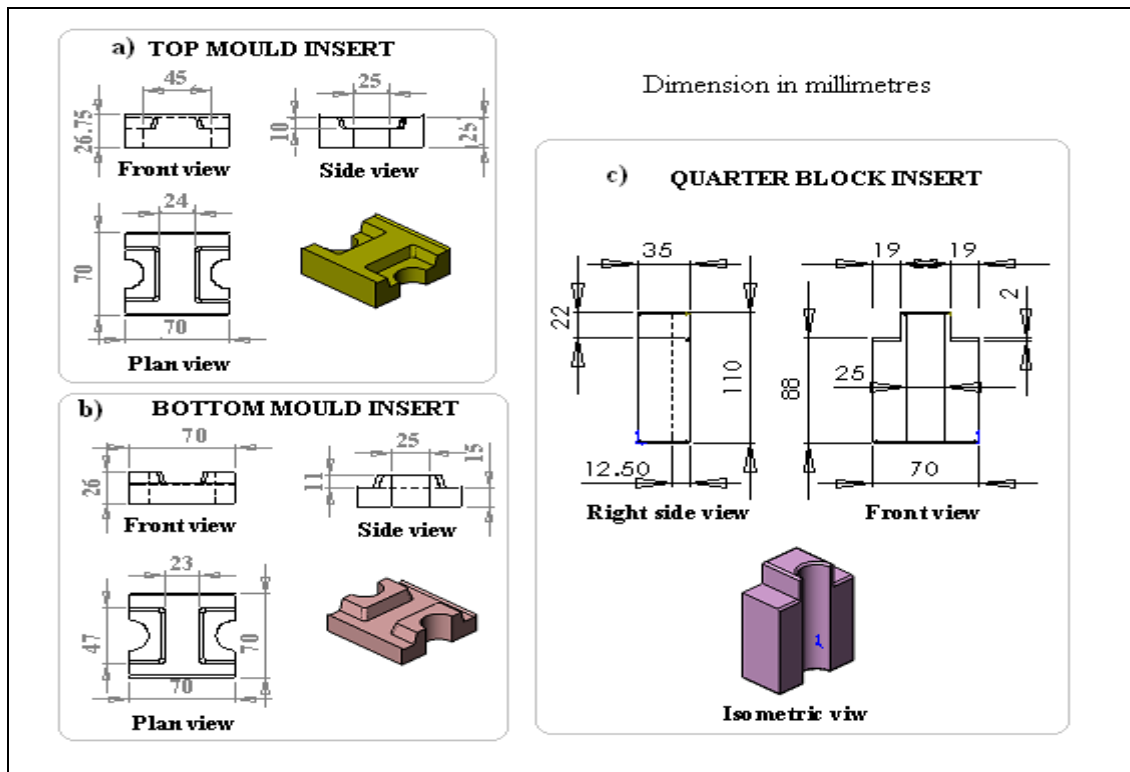


**NOTE:** These inserts were for making half-scale experimental bricks; for full-size bricks, all dimensions should be doubled.

**Figure 6.3 Three-quarter bat ( $\frac{3}{4}B$ ) moulding inserts** (*dimensions in millimetres*)

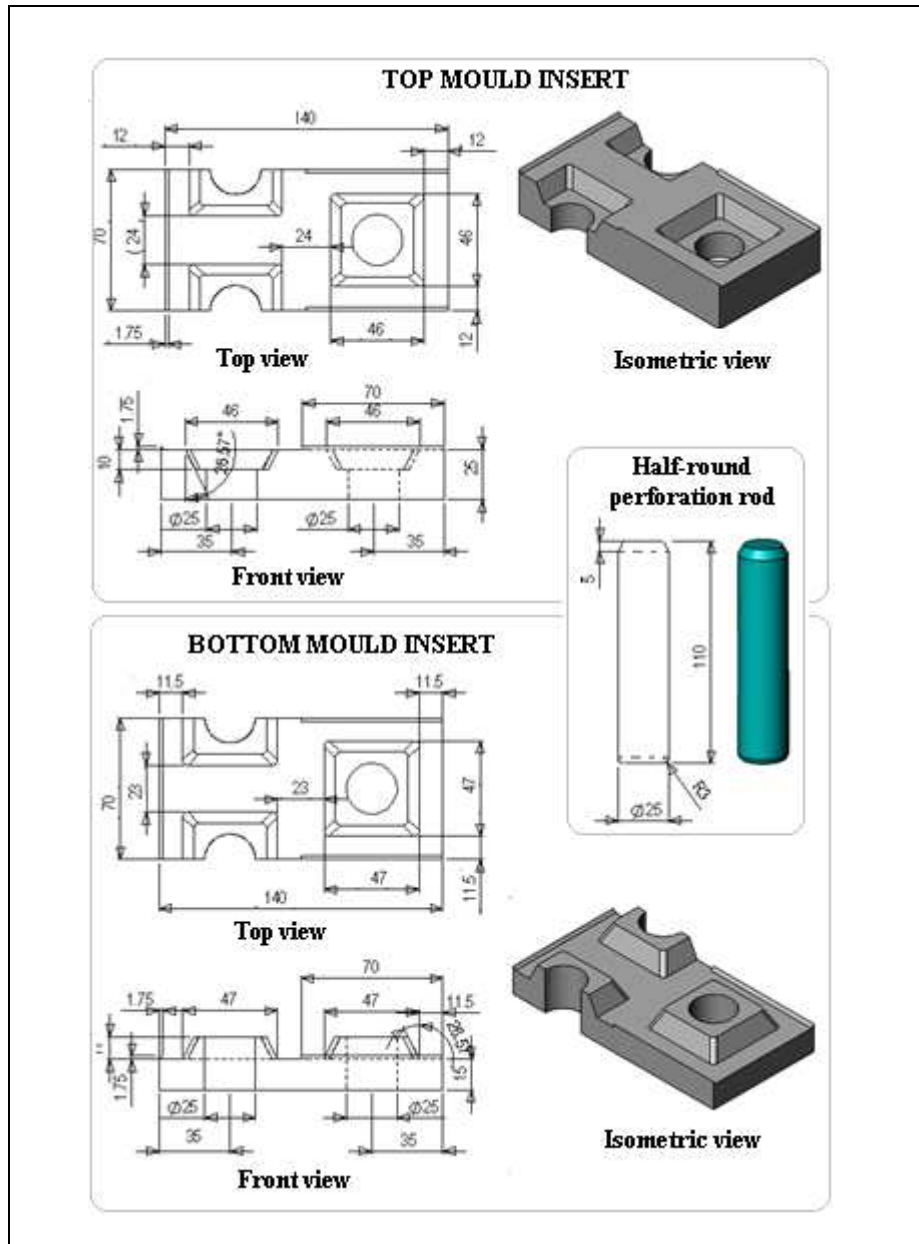


**Figure 6.4 Centre-half bat ( $C\frac{1}{2}B$ ) moulding inserts**



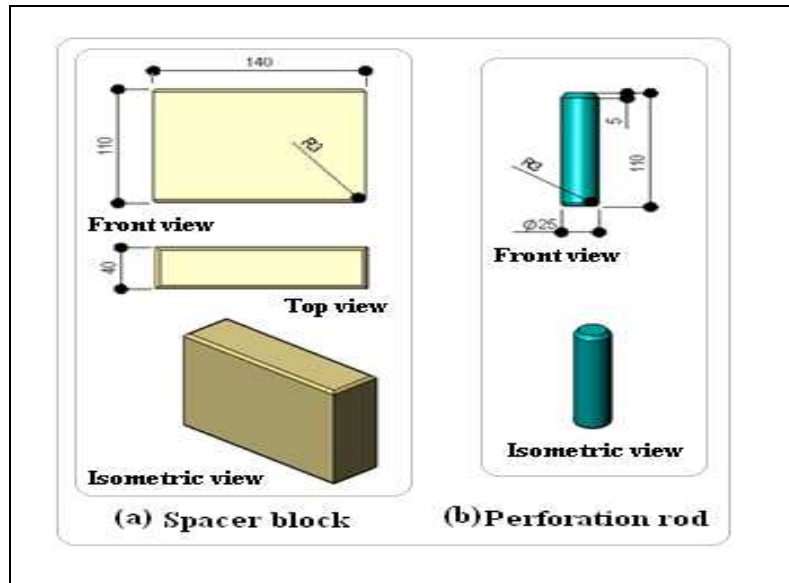
**NOTE:** These inserts were for making half-scale experimental bricks; for full-size bricks, all dimensions should be doubled.

**Figure 6.5 Tee brick mould inserts** (*dimensions in millimetres*)

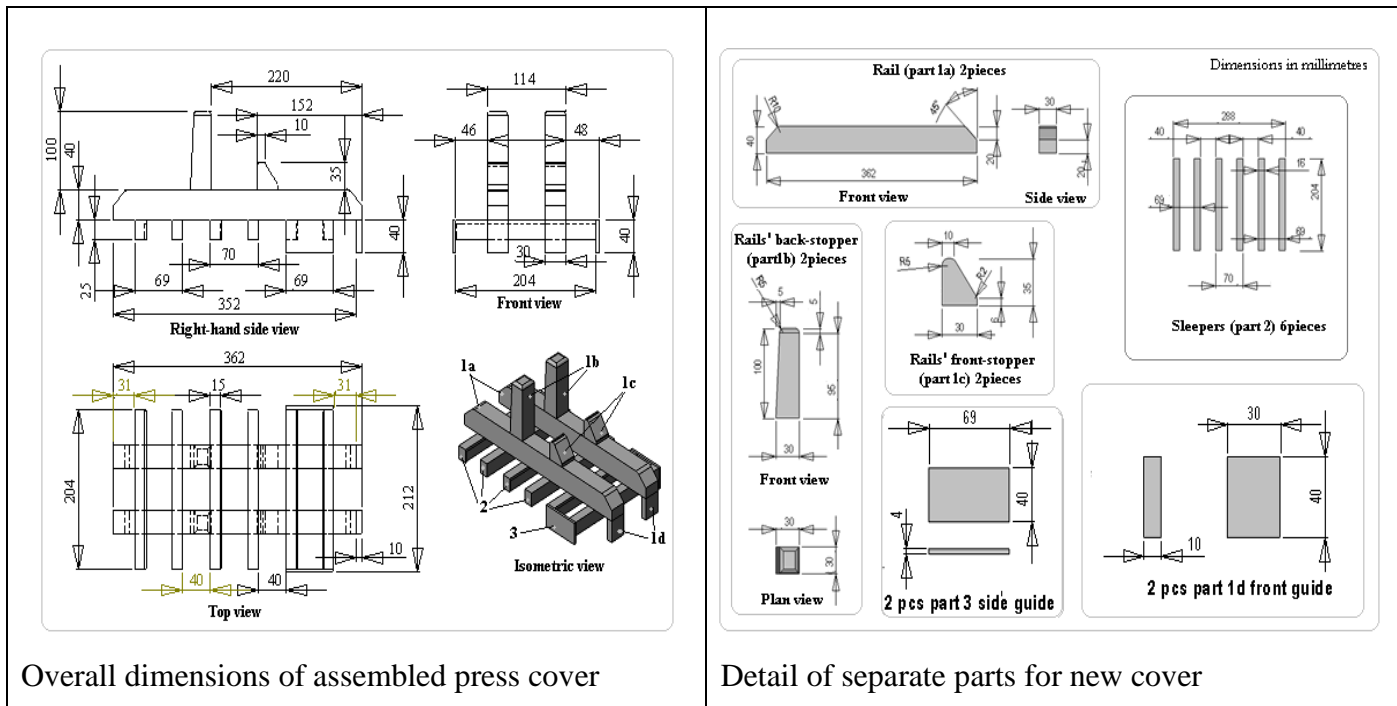


**NOTE:** These inserts were for making half-scale experimental bricks; for full-size bricks, all dimensions should be doubled.

**Figure 6.6 Common moulding inserts components**  
(dimensions in millimetres)



**Figure 6.7 New cover for MultiBloc press** (dimensions in millimetres)



**NOTE:** These inserts were for making half-scale experimental bricks; for full-size bricks, all dimensions should be doubled.



**Figure 6.8 Multibloc press with new cover and moulding inserts**



## **6.2.2 BRICK PRODUCTION**

### **I Soil preparations and mix design**

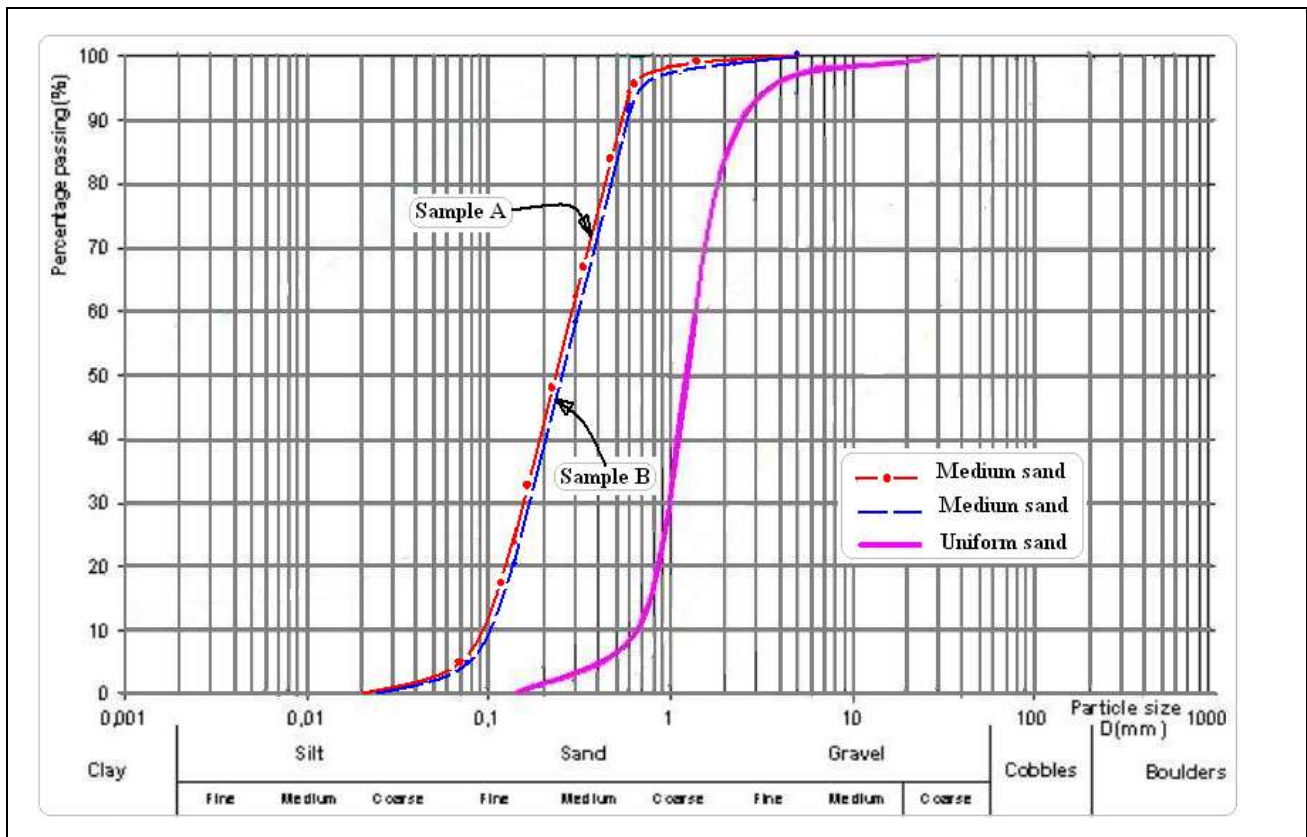
The material ordered from Coventry building material suppliers using normal procedures was builder's sand sieved through a 4mm sieve. That is good enough for stabilised-soil cement brick production. Sand particle-size distribution test was performed (Table 6.1 and Graph 6.1 showing a uniform medium sand with only 5% fines passing sieve 0.075) before adding kaolin to achieve the required fines (clay) content and thus adequate mix cohesion.

**Table 6.1 Sand particle distribution test results**

S/No.	Sieve diameter (mm)	Sample A (500g)		Sample B (500g)	
		Sand retained in each sieve (g)	Sand passing each sieve (%)	Sand retained in each sieve (g)	Sand passing each sieve (%)
1	5	0	100.00	0	100.0
2	2.36	3.5	99.3	6	98.8
3	1.18	2.5	98.8	6.5	97.5
4	0.6	21	94.5	27	92.0
5	0.3	160	62.1	167.5	58.3
6	0.15	195	22.7	191	19.8
7	0.075	87	5.1	78	4.1
8	bottom dish	25	-	20.5	-
Lost sand		6		3.5	
Total		500	-	500	-

The soil was formed by mixing builder’s sand and kaolin at the ratio of 8: 1 by weight (3: 1 by volume). The material ratio used for the brick production is 1:14 (*cement to “soil” – C: S*, where soil includes kaolin and sand).

**Graph 6.1 Particle size distribution curve**



Thus during production the mix ratio used for cement, kaolin and sand was 1:3.5:10.5 (C: K: S) by volume. From total material by volume C = 6.7%; K = 23.3%; S = 70%, and by weight C= 7.5%; K = 10.7%; S = 81.8%.

The normally recommended maximum ratio of free water to cement is 0.8 (*Lea, 1976 and BS 5328-1:1997 Table 6*). However this did not work for manual brick pressing. It was increased to 1.4, which was found to be sufficient for easy moulding and handling. The high W: C ratio to achieve workability arise from (a) the very lean mix C:S (1:14) and (b) the presence of clay, both sand and clay having a water demand in addition to the water available to the cement.

## **II Brick pressing and curing**

The bricks produced for experiment were intended to portray real site conditions, but due to laboratory constraints on time and space, brick size was halved to 140 x 70 x 50mm from the original machine moulding box size - 290 x 140 x 90 mm available in the laboratory. All brick sample produced using one mix ratio (1:14 cement to soil). The bricks were cured for 28 days, covered by wet-sacking and plastic sheets for the whole period.

The numbers of brick components made were; 441 FBs, 80  $\frac{3}{4}$ Bs, 94  $E\frac{1}{2}$ Bs, 85  $C\frac{1}{2}$ Bs and 14 TBs. The bricks were produced from one press with three equal compartments (as described in the section 6.2.1), to allow production of three bricks in a stroke. It was expected that all bricks from one machine would be the same, but when inspected and measured were found to have variations of less than one millimetre. So the three compartments act like different and independent machines. Nonetheless during production the bricks from different compartments were not separated, the only separation made was between day production batches to control curing duration.

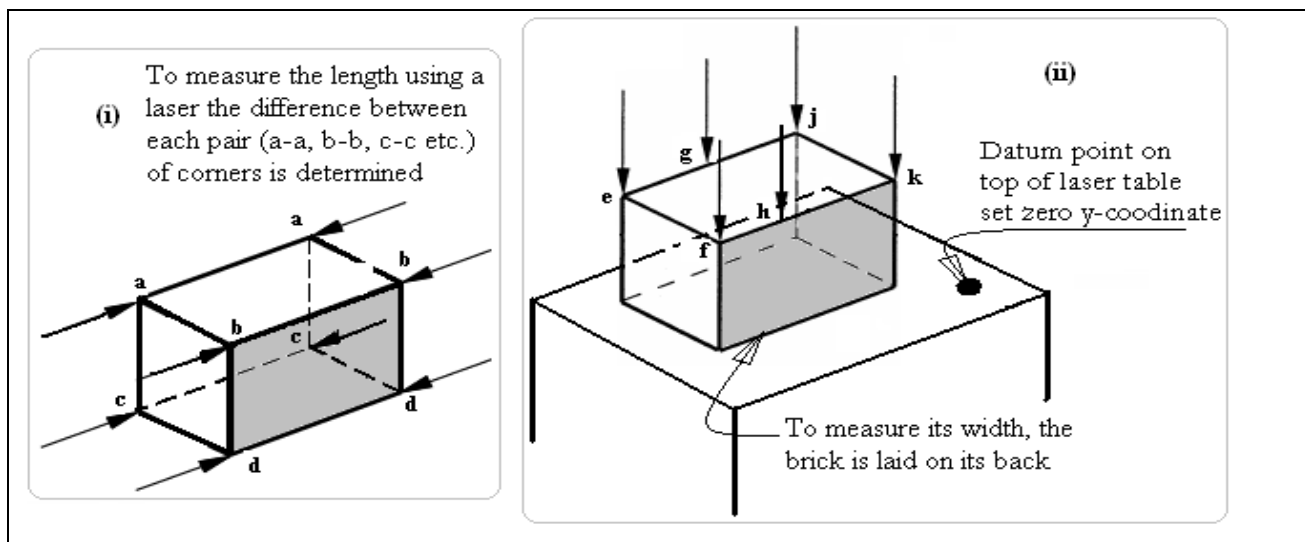
## 6.2.3 DETERMINATION OF BRICK CHARACTERISTICS

### I) Brick dimensions

Variability of bricks develops through the three processing stages (production, setting-out and assembly), resulting in deviation from the designed (desired or target) size *BS ISO 1803:1997*. The deviations due to human error and limitations of moulding instruments are termed induced deviations. A second type of variability, known as inherent deviations, is caused by variations in temperature, moisture content or chemical reactions, which may cause reversible or permanent change. In practice, to check the compliance of components' dimension and tolerance limits are set (*BS ISO 1803:1997*).

**Figure 6.9 Positions on brick for determination of its (i) length and (ii) width**

*(Bottom of brick is shown shaded, diagrams per BS EN -16:2000)*

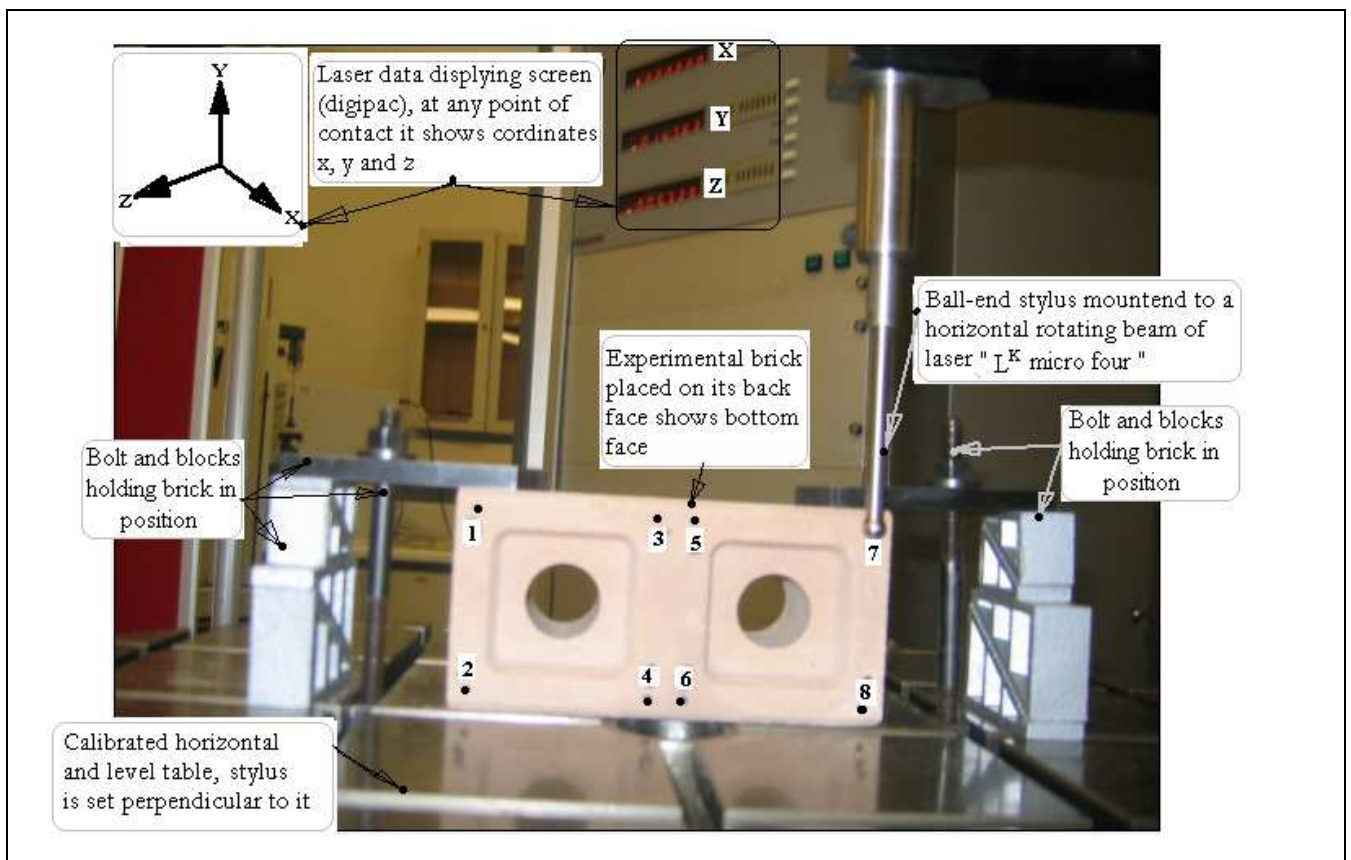


The method used to determine the dimension compliance of experimental IBs is that described in *BS EN 772-16:2000* see Figure 6.9, ten sample bricks were measured. The brick sizes were measured by the use of laser "L<sup>K</sup> micro four" (Figure 6.10) as follows: to measure the length of a brick, the difference between four end to end corner points' (aa, bb, cc and dd)

readings Figure 6.9(i) (Z-axis readings displayed by digipac screen Figure 6.10), and to measure the width Figure 6.9(ii), the brick was laid on its back with front face on top. Using the laser table as zero datum, readings of six points (e, f, g, h, j, k) were taken i.e.y-axis readings were recorded as brick widths.

The heights were measured at the eight points marked for the flatness determination between bottom and top faces (Figure 6.10 shows bottom face and top face is shown in Figure 6.11).

**Figure 6.10 Brick in position for dimensional and surface flatness determination**



The summarised experimental data in Table 6.2 (obtained from raw data Tables 6.5, 6.6 and 6.8) were compared with the permitted tolerances from *BS EN 771-3:2003 category D4 Table 1* and *BS 6649:1985 Table 3*, in reference to the designed brick size 140 x 70 x 50mm. In the *BS 6649:1985 Table 3*, it is given a tolerance of  $\pm 2$ mm for all brick side dimensions, with the condition that of the ten sample bricks measured, nine shall be within the given limits. Table 6.2 shows that the standard tolerance compliance was met only for the length and width. The

measured height did not meet the given standards in comparison to the designed height. However using the average ( $\mu$ ) height and standard deviation ( $\sigma$ ) of the measured samples, give a coefficient of variation ( $COV = \sigma/\mu$ ) of only 0.01 (Tables 6.8), confirming the similarity of brick heights.

**Table 6.2 Data comparison between experimental and standards**

Measured Item	Designed size (mm)	Actual* mean size (mm)	Design minus actual size (mm)	BS EN 771-3:2003 Category D Tolerance (mm) between	BS 6649:1985 Table 3 (limits of manufacturing) (mm)
Length	140	139.96	-0.04	-3 and +1	$\pm 2$
Width	70	70.54	+0.54	-3 and +1	$\pm 2$
Height	50	48.30	-1.70	-1 and +1	$\pm 2$

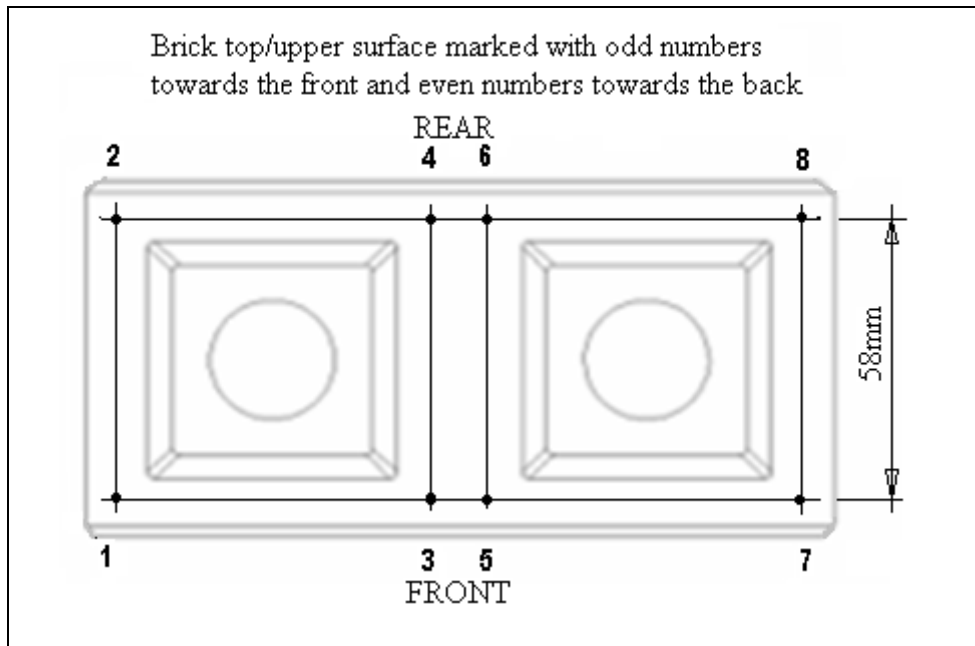
\*See Tables 6.5, 6.6 and 6.8

## II Brick flatness and parallelism

For IBs the important parameters are the flatness and parallelism of top and bottom surfaces, and the height variations that require more attention of this research programme. *BS EN 772-20:2000* recommends a diagonal method for determining surface flatness, using a straight edge and a set of feeler gauges. The method was not used for IBs because of their protrusions, which prevent measurement along diagonals.

Possible alternative measures were the mean square, least square and local flatness, as described in *BS 7307:1:1990 (ISO 7976-1:1989)*. The experimental data was generated using laser “L<sup>K</sup> micro four”, from the marked points on top and bottom surfaces (Figures 6.10 and 6.11). One bottom point (Figure 6.10 point 1) of each brick was set to zero as a bench mark (Table 6.7 a bottom front reading B<sub>1</sub>) from which other point levels were calculated for both top and bottom faces.

**Figure 6.11 Brick marked for surface flatness determination**



To prepare the experimental bricks for measurements, they were marked along the plane surfaces lying to front and rear of the interlock depressions (bottom face Figure 6.10), and the interlock protrusions (top face Figure 6.11). By the use of a template, all sample bricks (44 pieces) were marked to maintain similarity of the point's positions and distances. The position of a stylus point (in contact with the brick) was displayed on a laser digipac screen (Figure 6.10 in three dimensions x,y and z).

The raw data (Table 6.7) for brick flatness were recorded in the order of 1, 3, 5, 7 (front points) and 2, 4, 6, 8 (rear points) for the top/upper surface, and similarly for the bottom surface.

### **III Analysis of brick data measurements**

The raw data in Table 6.7 was processed using an Excel programme to determine planes representing the top and bottom surfaces respectively, and the angles  $\alpha$  and  $\beta$  between these actual planes and an ideal plane perpendicular to the front face Table 6.8.

Data for the top (upper – U) of a particular example brick is displayed in Table 6.3. The table also shows as derived data:

- The average of the four front readings ( $U_f$ ) measured upwards from a reference plane passing through point 1 on bottom of brick ( $B_1$ ).
- The average of the four rear readings ( $U_r$ )
- The inclination  $\beta$  (defined in Figure 6.12) =  $\tan^{-1}\{(U_r - U_f)/58\}$ , where 58mm is the distance between the front and rear lines of the measurements shown in Figure 6.11.

**Table 6.3 Determination of a bricks' upper plane**

S/No	Bricks' upper coordinates readings (as laid)								Average		Angle ( $\beta$ )
	Front readings ( $U_f$ )				Rear readings ( $U_r$ )				$U_f$	$U_r$	$(U_r - U_f)/58$
	$U_1$	$U_3$	$U_5$	$U_7$	$U_2$	$U_4$	$U_6$	$U_8$	1,3,5,7	2,4,6,8	$\tan^{-1}(-0.396/58)$
1	48.376	48.530	48.598	47.682	48.068	47.920	47.906	47.708	48.296	47.900	-0.39°

For example Table 6.3 show a result of top face of brick sample 1 (raw data Table 6.7), with the rear of the top face lower than the front by 0.396mm ( $\delta y_U = U_r - U_f = -0.396$ ), it causes the top face to incline by  $\beta = -0.39^\circ$  (i.e. downwards to the rear) when the brick front face is vertical.

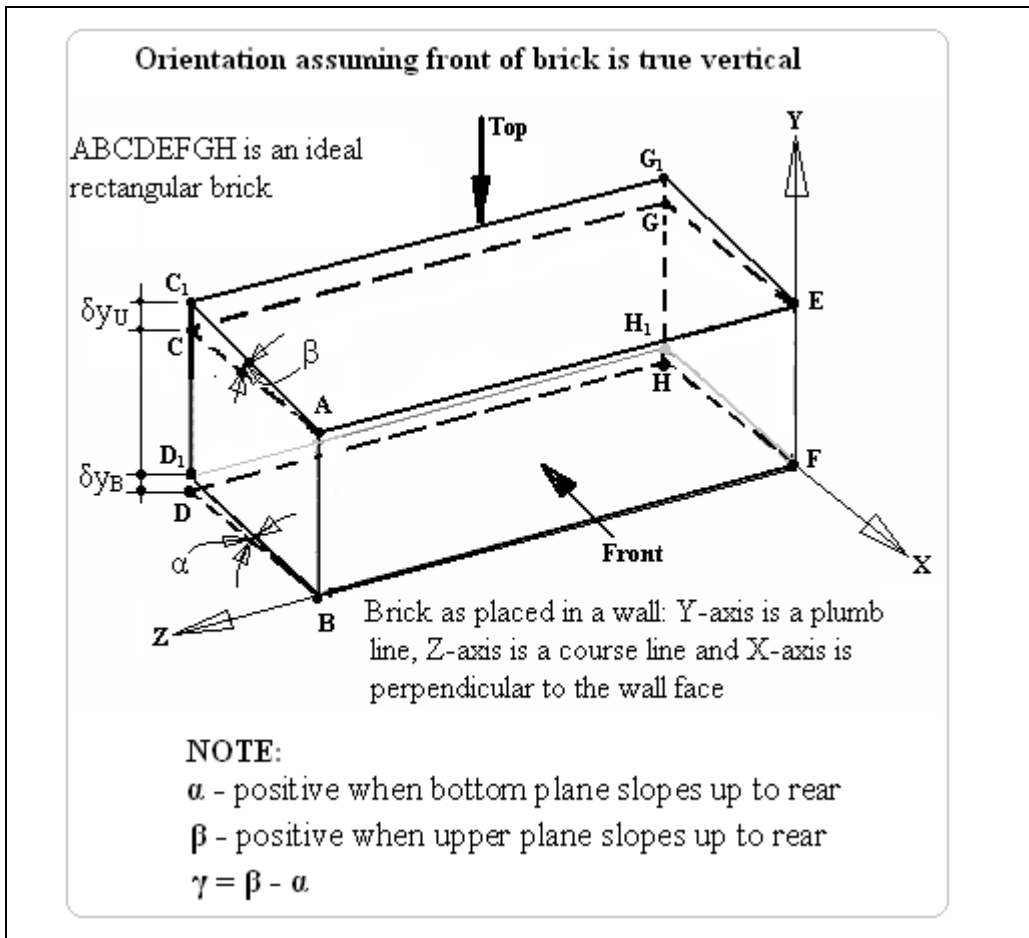
**Table 6.4 Determination of a bricks' bottom plane**

S/No	Bricks' bottom coordinates readings (as laid)								Average		Angle ( $\alpha$ )
	Front readings ( $B_f$ )				Rear readings ( $B_r$ )				$B_f$	$B_r$	$(B_r - B_f)/58$
	$B_1$	$B_3$	$B_5$	$B_7$	$B_2$	$B_4$	$B_6$	$B_8$	1,3,5,7	2,4,6,8	$\tan^{-1}(-0.225/58)$
1	0.000	0.740	0.428	0.112	0.130	0.298	-0.086	0.038	0.32	0.095	-0.09°

Table 6.4 shows the same data processing for the bottom surface of the brick. The rear side is lower than the front by 0.225mm ( $\delta y_B = B_r - B_f = -0.225$ ) Figure 6.12.



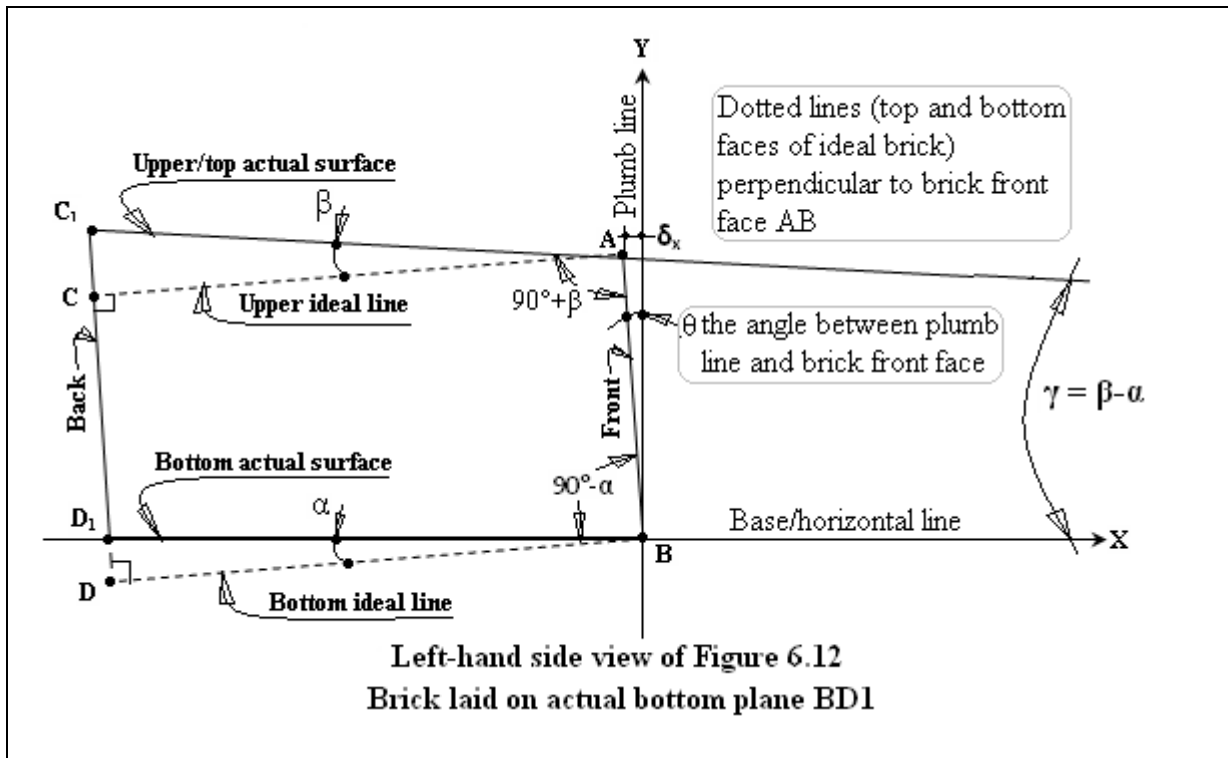
**Figure 6.12 Representing top and bottom brick planes as in position**  
*(Ideal planes, perpendicular to front face, are shown dashed)*



So the brick bottom plane inclines by  $\alpha = -0.09^\circ$  (i.e. downwards to the rear) when the front face maintained vertical (Figure 6.12). Figure 6.13 shows the same brick but with its actual bottom face laid horizontal. The front face is now no longer vertical but leans at angle  $\theta = \alpha = -0.09^\circ$  (i.e. leans forward by  $0.09^\circ$ )

Note that  $\alpha$  and  $\beta$  are permanent properties of the brick, whereas  $\theta$  varies according to how the brick is laid.  $\theta = 0$  in Figure 6.12 because the bricks' bottom face is laid on its ideal face perpendicular to front face, while  $\theta = \alpha$  in figure 6.13 as the brick is laid on its actual bottom surface.  $\gamma = \beta - \alpha$ .

Figure 6.13 Orientation assuming bottom of brick is laid on a true horizontal base



Although the datum for all point measurements was the location of bottom front point one ( $B_{f1}$ ), the derived angles  $\alpha$  and  $\beta$  for the imperfection of top and bottom mean planes are not affected by which datum point employed i.e. we would not expect due to datum choice alone any difference in the statistics;  $SD_{\alpha}$  and  $SD_{\beta}$ . The difference in these two SDs (Table 6.8) actually observed is therefore due to real production factors such as rocking of the top or bottom plate of the press.

**Table 6.5 Brick length (ℓ)**

S/No	Measurements (mm)				SUM	Mean
	a-a	b-b	c-c	d-d	$\sum x$	$\mu$
1	140.589	140.948	140.434	140.704	562.675	140.669
2	139.796	140.464	140.220	140.512	560.992	140.248
3	139.754	140.312	140.042	140.466	560.574	140.144
4	139.346	139.226	139.372	139.140	557.084	139.271
5	139.722	139.243	139.498	139.306	557.769	139.442
6	140.064	139.938	140.420	139.922	560.344	140.086
7	141.038	141.296	140.744	141.154	564.232	141.058
8	139.592	140.100	139.960	140.438	560.090	140.023
9	139.452	139.098	139.092	138.874	556.516	139.129
10	139.806	139.530	139.618	139.340	558.294	139.574
Whole sample set					5598.570	139.964*
STDEV of mean of (ℓ)						0.617
COV of (ℓ)						0.004
* Mean of all 40 points equals mean of the each sample means						

**Table 6.6 Brick width (w)**

S/No	Measurements (mm)						Sum	Mean
	e	f	g	h	j	k	$\sum x$	$\mu$
1	70.108	70.064	70.164	70.184	70.436	70.388	421.344	70.224
2	70.536	70.780	70.568	70.358	70.546	70.382	423.170	70.528
3	70.480	70.540	70.358	70.330	70.278	70.238	422.224	70.371
4	70.418	70.358	70.484	70.586	70.502	70.548	422.896	70.483
5	70.422	70.518	70.606	70.756	70.682	70.798	423.782	70.630
6	70.890	70.840	71.000	71.138	71.028	71.150	426.046	71.008
7	70.638	70.718	70.628	70.658	70.604	70.554	423.800	70.633
8	70.500	70.440	70.444	70.388	70.318	70.378	422.468	70.411
9	70.420	70.500	70.620	70.634	70.648	70.811	423.633	70.606
10	70.492	70.550	70.546	70.612	70.522	70.594	423.316	70.553
Whole sample set							4232.68	70.545
STDEV of mean of (w)								0.208
COV of (w)								0.003

**Table 6.7a Experimental interlocking bricks' measured data for flatness determination**

Brick Sample NO.	Top coordinate readings (mm)							
	Upper front reading (U <sub>f</sub> )				Upper rear readings (U <sub>r</sub> )			
	U <sub>1</sub>	U <sub>3</sub>	U <sub>5</sub>	U <sub>7</sub>	U <sub>2</sub>	U <sub>4</sub>	U <sub>6</sub>	U <sub>8</sub>
1	48.376	48.530	48.598	47.682	48.068	47.920	47.906	47.708
2	48.560	48.822	48.454	48.966	48.304	49.010	48.842	48.822
3	48.328	48.632	48.872	48.440	48.594	48.494	48.128	48.668
4	49.266	48.746	48.836	48.494	48.824	48.592	48.646	48.004
5	49.220	49.098	49.120	49.522	49.748	49.464	49.274	49.762
6	47.580	47.834	48.082	47.782	48.264	47.910	47.988	47.694
7	48.174	48.208	48.040	47.754	48.228	48.260	48.200	48.198
8	49.610	49.504	49.472	49.758	48.972	49.148	49.318	49.482
9	47.716	48.294	48.236	47.932	47.896	47.294	48.196	48.142
10	47.346	47.286	47.668	47.708	47.400	47.806	47.404	47.760
11	48.576	48.770	48.578	48.240	48.842	48.558	48.000	48.364
12	48.840	48.942	48.728	48.946	48.858	48.866	48.678	48.826
13	48.228	47.720	47.782	47.568	47.978	47.540	47.628	47.204
14	48.420	48.360	48.320	48.128	48.666	48.262	48.574	48.110
15	48.244	48.254	48.184	47.978	48.410	48.138	47.846	48.224
16	47.976	47.872	47.862	48.134	47.954	48.156	47.914	48.040
17	47.270	47.228	47.318	47.312	47.608	47.672	47.248	47.328
18	47.946	47.960	48.090	47.866	47.740	47.630	47.930	47.850
19	47.350	47.778	48.168	48.046	47.664	48.324	47.894	48.432
20	48.568	48.502	48.534	48.130	48.132	47.904	48.150	48.102
21	48.502	48.246	48.410	48.580	47.874	48.038	47.888	47.652
22	48.698	48.408	48.560	48.000	48.518	48.392	48.374	48.388
23	48.062	48.132	48.264	47.826	48.664	48.614	48.556	48.036
24	49.002	48.546	48.746	48.312	48.988	48.674	48.806	48.612
25	49.012	49.476	49.202	49.320	48.072	48.524	49.564	48.702
26	49.088	49.668	49.624	49.032	49.244	49.194	49.372	49.214
27	48.748	48.542	48.258	48.026	48.620	48.440	48.654	47.632
28	47.854	47.364	47.272	46.906	47.180	46.830	47.502	46.870
29	47.554	47.784	47.530	47.364	47.598	47.718	47.462	47.846
30	48.996	48.906	48.742	48.650	48.688	48.484	48.446	48.930
31	49.186	48.322	48.448	48.634	49.176	49.000	48.324	48.378
32	47.824	47.278	47.618	47.368	47.718	47.478	47.326	47.164
33	48.030	48.152	48.332	48.022	48.242	48.008	48.058	47.890
34	48.280	48.236	48.302	47.808	48.402	47.926	47.488	47.676
35	48.552	48.084	48.080	48.054	48.342	48.054	48.146	47.848
36	47.456	47.918	47.754	48.486	47.602	47.738	47.746	47.788
37	49.378	49.044	49.216	49.320	49.310	48.980	49.032	49.028
38	48.640	48.214	48.378	48.342	48.712	48.358	48.374	48.470
39	49.642	49.480	49.676	49.390	49.616	49.266	49.390	49.376
40	49.318	49.350	49.546	49.414	49.666	49.496	49.342	49.654
41	48.498	48.856	48.978	48.798	48.688	48.848	48.620	48.828
42	49.436	49.734	48.952	48.992	50.508	50.388	50.230	50.052
43	48.346	48.134	48.466	48.102	48.252	48.466	48.426	48.284
44	48.338	48.540	48.632	48.660	48.598	48.814	48.586	48.898
	<b>Upper coordinate readings (mm)</b>							
	<b>Average of upper coordinates (Av.U)</b>						<b>48.39</b>	
	<b>Average brick height (Av.U – Av.B)</b>						<b>48.30</b>	

**Table 6.7b Experimental interlocking bricks' measured data for flatness determination**

Bottom coordinate readings (mm)							
Bottom front reading (B <sub>f</sub> )				Bottom rear readings (B <sub>r</sub> )			
B <sub>1</sub>	B <sub>3</sub>	B <sub>5</sub>	B <sub>7</sub>	B <sub>2</sub>	B <sub>4</sub>	B <sub>6</sub>	B <sub>8</sub>
0.000	0.740	0.428	0.112	0.130	0.298	-0.086	0.038
0.000	-0.102	0.018	-0.068	-0.550	-0.490	-0.628	-0.478
0.000	0.022	0.062	0.136	0.158	0.076	-0.156	-0.164
0.000	0.114	-0.072	0.044	-0.500	-0.400	-0.272	-0.436
0.000	-0.318	-0.206	-0.012	-0.470	0.000	-0.174	-0.202
0.000	0.034	-0.050	0.086	0.160	0.392	0.570	0.404
0.000	0.050	0.088	-0.016	0.364	0.578	0.566	0.624
0.000	0.074	0.162	0.046	-0.536	-0.616	-0.500	-0.576
0.000	0.020	0.116	0.226	-0.074	-0.016	0.002	0.152
0.000	-0.156	0.030	0.302	0.708	0.694	0.656	0.680
0.000	0.070	-0.136	-0.136	-0.238	-0.298	-0.340	-0.048
0.000	-0.146	-0.126	0.088	0.012	0.056	0.240	0.110
0.000	0.200	0.334	0.156	-0.260	-0.140	-0.238	-0.248
0.000	0.170	0.114	-0.010	0.160	0.328	0.160	0.254
0.000	0.126	0.002	0.198	0.034	0.014	-0.030	-0.038
0.000	0.056	0.022	0.010	-0.240	-0.108	0.016	-0.066
0.000	0.116	0.100	0.206	0.662	0.664	0.634	0.600
0.000	-0.188	-0.288	-0.040	0.538	0.632	0.588	0.502
0.000	0.116	0.088	0.114	-0.214	-0.098	-0.038	-0.126
0.000	0.306	0.306	0.312	0.522	0.846	0.664	0.500
0.000	0.360	0.388	0.270	-0.486	-0.336	-0.042	-0.384
0.000	0.288	0.294	0.138	0.652	0.872	0.764	0.712
0.000	0.218	-0.002	0.042	-0.288	-0.238	-0.014	-0.266
0.000	0.190	0.172	-0.032	-0.278	-0.076	-0.152	-0.168
0.000	0.380	0.426	0.608	-0.018	0.498	0.352	0.394
0.000	0.232	0.046	0.274	-0.292	0.190	-0.288	-0.082
0.000	0.276	0.256	0.180	-0.640	-0.524	-0.516	-0.486
0.000	0.072	0.066	0.132	-0.016	0.200	0.414	0.144
0.000	0.424	-0.324	0.306	-0.088	-0.008	0.002	0.114
0.000	0.374	0.146	0.016	0.910	0.558	0.676	0.438
0.000	0.248	0.430	0.272	0.358	0.510	0.456	0.438
0.000	-0.062	0.122	0.266	0.470	0.478	0.838	0.442
0.000	0.090	0.040	-0.004	-0.134	0.116	-0.040	-0.072
0.000	0.174	0.332	0.118	-0.410	-0.214	-0.344	-0.382
0.000	0.140	0.250	0.338	0.250	0.468	0.430	0.338
0.000	0.032	-0.078	-0.172	0.300	0.514	0.494	0.488
0.000	0.226	0.230	0.100	-0.214	0.120	0.174	-0.030
0.000	0.162	0.126	0.082	-0.070	-0.052	0.058	0.046
0.000	0.084	0.194	0.102	0.482	0.560	0.668	0.552
0.000	0.268	0.144	0.112	-0.198	-0.184	0.066	-0.126
0.000	0.018	-0.006	-0.096	-0.074	0.036	0.022	0.120
0.000	0.144	0.192	0.298	0.678	0.652	0.634	0.704
0.000	0.260	0.322	0.582	-0.354	-0.222	-0.266	0.080
0.000	0.114	0.328	-0.070	-0.412	0.044	-0.088	-0.378
Bottom coordinate readings (mm)							
Average of bottom coordinates (Av.B)					0.096		

**Table 6.8 Brick-plane inclinations of top(upper) and bottom surfaces**

Brick Sample NO	Upper coordinates (mm)		Bottom coordinates (mm)		Alpha( $\alpha$ )	Beta( $\beta$ )	Gamma( $\gamma$ )	Average Brick height
	Av. $U_f$	Av. $U_r$	Av. $B_f$	Av. $B_r$	$(B_r-B_f)/58$	$(U_r-U_f)/58$	$\beta-\alpha$	$\frac{\{(Av.U_f+Av.U_r)-(Av.B_f+Av.B_r)\}}{2}$
1	48.2965	47.9005	0.3200	0.0950	-0.0039	-0.0068	-0.0029	47.891
2	48.7005	48.7445	-0.0380	-0.5365	-0.0086	0.0008	0.0094	49.010
3	48.5680	48.4710	0.0550	-0.0215	-0.0013	-0.0017	-0.0004	48.503
4	48.8355	48.5165	0.0215	-0.4020	-0.0073	-0.0055	0.0018	48.866
5	49.2400	49.5620	-0.1340	-0.2115	-0.0013	0.0056	0.0069	49.574
6	47.8195	47.9640	0.0175	0.3815	0.0063	0.0025	-0.0038	47.692
7	48.0440	48.2215	0.0305	0.5330	0.0087	0.0031	-0.0056	47.851
8	49.5860	49.2300	0.0705	-0.5570	-0.0108	-0.0061	0.0047	49.651
9	48.0445	47.8820	0.0905	0.0160	-0.0013	-0.0028	-0.0015	47.910
10	47.5020	47.5925	0.0440	0.6845	0.0110	0.0016	-0.0095	47.183
11	48.5410	48.4410	-0.0505	-0.2310	-0.0031	-0.0017	0.0014	48.632
12	48.8640	48.8070	-0.0460	0.1045	0.0026	-0.0010	-0.0036	48.806
13	47.8245	47.5875	0.1725	-0.2215	-0.0068	-0.0041	0.0027	47.731
14	48.3070	48.4030	0.0685	0.2255	0.0027	0.0017	-0.0011	48.208
15	48.1650	48.1545	0.0815	-0.0050	-0.0015	-0.0002	0.0013	48.122
16	47.9610	48.0160	0.0220	-0.0995	-0.0021	0.0009	0.0030	48.027
17	47.2820	47.4640	0.1055	0.6400	0.0092	0.0031	-0.0061	47.000
18	47.9655	47.7875	-0.1290	0.5650	0.0120	-0.0031	-0.0150	47.659
19	47.8355	48.0785	0.0795	-0.1190	-0.0034	0.0042	0.0076	47.977
20	48.4335	48.0720	0.2310	0.6330	0.0069	-0.0062	-0.0132	47.821
21	48.4345	47.8630	0.2545	-0.3120	-0.0098	-0.0099	-0.0001	48.178
22	48.4165	48.4180	0.1800	0.7500	0.0098	0.0000	-0.0098	47.952
23	48.0710	48.4675	0.0645	-0.2015	-0.0046	0.0068	0.0114	48.338
24	48.6515	48.7700	0.0825	-0.1685	-0.0043	0.0020	0.0064	48.754
25	49.2525	48.7155	0.3535	0.3065	-0.0008	-0.0093	-0.0084	48.654
26	49.3530	49.2560	0.1380	-0.1180	-0.0044	-0.0017	0.0027	49.295
27	48.3935	48.3365	0.1780	-0.5415	-0.0124	-0.0010	0.0114	48.547
28	47.3490	47.0955	0.0675	0.1855	0.0020	-0.0044	-0.0064	47.096
29	47.5580	47.6560	0.1015	0.0050	-0.0017	0.0017	0.0034	47.554
30	48.8235	48.6370	0.1340	0.6455	0.0088	-0.0032	-0.0120	48.341
31	48.6475	48.7195	0.2375	0.4405	0.0035	0.0012	-0.0023	48.345
32	47.5220	47.4215	0.0815	0.5570	0.0082	-0.0017	-0.0099	47.153
33	48.1340	48.0495	0.0315	-0.0325	-0.0011	-0.0015	-0.0004	48.092
34	48.1565	47.8730	0.1560	-0.3375	-0.0085	-0.0049	0.0036	48.106
35	48.1925	48.0975	0.1820	0.3715	0.0033	-0.0016	-0.0049	47.868
36	47.9035	47.7185	-0.0545	0.4490	0.0087	-0.0032	-0.0119	47.614
37	49.2395	49.0875	0.1390	0.0125	-0.0022	-0.0026	-0.0004	49.088
38	48.3935	48.4785	0.0925	-0.0045	-0.0017	0.0015	0.0031	48.392
39	49.5470	49.4120	0.0950	0.5655	0.0081	-0.0023	-0.0104	49.149
40	49.4070	49.5395	0.1310	-0.1105	-0.0042	0.0023	0.0064	49.463
41	48.7825	48.7460	-0.0210	0.0260	0.0008	-0.0006	-0.0014	48.762
42	49.2785	50.2945	0.1585	0.6670	0.0088	0.0175	0.0087	49.374
43	48.2620	48.3570	0.2910	-0.1905	-0.0083	0.0016	0.0099	48.259
44	48.5425	48.7240	0.0930	-0.2085	-0.0052	0.0031	0.0083	48.691
Average	48.4120	48.3779	0.0950	0.0961	-0.0013	0.0008	-0.0020	48.30
STDEV	0.5994	0.6516	0.1070	0.3742	0.0037	0.0015	0.0038	0.67
COV of brick heights (T)								0.01

## 6.3 REPRESENTING BRICK GEOMETRY IN ALIGNED POSITION

### 6.3.1 BRICK ALIGNMENT FACTORS

Mortarless bricks are generally made with an interlock between successive courses: this takes various forms; some of these only constrain the location of a brick perpendicular to the wall face whilst others also constrain the brick longitudinally along the course. However these constraints are designed to include a considerable vertical clearance so that the vertical position of a laid brick is determined by the meeting of parts of the top and bottom brick faces *other than* the interlock protuberances. Irregularities or biases in these faces will result in a wall leaning out of plumb (*henceforth called 'x-deviation'*) and courses undulating (*henceforth called y-deviation*) – effects that can or might magnify strongly as the wall gets higher.

As well as the degree of imperfection in the bricks themselves (as expressed by bias across the whole set and by random variation from brick to brick), several other factors affect the plumb (x-deviation) of a wall built of mortarless interlocking bricks. The author notes the following as ideas guiding the series of tests performed.

Most obvious is the number *of courses*; doubling this number will normally more than double the x-deviation at the top of the wall. A typical number of courses are between 26 and 28 for a single-storey house, and between 52 and 56 for a two-storey house.

Second is *brick orientation* namely; whether a brick is laid as randomly picked up by the mason or is laid reversed. Most bricks, even those with interlocks, can be reversed – their inside and outside faces are of similar quality. There is no advantage in rotating bricks at random. However if the brick is somehow marked to show its orientation during moulding or

if the mason can note any lack of brick-to-brick symmetry, then this information can enable the assembly of a straighter wall.

Thirdly, is *brick selection*, in which the mason selects the most suitable brick from his stack to fit a particular location on a wall, again it is desirable that the mason can observe the properties of an individual brick before laying it (although the mason can also test its suitability by ‘trying’ it in the wall, an option only available if there is no mortar).

Fourthly comes *build sequence*, namely whether corners, the sides of openings and other joints are raised before, after or on a level with the intervening walls. Normally corners are raised a few courses ahead of straight walls and this practice is even more attractive when using interlocking bricks.

Fifthly there is the accuracy of levelling the first course onto its (*possibly irregular*) foundation. The penalty for imperfect orientation of this first course is so high in mortarless construction that it is usual to lay it on mortar (Figure 6.14).

Lastly we may mention *bond* (Chapter 4). New MT bonds that allow assembly of double thickness wall (e.g. 300mm) will generally produce walls that vary less than a single thickness wall.

In this thesis we disregard the last two factors by assuming our wall is of single-thickness stretcher-bond laid onto a perfectly level and bump-free foundation.

### **6.3.2 Brick-to-brick contact**

When a new mortarless brick is laid onto an existing course, it will normally touch at three points on its bottom surface. The centre of gravity of the brick will lie inside the triangular wedge formed by raising vertical planes along the three lines connecting these three points. To achieve this pattern of contact, we may imagine the mason firstly presenting the brick to



the wall horizontal, parallel to the course below in the correct longitudinal position and guided perhaps by the locking features (*Jaafar et al. 2006. Haener, 1984*). There then follows, not necessarily in the order given, the following four movements:

- i. The brick is aligned so that its front face is parallel to and vertically above the front faces of normally two bricks below;
- ii. The brick is lowered until contact is made (*at the point of greatest vertical interference*);
- iii. The brick is rolled about its longitudinal axis until a second point of contact is made;
- iv. The brick is pitched (*in the same sense as fore-and-aft pitching of an aeroplane or ship*) until a third point contact results.

The first of these movements may be relaxed slightly, within the constraints of the interlock, however most masons try to avoid any steps in the vertical face of the wall they are building. The other motions of the brick are largely determined by the two mating surfaces.

Contact at just three points implies a strong concentration of vertical loads on the brick's underside. (Although local deformations will convert each 'point' into a disc of contact maybe 3mm in diameter.) This concentration will generally result in bending moments occurring within the brick. However even where such local redistributions are highest (e.g. low down in the wall) the deformation they generate in a brick's surface are low (*Marzahn (1999), Jaafar et al. (2006)*). Surface irregularities are usually much bigger than this, so the bending does not usually result in additional points of contact forming. However the laying of subsequent courses may so load an already-laid brick that it rocks to a new 3-point contact no longer surrounding its own centre of gravity. This complex possibility we shall ignore in our wall-simulations by computer but may well be present in the physical experimental walls.

### 6.3.3 REAL BRICK GEOMETRY

To fully describe a real (*as opposed to an ideal*) brick requires hundreds of data. This is both impractical and confusing. Moreover there is difficulty in choosing from what datum to measure the location of points or the angular orientation of faces (*Jaafar et al. 2006*). A sample of the half-size experimental bricks (44 pieces) was measured by laser (Figure 6.10) using a stylus erected perpendicular to its front face. 8 points on the top and 8 on the bottom of each brick were measured (sample brick 1 Tables 6.3 and 6.4). Brick length and brick width were also measured (Tables 6.5 and 6.6); but these have little effect on plumbness (x-deviation) of a built wall or course straightness (y-deviation/height error).

If we are to discuss the accuracy of a set of bricks, we cannot avoid defining an *ideal* brick (Figure 6.12 brick ABCDEFGH), perfectly rectangular and having specified height, length and width. It is the deviations from height and rectangularity that concern us, so it is convenient to consider only three faces: the front, top and bottom. The back will also interest us if the brick is reversed before placement, but we may normally assume that both front and back are parallel and flat, since they were formed in contact with the sides of the same mould. In addition to the *ideal* brick, we can easily imagine an *average* brick whose size and angles equal the average of all bricks in the set. For example its height (T) might be 0.5mm greater or smaller than the specified ideal brick height. Now we can describe each individual brick by its deviations from the *average* brick and statistically we could describe the consistency of the whole set by the *standard deviations SD* of these deviations.

The simplest approximation we can use is to describe each brick (Figure 6.12) by:

- The angles  $\alpha$  and  $\beta$  that the bottom and top faces respectively are out of square with the front face of the brick. (Thus  $\alpha = -0.09^\circ$  Table 6.4) means the bottom face of the

brick falls  $0.09^\circ$  below a plane perpendicular to the brick's front – the angle between bottom and front is  $90.09^\circ$  instead of the ideal  $90^\circ$ .)

- The deviation/brick error -  $e_T$  (from its average) of the brick height/thickness (T) between the centre of the top and bottom faces.

And for the whole set of bricks we could record the average and standard deviations of these three variables  $e_T$ ,  $\alpha$  and  $\beta$ . It is often useful to record the angle *between* the top and bottom faces, namely

'Roll-wedge angle'  $\gamma = \beta - \alpha$  (Figure 6.13) and its associated average ( $m_\gamma$ ) and S.D. ( $\sigma_\gamma$ ) Table 6.8.

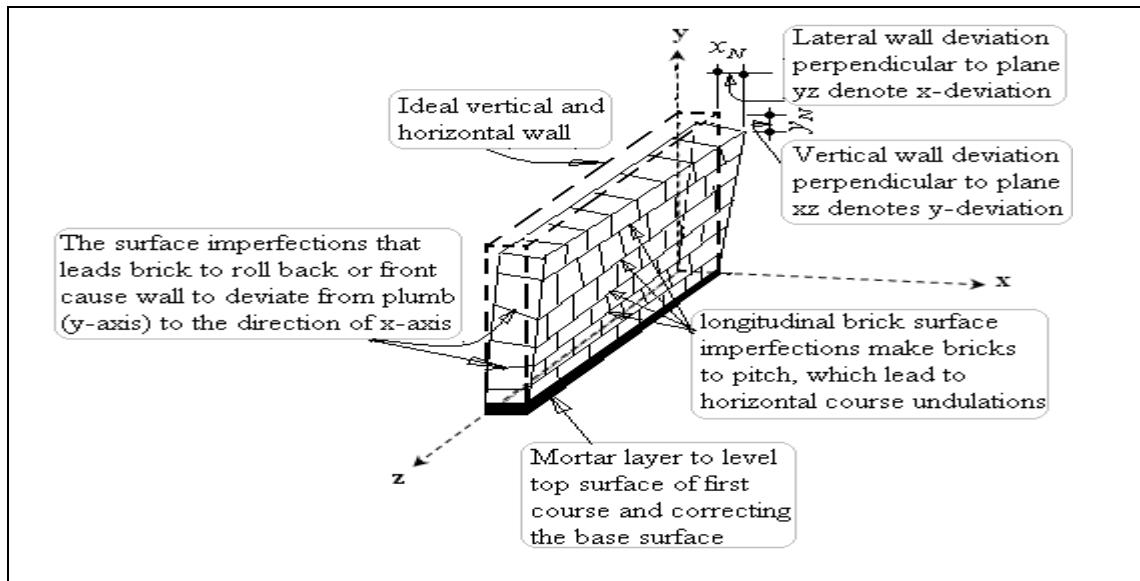
In using this simplification we are effectively treating the top and bottom surfaces as planes, disregarding their bumpiness, and we are taking no notice of longitudinal pitch angle (Figure 6.12).

### **6.3.4 EFFECTS OF ROLL AND PITCH WEDGE ANGLES TO WALL ALIGNMENT**

Any surface deviations (in mm) of a brick-top and/or brick-bottom from the ideal brick will result in roll and pitch deviations once one brick is placed on another. Because a brick is less wide than it is long, the roll angle resulting from such deviations tends to be about twice the size of the resulting pitch angle. Moreover the long length of a course of overlapping stretcher-bonded bricks tends to reduce pitch angles, whereas there is no corresponding 'length' to reduce roll-angles. In consequence the roll angle (outward lean) of the top of a mortarless wall will generally be much more than the pitch angle there (Figure 6.14). It follows that the x-displacement at the top of the wall is normally much greater than any 'y-

displacement' (*parallel to the wall top – z-axis*). As a 'worst case' we may consider a single-brick column and look only at its x-deviation ( $x_N$ ) from plumb and its y-deviation ( $y_N$ ) from its intended height. Figure 6.14 show an imperfect wall which reduces pitching by longitudinal overlapping.

**Figure 6.14 The brick imperfection characteristics as implied on wall**



There will be some relationship between *brick* properties (surface irregularity expressed via some statistical measure) and *wall* properties (expressed statistically). This relationship, mainly for a column of bricks but also extended to a wall of interlocked and overlapping bricks, has been derived:

- (i) From a simple *theory* (as a formula),
- (ii) From physical *measurements* (in this case using half-size bricks) and
- (iii) From *computer simulations* in which simulated bricks are 'assembled' into columns.

In this last case, two different approaches were employed, one using a pile of *simulated* bricks based directly on the actual measured set, and the other using a pile of *random* bricks

whose dimensions were generated using a random number generator so as to have the statistical properties as the set of measured bricks.

The relationship between *column* accuracy and brick accuracy is affected by the brick-laying strategy – for which several variants were considered. The relationship between *wall* accuracy and brick accuracy is further determined by such wall parameters as its length and the degree of constraint at the wall ends.

The study considered a column of 20 courses of mortarless bricks laid on an exactly horizontal base, recording the statistics of the vertical, horizontal and angular displacements (from ideal) of the top surface of the 5<sup>th</sup>, 10<sup>th</sup> and 20<sup>th</sup> courses. So the *underside* of course-1 is taken as the datum in terms of orientation. This does not universally reflect wall-building practice (Figure 6.14), since the mortar under course-1 could be adjusted to make the *top* surface of course-1 horizontal; however our modelling simplifies the comparisons.

## **6.4 RESEARCH TECHNIQUES FOR EXAMINING BRICK-TO-COLUMN ALIGNMENT RELATIONSHIP**

The task ahead is to relate column alignment in accuracy to brick geometric imperfection, their measurement and characteristics described in section (6.2.3-III) for the randomly selected brick sample from the production batches. Ten percent (44 pieces) of the manufactured FBs were measured for their top and bottom surface flatness. The readings were statistically processed in Table 6.8, to facilitate their use in:

- i) The theoretical statistical analysis of column alignment and
- ii) The computer simulation of column alignment using a stack of imaginary bricks whose statistical properties have been predetermined.

Both theoretical and simulation results be compared to;

- iii) The physical repeatedly assembling of column of actual-bricks whose deviations from ideal have been measured.

**Table 6.9 Research techniques and the variables each can allow**

<b>Technique</b>	<b>Variables</b>	<b>Advantages</b>	<b>Problems</b>
<b>Theory</b>	<ul style="list-style-type: none"> <li>• Brick statistics</li> <li>• Number of courses (N)</li> </ul>	Universality	Very crude control model
<b>Laboratory (physical test)</b>	<ul style="list-style-type: none"> <li>• N,</li> <li>• Bricklaying options,</li> <li>• Length of wall,</li> <li>• Constraints on walls</li> </ul>	Realism	Expensive on material and time
<b>Simulation</b>	<ul style="list-style-type: none"> <li>• N,</li> <li>• Brick statistics,</li> <li>• Sample size,</li> <li>• laying options,</li> <li>• Number of assemblies</li> </ul>	Reliable statistic data	Only approximate modelling of brick-to-brick contact

The three methods supplement each other to fulfil the research objectives as shown in Table 6.9 that, with physical column assembling, it is not easy to vary the characteristics of bricks although you can change the method of bricklaying i.e. random picking and placing, or reversing, or selecting and replacing bricks for better orientation and positioning. Using simplified theoretical equation and knowing certain brick characteristics, it is possible to predict the column lean at any course number (height). With computer simulation we can vary brick characteristics, increase the number of assemblies to improve statistical data and vary the orientation of laid bricks. However the simulation results are limited in accuracy by approximations in modelling brick-to-brick contact.

## 6.5 THEORETICAL ANALYSIS OF BRICK COLUMN

### 6.5.1 THE RELATIONSHIP BETWEEN BRICK CHARACTERISTIC CONDITIONS AND COLUMN-ALIGNMENT

The theoretical analysis is for a column with a horizontal cross-sectional area of a single brick. Each brick is assumed to have a flat (bump-free) top, bottom and front face, but these faces are not always parallel/perpendicular to each other. We considered only three brick types:

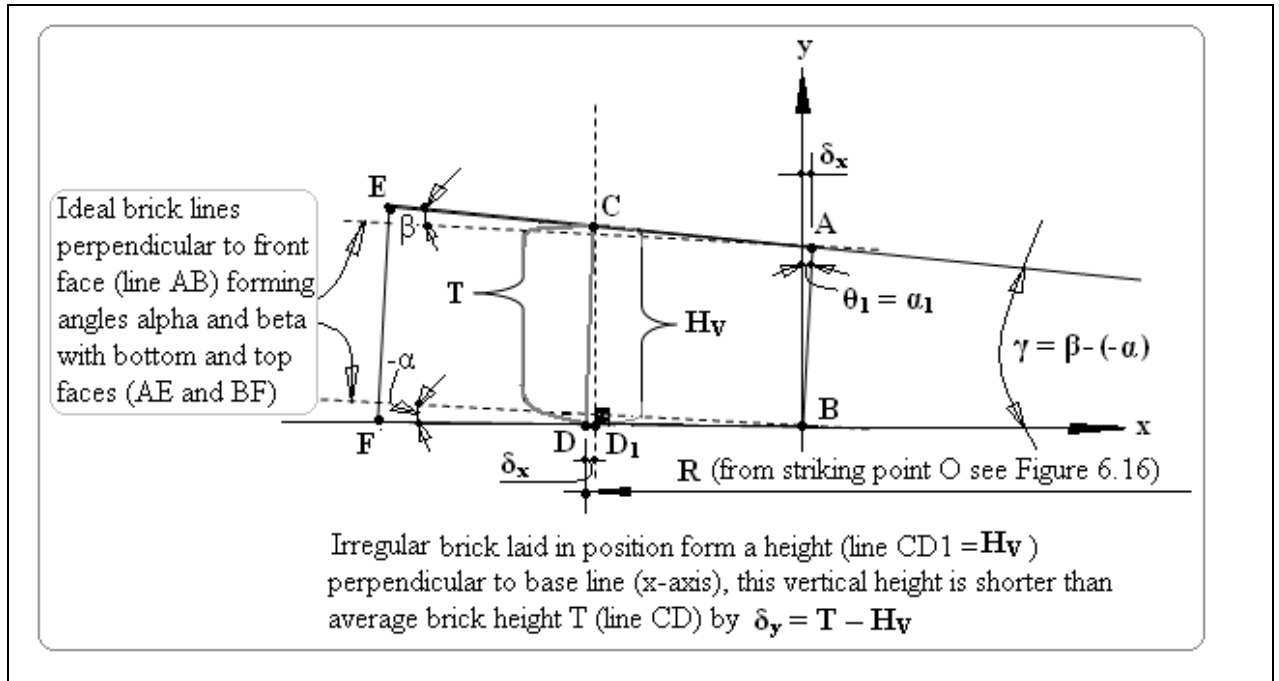
- Bricks with constant height but non-zero roll-wedge angle
- Top and bottom faces are parallel but non-square to front face
- Randomly-varying bricks whose *average* dimensions are however perfect

#### 6.5.1.1 Brick with constant height but non-zero roll-wedge angle

**Theory** If both angles  $\alpha$  and  $\beta$  are zero, and brick thickness ( $T = T_0 + \delta_y$ ), where  $T_0$  is the intended thickness and  $\delta_y$  is *constant height* deviation. Then y-deviation (total vertical deviation) of the top of the  $N^{\text{th}}$  course will be simply: -

$$y_N = N\delta_y \quad (6.1)$$

**Figure 6.15 Analysis of an imperfect dry-stack brick in position**



If however  $\alpha$  and  $\beta$  are equal in size but opposite in sign, the brick will be simply trapezoidal (Figure 6.15), there will be a small *negative* addition to y-axis direction. We take the nominal brick height (T) as occurring half way between the front and the back faces of the brick.

The roll angle  $\gamma$  is equal to  $\beta - \alpha = 2\beta$ . This will reduce the rise of one course by the quantity

$$\delta_y = T - H_V$$

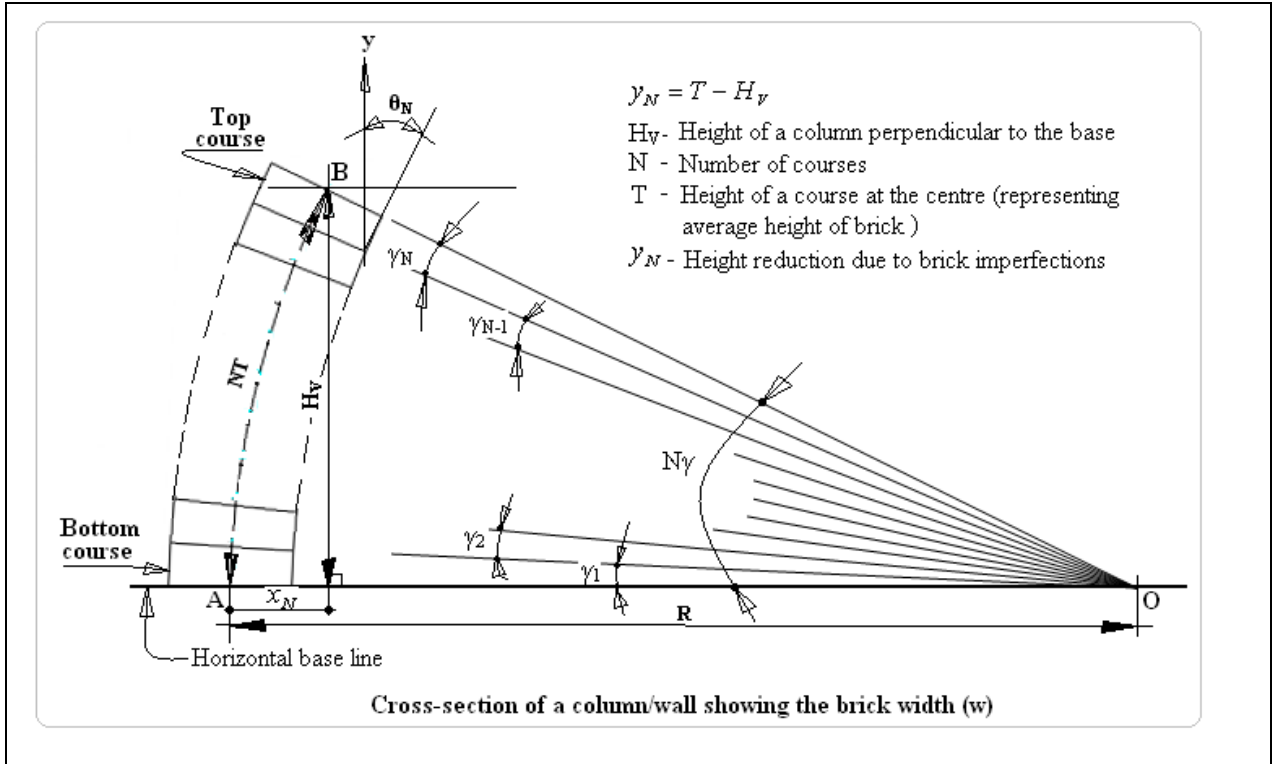
Where;  $H = R \sin \gamma$  and  $R = \frac{T}{\gamma}$  (from trigonometry equality) then

$$\delta_y = T - \frac{T}{\gamma} \sin \gamma = T \left( 1 - \frac{\sin \gamma}{\gamma} \right)$$



For a column of N courses (Figure 6.16);  $y_N = \sum_{y=1}^{y=N} \delta_y$

**Figure 6.16 Effect of brick irregularity on column height**



So, 
$$y_N = NT \left( 1 - \frac{\sin N\gamma}{N\gamma} \right)$$

Using the small angle approximation and taking only the first two non-zero terms of the Maclaurin expression for  $\sin(N\gamma)$ .

We get:

$$y_N = NT \left\{ 1 - \left( \frac{N\gamma - \frac{N^3\gamma^3}{6}}{N\gamma} \right) \right\} = NT \left\{ 1 - \left( \frac{N\gamma \left( \frac{1 - N^2\gamma^2}{6} \right)}{N\gamma} \right) \right\} = \frac{1}{6} N^3 T \gamma^2$$

$$y_N = 0.17N^3T\gamma^2 \quad (6.2)$$

Thus a constant roll angle per brick of say  $\gamma = 0.01$  radians ( $0.6^\circ$ ) will reduce a 20-course wall height by only 0.7%. (If some of these bricks are laid with alternate orientations, the reduction in wall height will be very much less, indeed so small that we can neglect it in any analysis).

The x-deviation perpendicular to wall face is more complicated.

Consider the case  $\beta = -\alpha = \frac{a}{2}$ , so that the roll wedge angle  $\gamma = \beta - \alpha = a$  for every brick. Also suppose the first course is laid in mortar to make the top surface horizontal.

The angle that the front of any course ( $N^{\text{th}}$  brick) Figure 6.16 makes with the vertical is  $\theta_N$  and if the horizontal deviation (out of plumb) of each brick's top front edge *relative to its bottom first edge* is  $\delta x_N$  (Figure 6.13), then:  $\delta x_N = T \sin(\theta_N)$ .

Or to a very good approximation for small angles:

$$\delta x_N = T\theta_N \quad \text{Where } \theta_N = a(N - \frac{1}{2}), \text{ hence } \delta x_N = Ta(N - \frac{1}{2})$$

The *horizontal error* ( $\delta_x$ ) of the top front of the  $N^{\text{th}}$  brick *relative to the column base* will be

$$x_N = \sum_{x=1}^{x=N} \delta_x \quad \text{Is the sum of the horizontal-deviations of N individual course.}$$

$$x_N = Ta[\frac{1}{2} + 1\frac{1}{2} + 2\frac{1}{2} + 3\frac{1}{2} + \dots + (N - \frac{1}{2})] = Ta\{(1 + 2 + 3 + \dots + N) - \frac{1}{2}N\}$$

$$x_N = \frac{1}{2}TaN^2 \quad (6-3)$$

Thus the  $x$ -deviation of a column built with identical but imperfect (roll wedge angle =  $a$ ) bricks are:

- Proportional to  $a$
- Proportional to the square of the number of courses

So doubling the wall height will increase its  $x$ -deviation (out of plumb) 4-fold.

### 6.5.1.2 Parallel but not-square bricks

If the bricks have parallel top and bottom faces (hence wedge angle  $\gamma$  equals 0) but these faces are not square to the front face, i.e.:

$$\beta = a; \alpha = -a; \gamma = \beta - \alpha = 0$$

Then the whole wall has a leaning front face and the deviation at the top of  $N$  courses each of height ( $T$ ) will simply be;  $x_N = NT \sin a$  and for the approximation of small angles, then

$$x_N \cong NTa \tag{6-4}$$

This deviation *equation 6-4* (confirmed by simulation) is generally 10-fold or more *less* than the deviation *equation 6.3* caused by the corresponding degree of roll-wedge distortion. Thus the brick moulder must place achieving parallel top and bottom faces much higher than achieving true square.

### 6.5.1.3 Randomly-varying bricks whose average dimensions are ideal

A brick's geometry could vary from ideal in many ways. We will consider only bricks with small random roll-wedge angles  $\gamma$ .

Across the set of bricks the average value  $m_\gamma$  of  $\gamma$  we assume will be zero but its standard deviation we can specify – for example as having value  $\sigma_\gamma$  (using standard probability notation). We need in addition to specify the way  $\gamma$  varies, and there are good reasons for choosing a 'normal' distribution, (for which the chance of  $\gamma$  lying outside  $\pm 2SD$  is only 4.6%).

**Theory** If the bricks have randomly-distributed roll angles, then the resultant  $x_N$  (horizontal-deflection at the top of the column/wall) will also be a random quantity. And as the average of  $\gamma$  is zero, so will be the average of  $x_N$ . However we can characterise the variability of  $x_N$  by its standard deviation (let us call it  $\sigma_x$ ), knowing that there is a low probability of the deviation  $x$  of an actual wall-top exceeding  $\pm 2\sigma_x$ . So we want the relationship between  $\sigma_x$  of the column-top and the standard deviation ( $\sigma_\gamma$ ) of the roll-wedge angle of the bricks.

As for independent random variables, the variance of their sum equals the sum of their individual variances; we can obtain the statistical equivalence of equation 6.3 as

$$\sigma_x^2 = T^2 \sigma_\gamma^2 \left[ \left(\frac{1}{2}\right)^2 + \left(1\frac{1}{2}\right)^2 + \left(2\frac{1}{2}\right)^2 + \dots + \left(N - \frac{1}{2}\right)^2 \right]$$

From the above equation we can sum values in the square bracket as follows: -

$$0.5^2 + 1.5^2 + 2.5^2 + \dots + (N + 0.5)^2 = \frac{1}{12} (4N^3 - N) \quad \text{and therefore}$$

$$\sigma_x = \frac{1}{\sqrt{3}} T \sigma_\gamma \sqrt{(N^3 - N/4)} \quad (6-5)$$

Since in practice  $N^3 \gg \frac{N}{4}$ , and for  $N \geq 5$ , the approximation error of neglecting the  $N/4$  is less than 1/2%. Therefore we can use the approximate and simplified equation as,

$$\sigma_x = 0.577 T \sigma_\gamma N^{1.5} \quad (6.6)$$

Where:

$T$  is the brick average height/thickness

$\sigma_\gamma$  SD of roll-wedge angle ( $\gamma$ ) of sample bricks

$N$  Column course numbers

## 6.5.2 SUMMARY OF THEORETICAL ANALYSIS

### 6.5.2.1 Models comparison

The out-come of the three cases (i) roll wedge-angle constant, (ii) roll wedge-angle zero but front face sloping and (iii) random roll wedge-angle, exhibit a more than ten-fold difference between the first and second cases, and therefore confirm that brick moulders should place achieving parallel top and bottom faces much higher than achieving true square-ness.

With the randomly varying bricks, equation 6.6 was formulated to the column lean for given brick statistics.

## **6.6 PHYSICAL EXPERIMENTS AND TESTING TECHNIQUES**

### **6.6.1 INTRODUCTION**

The primary experiment was to identify the relationship between brick accuracy and wall alignment accuracy measured in two dimensions, namely wall plumb-error ( $x$ -deviation) and height-error ( $y$ -deviation) as shown in Figure 6.14. To study how the plumb-error is magnified as the column/wall height increases, measurements were recorded at three levels (courses 5, 10 and 20) from the steel rig-structure (Figure 6.17) to a built column/wall. Figure 6.17a shows a rig (to be discussed in section 6.6.2) with three vertical members from where the walls'/columns' plumb is checked at selected heights Figure 6.17b.

Three assembly strategies were compared to observe how the accuracy and quality of bricks and the method of bricklaying contribute to the wall alignment quality. In the investigations, shimming (insertion of filling material to correct for roll or pitch) was not permitted, as doing so would have hidden the accumulative column/wall plumb-error under scrutiny caused by the inaccuracy of bricks. Three types of walls (1400mm long by 1000mm high) were built, see Figures 6.27 and 6.28; first a wall with both ends free, second a wall with one free end and the other end restrained or fixed, and third a wall with both ends restrained.

The columns/walls were assembled using three different brick-laying strategies. The first named as Column one (C1) or Wall one (W1), bricks are randomly picked from a pile and placed as found, with no reversing for proper orientation or selection for proper brick. In the second (C2/W2), the bricks are also randomly picked from the pile, i.e. no

selection, but are then allowed to be reversed by the brick-layer for best orientation. In the third (C3/W3), bricks are laid with both selection and orientation permitted. The bricklayer is allowed to measure using a spirit level or plumb and rectify horizontal out-of-plumb deviations if need arises. Also use a straight-level on the front face (the same for all assembly strategies) to make the wall course straight.

## **6.6.2 COLUMNS AND WALLS ALIGNMENT ACCURACY TEST**

### **6.6.2.1 Experimental design**

Bricklaying, even in mortarless wall construction, entails placing and fitting the bricks one over the other, to make them straight in line with the building line, spirit level or plumb. A series of actions (*pushing, pulling, rolling, pitching and squeezing*) are performed. These actions cause a lot of disturbance to the already-built courses of a block-wall with bricks dry-stacked. Due to the absence of joint mortar the wall's accuracy entirely depends on the locking mechanism between bricks, and on the top and bottom surface flatness and parallelism of these bricks. However the disturbances cause the wall to wobble. As the height and length increases, it will reach a point where the block wall may not be stable enough to resist any further creation of vibration. That's why in conventional bricklaying there is a limit of 6 to 9 courses to be laid in a day (*to allow mortar to strengthen before continuing*), otherwise the wall will not be stable enough to resist further accidental or normal shaking from masons during brick assembling and thus unable to retain positional accuracy.

We need to investigate the maximum allowable brick error that will allow building a

stable mortarless wall to the designed height (2.4 to 2.8m) without excessive vertical deviation.

### **Rig structure**

Tables 6.5 to 6.8 showed the governing dimensions measured on a sample of bricks.

From these sample bricks, was derived statistical characterisation of the whole brick population.

To measure column/wall deviations required a vertical reference datum (Figure 6.17 a).

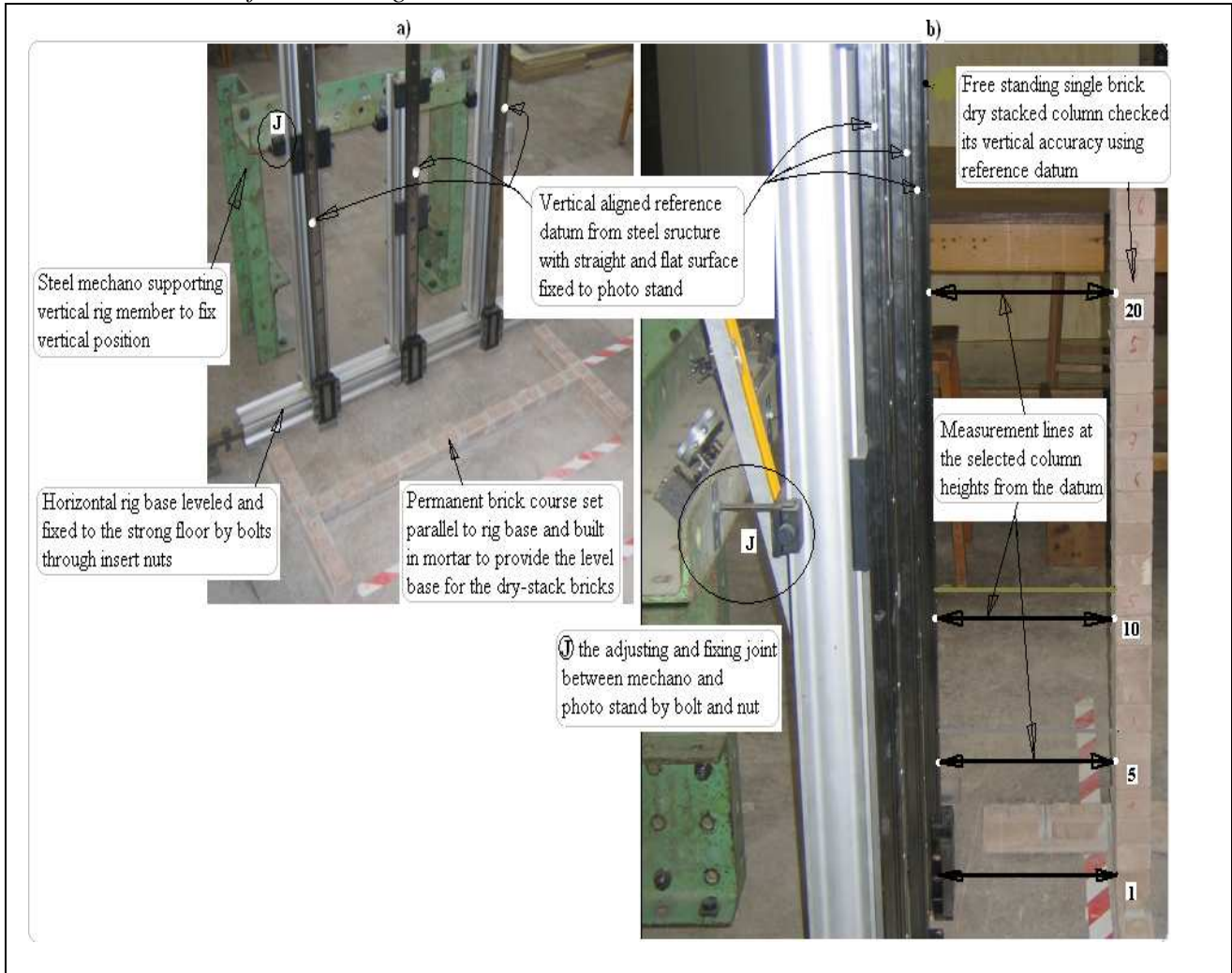
Several structure frame alternatives were considered, and the Optical Bench System from Newport X-48 Series Rails and Carriers was found to be the most appropriate for the purpose. The horizontal base member of the rig was set level and rigidly fixed on the standard laboratory strong floor designed to carry heavy loads; the three vertical members were fixed one at the centre and the two at 420mm (*three lengths of experimental brick*) from the centre. The two end vertical rig members were are also set 280mm (*two lengths of experimental bricks*) from the ends of experimental wall with assumptions that when the wall is fixed at both ends any deflections start at the second brick not the first. For measurement of column out-of-plumb deviations only the central reference member was used.

The plumbness of the rig vertical members were accurately checked by theodolite and safely and strongly fixed to the steel mechano (Figure 6.17). The permanent (built-in and mortared) first course of the experimental wall was set 390mm from the horizontal base member of the rig.



**Figure 6.17 Column/wall vertical alignment test rig**

- a) Rig with permanent brick first course in mortar parallel to the rig base
- b) Selected column heights and horizontal distances to be measured to check plumbness in reference to rig-datum

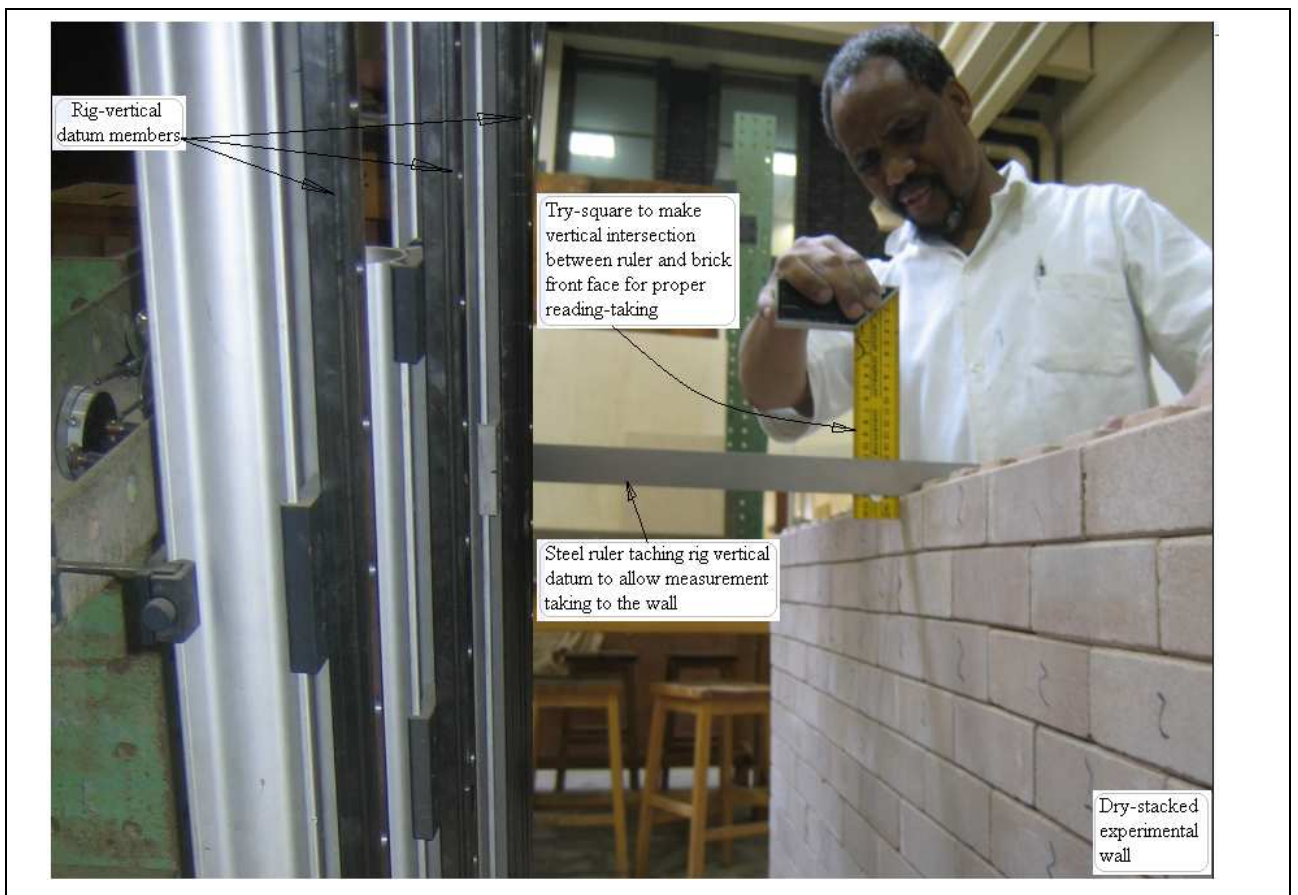


### 6.6.2.3 Instrumentation

There are number of instruments for measuring out-of plumb displacements. For dry-stacked structures as the height increases the more the wall becomes unstable; therefore we need an instrument that would not exert any significant lateral force ( $>0.5N$ ) on the

column/wall. From the many existing instruments, the most suitable options (considered in terms of accuracy, speed, cost and convenience) were deemed to be: linear position sensors (low force), dial gauges (low force) and manual measurement by ruler. However the linear positional sensors were not used, because it was found there was no secure means of fixing them. Moreover even with low spring stiffness, the dial gauges available affected a column's position by pushing it, and therefore manual measurement-taking (Figure 6.18), though laborious, was found the only proper method for the experiment that allowed data recoding without disturbing the column/wall.

**Figure 6.18 Wall out-of-plumb deviation measurement-taking in reference to rig-vertical-datum**



As shown in Figure 6.17 b, the measurements were taken at three wall levels, the fifth, tenth and twentieth courses respectively. For each column, six measurements were made i.e. three out-of-plumb displacements and three heights (at 5<sup>th</sup>, 10<sup>th</sup> and 20<sup>th</sup> courses respectively). For each wall, twenty-one measurements were made, namely at each level seven readings were taken from the three courses (Figure 6.28): length of the course, three heights and three measurements of horizontal distance from rig vertical members to the wall.

#### 6.6.2.4 Test procedure

##### Column and wall construction

The experimental wall used for the analysis was a half-scale model of a wall 2m high (20 courses) and 3m long (10 bricks). These measurements were derived from the size of the reference (Tanzanian) interlocking brick (300 x 150 x 100mm). The base or first course was properly prepared i.e. straight, level and vertical to plumb (Figure 6.17).

Three methods of fixing (*free ends, one end restrained and both ends fixed*) the wall panels were used to test the plumbness control of mortarless technology (MT). Three bricklaying strategies (*randomly stacking, reversing, reversing and selecting*) were used during brick assembly to construct nine walls and three columns types. And each wall or column type was assembled five times using bricks newly selected from the brick-pile, to observe the change or variation in alignment accuracy.

**Table 6.10 columns assembling sequence**

Designation	Method of assembling	Size of set built
C1	Random picking and stacking	5
C2	Reverse allowed	5
C3	Reversing and replacement allowed	5

### **Assembling sequence**

In reference to rig Figure 6.17a, the experimental columns were assembled in the sequence as summarised in Table 6.10. After each assembly the out-of-plumb and height deviations of columns were measured as shown in Figure 6.17, and then measurements were processed to obtain the standard deviations of the column out-of-plumb displacement (**x**-deviations) and height-error (**y**-deviations) as shown in Figure 6.14. The same procedure was applied to each (of three) selected vertical sections along walls in Section 6.8.

## **6.6.3 PHYSICAL ALIGNMENT ACCURACY TEST RESULTS AND DISCUSSIONS**

### **6.6.3.1 Bricklaying analysis approach**

Columns were constructed using the three brick-laying strategies, as described in Section 6.6.1 i.e. bricks randomly picked and assembled to a column (C1), bricks reversal allowed when forming column (C2) and the assembly of column (C3) with the provision of selecting and replacing for better orientation.

The first expectation of the experiments was that moving from strategy C1 to C2 to C3 would give successive improvements in column alignment – as measured by the SD of the displacement from plumb of various courses in a 20-course column. The other expectation, is that reducing the variability of the brick themselves (as measured by the SD of the roll wedge-angle within the brick set) would improve the column's alignment. While we could not control the brick variability in the physical experiments, we did so in the computer simulations reported in Section 6.7. The theoretical equation 6.6 (given in

Section 6.5.1.3) was developed only for randomly placed bricks i.e. strategy C1. Therefore, when applied using as data the roll-angle characteristics of the experimental bricks, it should agree with the experimental results for randomly laid bricks columns C1. For strategies C2 and C3, the column assembly is no longer random, so the assumptions underlying the theory are no longer valid. In fact the displacements for a given height are not only less than for strategy C1, but also obey a lower power-law than that ( $SD \propto N^{1.5}$ ) shown by the strategy C1 columns.

### **6.6.3.2 Experimental data for columns**

The three data sets shown in Tables 6.11, 6.12, and 6.13 correspond to the three bricklaying strategies used in the research (namely: random, reverse and replace). A set of 20 bricks randomly selected from a pile of 44 bricks.

The ‘reverse’ and ‘replace’ strategies were performed to check if (and by how much) they make any improvement compared to the random picking and placing strategy (Table 6.11). Five columns were assembled for each of reverse and replace strategies: results presented in Tables 6.12 and 6.13. Note that five is a very small set of data and the consequent statistical data is very approximate.

**Table 6.11 Physical columns assembled using random laying strategy (C1)**

Column number	Column height (Number (N) of courses each 48.3mm high)		
	5	10	20
	Out-of-plumb deviation (x-mm)		
1	0.0	3.0	0.0
2	-1.0	-3.0	2.0
3	0.0	1.0	14.0
4	5.0	-6.0	-29.0
5	-3.0	-11.0	-33.0
Average of 5 columns out-of-plumb ( $\bar{x}_N$ - deviation.)	0.2	-3.2	-9.2
SD of 5 Columns (mm) – ‘ $\sigma_x$ ’	2.9	5.6	20.7
SD ratios with respect to course 5 (e.g. $\sigma_{x,5}/\sigma_{x,5}$ , $\sigma_{x,10}/\sigma_{x,5}$ and $\sigma_{x,20}/\sigma_{x,5}$ )	1.0	1.9	7.0
and to course 10 (e.g. $\sigma_{x,10}/\sigma_{x,10}$ , $\sigma_{x,20}/\sigma_{x,10}$ )		1.0	3.7

**Table 6.12 Physical columns assembled using ‘allowed to reverse’ strategy (C2)**

Column number	Column height (Number (N) of courses each 48.3mm high)		
	5	10	20
	Out-of-plumb deviation (x-mm)		
1	-5.0	-9.0	-17.0
2	0.0	2.0	15.0
3	0.0	-2.0	-1.0
4	-2.0	-4.0	-15.0
5	-2.0	-1.0	-4.0
Average of 5 columns out-of-plumb ( $\bar{x}_N$ - deviation.)	-1.8	-2.8	-4.4
SD of 5 Columns (mm) – ‘ $\sigma_x$ ’	2.0	4.1	12.8
SD ratios with respect to course 5 (e.g. $\sigma_{x,5}/\sigma_{x,5}$ , $\sigma_{x,10}/\sigma_{x,5}$ and $\sigma_{x,20}/\sigma_{x,5}$ )	1.0	2.0	6.3
and to course 10 (e.g. $\sigma_{x,10}/\sigma_{x,10}$ , $\sigma_{x,20}/\sigma_{x,10}$ )		1.0	3.1

**Table 6.13 Physical columns assembled using ‘select and replace’ strategy (C3)**

*(Up to 2 attempts permitted)*

Column number	Column height (Number (N) of courses each 48.3mm high)		
	5	10	20
	Out-of-plumb deviation (x-mm)		
1	-3.0	-7.0	-14.0
2	0.0	-1.0	-3.0
3	-2.0	-2.0	-3.0
4	-3.0	-5.0	-11.0
5	-1.0	0.0	4.0
Average of 5 columns out-of-plumb ( $\bar{x}_N$ - deviation.)	<b>-1.8</b>	<b>-3.0</b>	<b>-5.4</b>
SD of 5 Columns (mm) – ‘ $\sigma_x$ ’	<b>1.3</b>	<b>2.9</b>	<b>7.2</b>
SD ratios with respect to course 5 (e.g. $\sigma_{x,5}/\sigma_{x,5}$ , $\sigma_{x,10}/\sigma_{x,5}$ and $\sigma_{x,20}/\sigma_{x,5}$ )	1.0	2.2	5.5
and to course 10 (e.g. $\sigma_{x,10}/\sigma_{x,10}$ , $\sigma_{x,20}/\sigma_{x,10}$ )		1.0	2.5

### 6.6.3.3 Comparison of the three assembly strategies

Table 6.14 exhibits the benefit of reversing (strategy 2) the bricks for better orientation during construction, and the further benefit of allowing a poorly aligned brick to be replaced (strategy 3) by a second choice from the available bricks in a pile. The data in Table 6.14 have been up-scaled by suitable value of factor  $K$  (see Table 6.20) to correct for the small brick-pile size.

**Table 6.14 The comparison of assembly strategies**

SD of out-of-plumb deviation (x-mm) for experimental columns				
Course No.	Strategy			Scaling factor
	C 1	C2	C 3	
5	3.2	2.2	1.4	1.1
10	6.7	4.9	3.5	1.2
20	29.0	17.9	10.1	1.4
<b>Data based on</b>	<b>5columns</b>	<b>5columns</b>	<b>5columns</b>	

Taking C1 as the worse case yielding a datum for out-of-plumb deviation, then the

reversing strategy C2 reduces the SD variations at the 20<sup>th</sup> course to 62% of that datum, while the “replace” strategy C3 reduces the deviation to 35% of that datum.

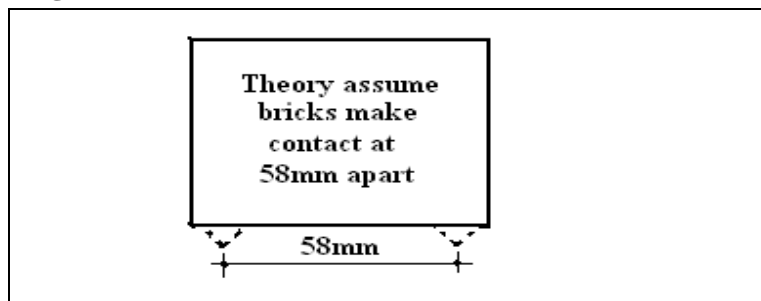
Therefore the Strategies behave as expected in the practical column construction. So we can conclude that mason skill (ability to correctly reverse and replace) is of paramount importance in MT as it reduces the out-of-plumb deviation up to 65% thus improving the overall alignment performance.

#### 6.6.3.4 The comparison between theoretical column alignment prediction and physical measured data

The theoretical equation (6.6) was formulated using the assumption that when bricks are stacked they only make contact along the two measured rows of bumps 58mm apart close to the front and rear edges

(Figures 6.10 and 6.11); the possibility of touching nearer the centre line was excluded as shown diagrammatically in Figure

**Figure 6.19 Theoretical brick surface contact distance**



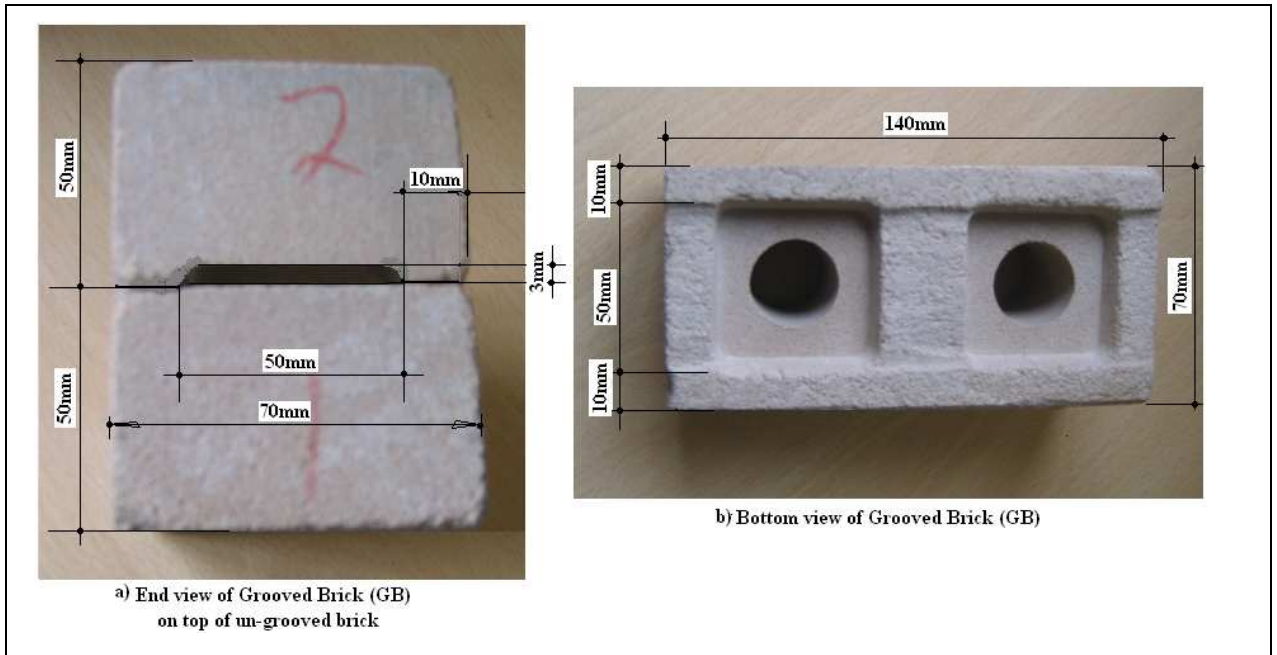
6.19. However in practice there is no guarantee where bricks will contact. In order to make the bricks behave the same as theory, we provided a groove on the bottom surface of the brick (figure 6.20) of about 3mm deep and 50mm wide to prevent brick-to-brick contact occurring close to the centreline.

From studies by *Thanoon at el. 2004, and Ramamurthy and Nambiar 2004*, the author observed that more than 65% of the available interlocking blocks have been designed to



prevent contact occurring within the central 70% of block width. There is no reason given for the design feature, so a test was designed to analyse the phenomenon and contribute to the understanding of the knowledge.

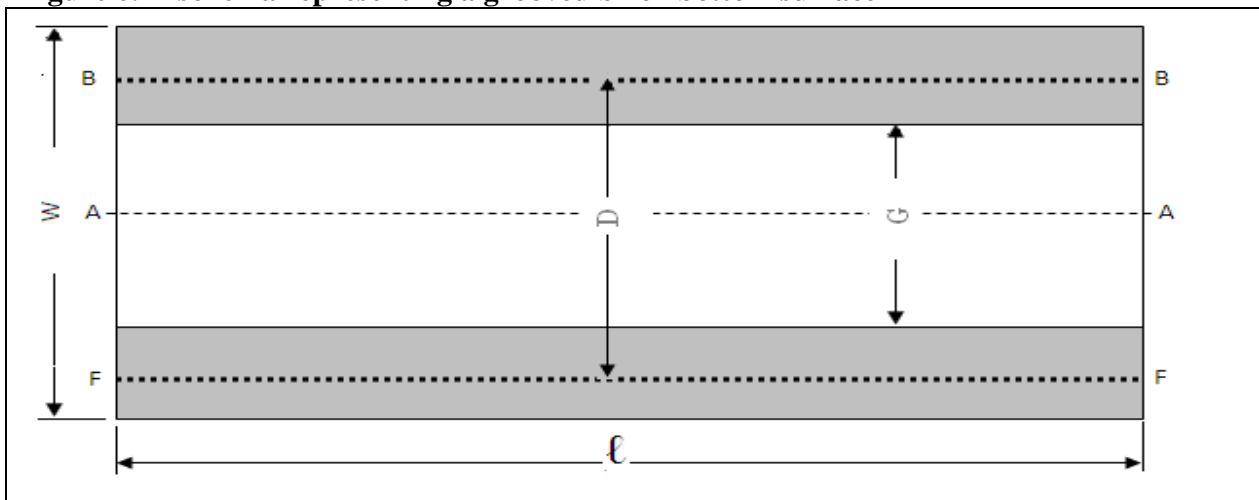
**Figure 6.20 Experimental grooved bricks (GB) (*the half scale bricks*)**



### **Brick-to-brick interface**

In general a stable contact between a brick in the  $i^{\text{th}}$  course of a column and the one above it in the  $(i+1)^{\text{th}}$  course will be at three points. Because the brick is very stiff and the vertical force between bricks is low, these three points are likely to spread only slightly into wider zones of contact. The points will lie in the shaded area (Figure 6.21) because the un-shaded area represents the interlock dents/grooves where there is generally enough clearance to prevent brick-to-brick contact (Figure 6.20b).

**Figure 6.21** schema representing a grooved brick bottom surface



Normally the contact points will straddle this ‘no-contact’ zone. The three contact points define a plane. This shaded plane can be considered to have a small ‘roll’ component, a smaller ‘pitch’ component, and a negligible ‘yaw’ component. It is the roll component that concerns us. The (roll) angle between this plane and the front face (Figure 6.13) of the lower brick we call  $90+\beta_i$  where  $\beta_i$  is a geometric property of that lower brick. If the lower brick were perfect,  $\beta_i$  would equal zero.

The plane through the three contact points similarly makes an angle  $(90+\alpha_{i+1})$  with the front face of the upper brick.

If, relative to vertical, the front faces of bricks  $i$  and  $i+1$  subtend small angles  $\theta_i$  and  $\theta_{i+1}$  respectively (ideally  $\theta$  would equal zero), then geometry shows that

$$\theta_{i+1} = \theta_i + \beta_i - \alpha_{i+1}$$

and thus we have a formula for recording the change in forward lean as we rise course by course through a column (Figure 6.16). We can also defined a ‘roll wedge angle’ for each brick

$$\gamma = \beta - \alpha,$$

which would equal zero for an ideal brick. There remains the task of calculating  $\alpha_{i+1}$  and  $\beta_i$  from the 16 spot-measurements made on the two bricks.

Although it would take an infinity of measurements to fully define each brick surface, only 8 measurements, each expressed as a deviation from an ideal surface perpendicular to the brick's front face, were made for each top and bottom surface – 4 distributed along each of the bold dashed axes B – B (back edge) and F – F (front edge) Figure 6.21.

In the development of a theoretical model (Figures 6.10 and 6.11), the way used to define the top surface roll angle  $\beta$  of a brick was to average the four measured surface deviations ('bump heights' Table 6.8) along the back edge B – B, subtract the average of the four measured deviations along the front edge F – F and divide by the spacing D. A similar process was used to derive the bottom surface roll angle  $\alpha$ . We call this approximation 'averaged contacts model'. Observe that  $\alpha_{i+1}$  is derived just from the (bottom face) measurements of brick  $i+1$  and  $\beta_i$  just from the (top face) measurements of brick  $i$ . There is no 'joint' modelling involving the measurements of both upper and lower brick.

For theory purposes we just model bricks with plane tops and bottoms (though there is the issue of how we measure the alpha, beta and hence SD of gamma for the real bricks to plug into the theory so it can be compared with experiment Tables 6.7 and 6.8).

For experiment we don't need to discuss MODELLING brick-to-brick contact. So it is only for simulation that we need to explain how we get from 16 surface deviation measurements to the quantity  $[\theta_{i+1} - \theta_i]$ .

#### **6.6.3.4 The alignment accuracy: comparison between columns built using grooved and un-grooved bricks**

From the normal-bricks (NB) 30 column assemblies were made Table 6.15, which were compared with the 30 column assemblies made from grooved-bricks (GB) Table 6.16. For fair comparison between the grooved-brick columns (GBC) and un-grooved (normal) brick columns (NBC), equal set of bricks were prepared and the same number of runs assembled using strategy one (random stacking) i.e. 30 columns were assembled for each type using 20 bricks shuffled before each new assembly.

The grooved-brick columns (GBC) Table 6.16 exhibit improved alignment accuracy compared to normal-brick columns (NBC) Table 6.15 e.g. SD of out-of plumb deviation of NBC at 20<sup>th</sup> course ( $\sigma_{NB,20} = 19.5\text{mm}$ ) whereas SD of GBC ( $\sigma_{GB,20} = 9.2\text{mm}$ ). This is a 53% reduction of columns' out-of-plumb deviation achieved from using GBs. However as commented in Section 6.6.3.2, the statistics are drawn from a very small sample and therefore have considerable uncertainty, thus the same 20 bricks 'shuffled'. This difference in pile size and set of bricks selected from it, for column assembly was investigated separately and discussed later in Section 6.7.

**Table 6.15 Normal-brick columns (NBC) randomly assembled**

Column number	Column height (Number (N) of courses each 48.3mm high)		
	5	10	20
	Out-of-plumb deviation (x-mm)		
1	-5.5	-18.0	18.0
2	0.0	0.0	5.0
3	-6.0	-13.0	-15.0
4	-3.5	-7.0	-14.0
5	-1.0	-3.0	-7.0
6	-3.0	-5.0	-16.0
7	-2.0	-13.0	-27.0
8	2.0	21.0	27.0
9	-2.0	-3.0	-15.0
10	-1.0	-3.0	-26.0
11	-8.0	-19.0	-12.0
12	4.0	11.0	28.0
13	-1.0	-8.0	-21.0
14	-5.0	-5.0	-4.0
15	-3.0	-9.0	-33.0
16	0.0	4.0	15.0
17	-2.5	-5.0	-19.0
18	0.5	-1.0	-4.0
19	-1.5	-4.5	-5.0
20	0.5	5.0	9.0
21	-1.0	-1.5	4.0
22	-1.0	3.0	9.0
23	-4.0	-7.0	-19.0
24	0.0	5.0	16.0
25	1.0	3.0	6.5
26	1.0	3.5	16.0
27	0.0	4.0	1.0
28	7.0	16.5	47.0
29	2.0	-3.0	-23.0
30	7.0	12.5	27.0
<b>Average out-of-plumb (<math>x_N</math> - deviation) in mm of 30 columns</b>	-0.9	-1.3	-1.1
<b>SD of out-of-plumb – '<math>\sigma_x</math>' in mm of 30 Columns</b>	<b>3.3</b>	<b>9.2</b>	<b>19.5</b>
<b>SD ratios with respect to course 5</b> (e.g. $\sigma_{x,5}/\sigma_{x,5}$ , $\sigma_{x,10}/\sigma_{x,5}$ and $\sigma_{x,20}/\sigma_{x,5}$ )	1.0	<b>2.7</b>	5.8
<b>and to course 10 (e.g. <math>\sigma_{x,10}/\sigma_{x,10}</math>, <math>\sigma_{x,20}/\sigma_{x,10}</math>)</b>		1.0	<b>2.1</b>

**Table 6.16 Practical column assemblies using grooved-bricks randomly stacked**  
(Strategy C1 – 20 bricks reshuffled each assembly)

Column number	Column height (Number (N) of courses each 48.3mm high)		
	5	10	20
	Out-of-plumb deviation (x-mm)		
1	-1.0	4.5	5.0
2	-2.0	-5.0	-0.5
3	1.5	4.0	15.0
4	-1.0	3.0	-6.0
5	-1.0	-4.0	-13.0
6	1.5	5.0	14.0
7	1.0	-1.0	2.0
8	4.0	-5.0	3.0
9	2.0	1.0	0.0
10	0.0	-3.0	-6.0
11	5.0	-1.0	-3.5
12	-2.0	-1.0	12.0
13	0.0	4.5	23.0
14	-1.0	4.0	21.0
15	-1.5	0.0	14.0
16	-1.5	-0.5	-11.0
17	2.0	19.5	10.0
18	2.0	2.0	10.0
19	0.0	2.0	-3.5
20	0.0	-1.5	9.0
21	-0.5	-3.5	13.0
22	-1.0	-0.5	5.0
23	-2.0	1.0	-2.0
24	0.0	0.0	5.0
25	-5.0	-5.0	-4.0
26	0.5	-3.0	-4.0
27	-1.5	-4.5	-3.0
28	0.0	0.0	1.0
29	-1.0	-3.0	-7.0
30	0.5	-2.0	-3.0
<b>Average out-of-plumb (<math>x_N</math> - deviation) in mm of 30 columns</b>	-0.1	0.2	3.2
<b>SD of out-of-plumb – ‘<math>\sigma_x</math>’ in mm of 30 Columns</b>	<b>1.9</b>	<b>4.8</b>	<b>9.2</b>
<b>SD ratios with respect to course 5 (e.g. <math>\sigma_{x,5}/\sigma_{x,5}</math>, <math>\sigma_{x,10}/\sigma_{x,5}</math> &amp; <math>\sigma_{x,20}/\sigma_{x,5}</math>)</b>	0.6	<b>1.4</b>	2.7
<b>and to course 10 (e.g. <math>\sigma_{x,10}/\sigma_{x,10}</math> &amp; <math>\sigma_{x,20}/\sigma_{x,10}</math>)</b>		0.5	<b>1.0</b>

The theoretical formulae 6.6 ( $\sigma_x = 0.577T\sigma_\gamma N^{1.5}$ ) uses measured bricks statistical values from Tables 6.7 and 6.8 ( $T = 48.3$ ,  $\sigma_\gamma = 0.0038$ ) to calculate SD of out-of-plumb deviations ( $\sigma_x$ ) of columns at N<sup>th</sup> course i.e. 5, 10 and 20, values shown in Table 6.17.

**Table 6.17 the comparison of out-of-plumb deviation between normal-brick and grooved-brick columns & theoretical predictions**

Course number (N)	SD of columns out-of-plumb deviations		
	NBC	GBC	TE
5	3.3	1.9	1.2
10	9.2	4.8	3.4
20	19.5	9.2	9.5

Table 6.16 shows for course 20 a ratio of 0.97 between theory and experimental GBC for  $\sigma_x$ , the standard deviation of out-of-plumb. However with a sample of 30 columns, any estimates of SD will (for 90% certainty and using Chi-square ( $\chi^2$ ) table) lie between  $\pm 9\%$  of the true (population) value. Therefore as a difference between theory and physical experiment for course  $N = 20$  lies within that 9% range, we can conclude that there is acceptable.

However, as already argued, the former has statistical uncertainty due to limited sample size. The theory is based on a value for roll-wedge angle SD ( $\sigma_\gamma$ ), which is hard to measure accurately from experimental bricks. The modelling of contact distance between the rear and front bumps relates with grooved bricks but not ungrooved-indented bricks, so this modelling will be discussed and analysed in Section 6.7.

So we can say theory is broadly confirmed by physical experiment using grooved bricks and indeed variation in out-of-plumb deviation is driven by variations in roll-wedge angle. Out-of-plumb deviation rises with height to the power of 1.5.

## **6.7 SIMULATION OF COLUMN ASSEMBLY**

A Column Assembly Simulation Model (CASM) is a computer model used for simplifying the process of brick assembling and arrangement of columns and walls. Thus, permitting many random runs made in order to achieve acceptable statistical data representation. This work done by computer took hours otherwise it would have taken months to complete the physical practical laboratory works.

The use of CASM made it possible to assemble simulated columns/walls of more than 40 courses high compared to actual physical columns/walls. However, due to practical conditions and time constraints, it was found not easy to build up to 40 courses of thin columns/walls using half scale experimental bricks. Similarly, a 40 course walls would have required many hundreds of bricks (manufactured and measured) hence, more time than was available.

In the practical experiments 20 course columns/walls were assembled for each brick laying strategy. A total of 75 columns and 45 walls were built. These are very small sample representative from which to deduce acceptable statistical properties yet they are sufficient number to be used for control purposes. By using simulation up to 240 assemblies were made for each strategy.

### **6.7.1 DEFINITIONS AND CLARIFICATIONS**

**Measured bricks and Measured brick Pile** is a physical measurement (see section 6.2.3 in Tables 6.2 and 6.3) for one brick while Tables 6.7a and 6.7b shows measurements of a



pile of 44 brick sample. From a pile/batch of bricks is where one can select few bricks (a set) for a certain purpose i.e. column or wall assembly.

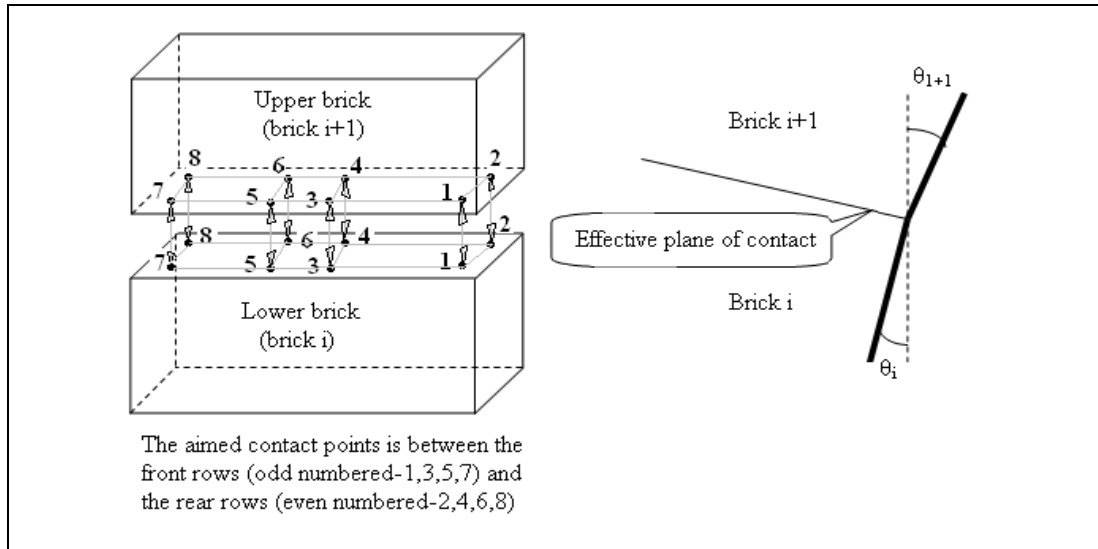
**Simulated brick and Simulated brick pile** are measurements representing brick characteristics generated using random numbers combined with the statistics taken from Measured bricks (Tables 6.7a, 6.7b and 6.8).

**Simulated brick stack assuming face to face contact** this is where the top and bottom of the surfaces of two bricks touch one another and their surfaces of contact are assumed plane. At the surface contact planes the roll-wedge angle is determined. The two methods used for determining these planes are:

**Average of bumps method** is the average heights of a row of 4 marked points at the rear and front predetermined points in the contact plains of the two bricks (figure 6.22). The differences of the two is divided by 58mm which is the distance between the opposite points (rear and front e.g. 1 and 2 in Figure 6.22)

**Point to point contact (“kissing”) method** is the re-alignment angle  $\omega = \beta_i - \alpha_{i+1}$  as described in section 6.7.2, and computed by combining data from the top surface of the lower brick with data of the bottom surface of the upper brick (Figure 6.22) in a way that mimics the four steps used by a mason when placing one brick on top of the other (see details in section 6.3.2). The angle ( $\omega$ ) gives the brick re-alignment and hence the orientation of the angle  $\theta_{i+1} = (\theta_i + \omega)$  of the brick above the contact brick surface

**Figure 6.22 Highest kissing (butting) bumps of the rear and front of meeting surfaces**



**Brick set:** are defined numbers of bricks picked from a pile to make a column or a wall

**Column or Wall statistics** were obtained by observing the building (real or computerized) of many columns or walls, each with a new set of bricks.

Whereby:

$N$  is the size of the brick set needed to build a column of  $N$  courses

$M$  is a pile of bricks where  $N$  is selected

$K$  is a function of a ratio  $\lambda = M/N$

If the pile from which bricks are selected ('with replacement') is of size  $M$ , then  $M$  should be much bigger than  $N$ . If this condition is not met then the variability of the columns (and hence the SD derived from the set of columns) will be biased, i.e. too small.

However we can correct these biased statistics using a multiplier  $K$ , where  $K$  is a function of the ratio  $\lambda = M/N$ , ( $K = 1$  when  $M \gg N$ )

## 6.7.2 COMPUTER MODEL

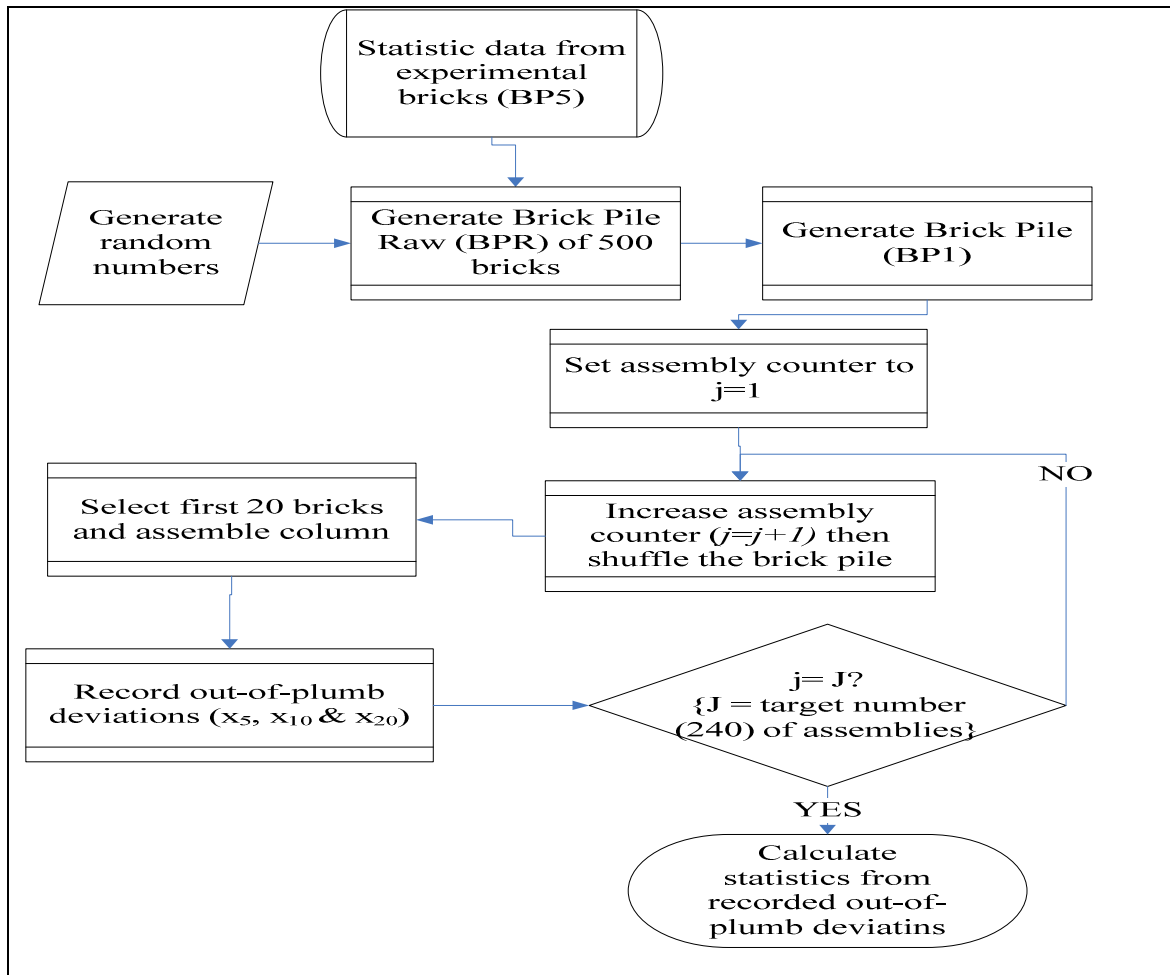
The Column Assembly Simulation model (CASM, see Figure 6.23) uses Excel to simulate column/wall assemblies for the alignment accuracy analysis, whose purpose is to relate the column/wall characteristics to the brick irregularities. Two sources of data are used in the simulations:

- From the experimental bricks measurement, brick data is set into the CASM as Brick Pile - BP5. From this pile, the statistics (mean and variance) for the bumps across the brick surfaces were computed.
- From Excel the random numbers were generated and multiplied by the experimental brick statistics from BP5 to formulate an imaginary Brick Pile Raw (BPR). From this BPR three piles were formulated as follows:

BP1	bricks randomly piled (simply by copying BPR)
BP2	all bricks reversed (opposite of BPR)
BP3	some bricks reversed - to give alternating +ve and -ve wedge-angles

The three brick piles saved into different working sheets and viewed through a common button selector (positioned in the column working sheet). The selection of piles, one at a time (BP1 and BP3) and their respective bricks specifications are displayed on the Brick Stack (BST) working sheet.

**Figure 6.23 Flowchart of a Column Assembly Simulation Model (CASM) for random brick laying strategy**



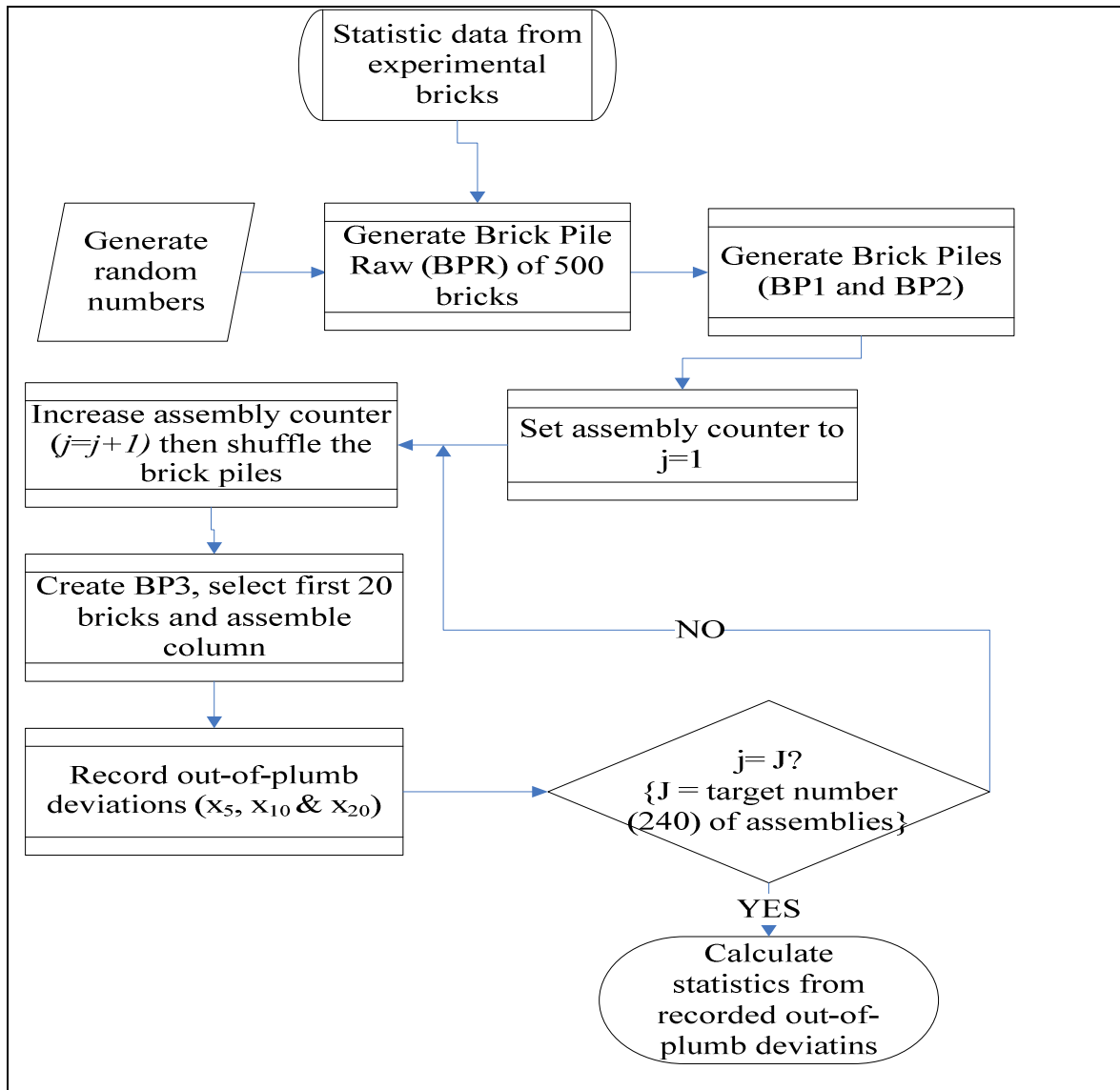
In the BST (common displaying screen) two methods are used to process brick-to-brick contact data (as described in the definitions) i.e. averaging the bumps and the maximum kissing points. For the convenience of recording and processing brick specifications into a computer working sheet (see Table 6.7 and 6.8), the pile of bricks are stacked into columns and subsequent statistics of each brick along the row. The merging angles ( $\omega$ ) and out-of plumb angles ( $\theta$ ) for each brick course are computed in this working sheet (BST).

BPR working sheet is the main working area of CASM, in order to make rearrangement of bricks before every new run (new column/wall assembly), the brick order is shuffled. This effectively creates a new random brick-set. When we shuffle BPR means as well change the order of bricks in BP1 and BP2 but not BP3. A new BP3 set has to be created using the shuffled BP1 and BP2 piles, the sequence is shown in Figure 6.24.

The necessary data for out-of-plumb deviation and height errors are displayed on the column/wall working sheet and data for courses 5, 10 and 20 are recorded for each run (assembly) see Figure 6.23.

To simplify and accelerate the shuffling, recording, editing and copying of data to the appropriate location, a 'macro' programme was used to automate the whole process.

**Figure 6.24 Flowchart of a Column Assembly Simulation using alternate wedge-angle**



The shuffling is done in the BPR, and then bricks are piled in two opposite orientations (BP1 and BP2). One of the brick from either of the stack is chosen to create BP3. This third order stacked column observe alternate wedge-angle signs aiming to reduce out-of-plumb deviation of a column

The conditions used to process BP1 and BP2 and create BP3 depend on the values of wedge-angles ( $\gamma_1$  of BP1 and  $\gamma_2$  of BP2):

- If the columns' course number ( $n$ ) is even and  $\gamma_2 > 0$  then use pile BP2
- If  $n$  is even and  $\gamma_1 < 0$  then use pile BP1
- If  $n$  is odd and  $\gamma_1 > 0$  then use pile BP1
- If  $n$  is odd and  $\gamma_2 < 0$  then use pile BP2

### **6.7.3 COMPUTATION OF COLUMN/WALL OUT-OF-PLUMB DEVIATION**

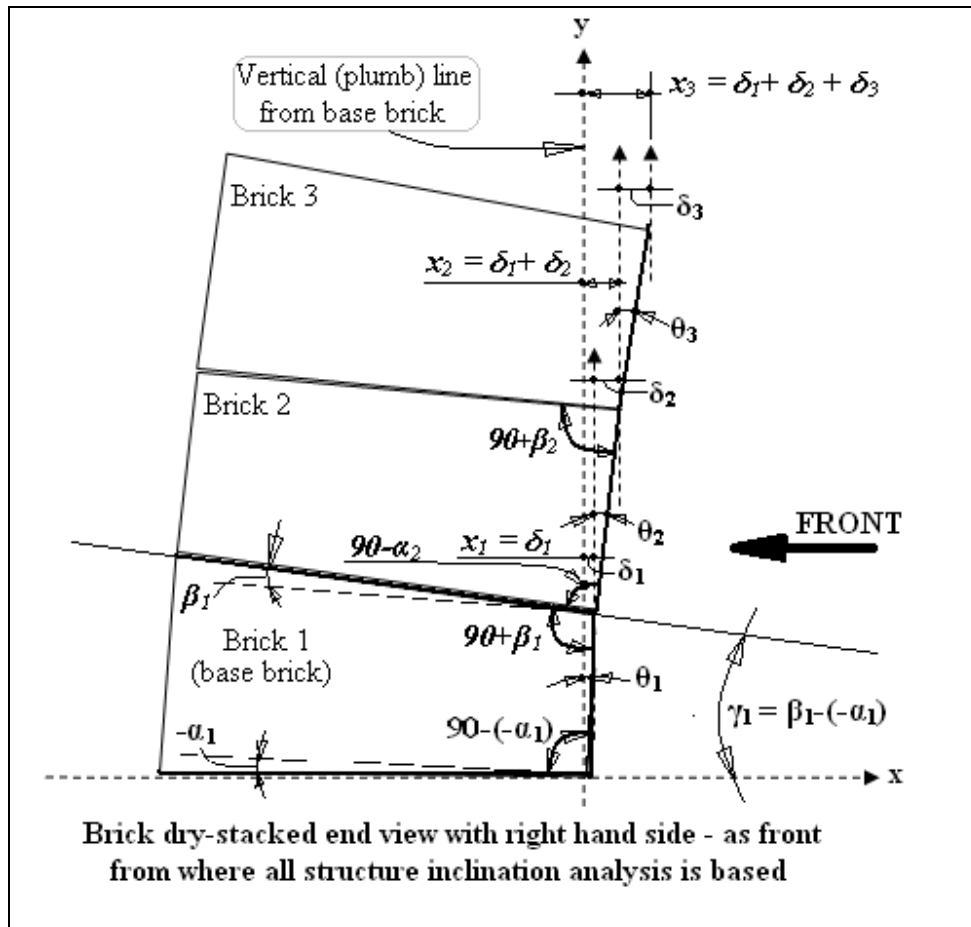
The theory and the simulation assume that the orientation of any brick depends in part on that of the brick below it. But the lowest (base) brick's orientation depends only on its bottom surface inclination named alpha ( $\alpha$ ) as in Figures 6.12 and 6.13. Considering the first three bricks from Figure 6.16 and the details of surface contacts are illustrated in Figure 6.25.

However, the deviation of the column at any height can be re-expressed in terms of the roll-wedge angles for each brick  $\gamma_i = \beta_i - \alpha_i$ . So the value of  $\gamma_i$  was computed for each brick in a brick stack (BST - this is a sets of brick selected after shuffling and assembled into a column).

The simulation of brick assembly sequence is represented by the formula inserted in the computer to perform assembly operations and automatically give out the result in form of

out-of-plumb deviation. The placement of brick one (Figure 6.25) in position with its bottom surface horizontal will make its front face to form an angle theta ( $\theta_1$ ) with the plumb line (y axis).

**Figure 6.25 Imperfect bricks placed in position showing successive vertical deviation**



Therefore;  $\theta_1 = \alpha_1$ , as the bottom brick is assumed to be placed on a horizontal mortar bed,

$$\theta_2 = \theta_1 + (\beta_1 - \alpha_2), \text{ and}$$

$$\theta_3 = \theta_2 + (\beta_2 - \alpha_3) \text{ and in general;}$$

$$\theta_i = \theta_{i-1} + (\beta_{i-1} - \alpha_i) = \theta_{i-1} + \omega_i \quad (6.7)$$



The computation of the angle  $\omega_i = \theta_i - \theta_{i-1}$  assumes the top surface of brick one (figure 6.25) is a plane of contact making an internal angle  $(90 + \beta)$  with its front face, the bottom surface of brick two is a plane of contact making an internal angle of  $(90 - \alpha)$  to its front face, and assembly makes these two planes coincide. There are several options for modelling these planes of contact: two options were considered in the simulations described in the definitions.

Note that  $\omega_i$  is a function of the irregularity of the top surface of brick  $i-1$  and the bottom surface of brick  $i$  ( $\omega_i = \beta_{i-1} - \alpha_i$ ) For ideal bricks  $\omega_i = 0$  for all  $i$ . We can now generalize this sequence of face angle computation as;

$$\theta_n = \alpha_1 + \omega_2 + \omega_3 + \dots + \omega_n$$

Where;  $n$  is the top course  
 $\theta_n$  is the angle that the front face of the  $n^{\text{th}}$  brick makes with the plumb line

Given this angle theta for each course, and the course height (T) we can calculate the change  $\delta_i$  as the horizontal out-of-plumb deviation of individual brick  $i$ , and  $x_i$  as the sum the individual out-of-plumb deviations up to brick-course  $i$  see Figure 6.25.

Overall out-of-plumb deviation will be:

$$x_i = \sum_{i=1}^i \delta_i .$$

In Section 6.5.1.1 it was analysed that:

$\delta_i = T_i \cdot \sin(\theta_i)$ , and as for small angles  $\sin(\theta_i) \approx \theta_i$  and assuming all bricks are the same height (T),

$$x_n = T \times \theta_n + x_{n-1}, \quad (6.8)$$

## **6.7.4 THE RELATION BETWEEN THE STATISTICS OF COLUMN OUT-OF-PLUMB DEVIATION AND THE SIZE OF THE BRICK-PILE FROM WHERE THE SET OF BRICKS WAS PICKED**

### **6.7.4.1 Brick selection**

The method used (to select the bricks for a particular column-assembly) in the simulations was done as follows: A large pile of brick-data was randomly shuffled and then the first 20 'bricks' (N) were used to construct a simulated column. The research was particularly interested in the ratio  $\lambda_{20} = \text{brick-pile size}/20$ . Where  $\lambda$  is large, the procedure is a good mapping of the process of choosing bricks from an infinite population. For most simulation runs,  $\lambda_{20}$  had the value 25, since as shown in Figure 6.24 the brick pile employed for simulations had 500 bricks. Indeed when looking at the properties of say the  $n^{\text{th}}$  course in a column, the effective ratio  $\lambda_n$  (now = brick-pile size/n) was even greater than 25 for all courses except the 20<sup>th</sup>. These ratios  $\lambda$  are sufficiently high to give confidence to the simulation results to represent selecting bricks from a very large population.

However, the brick pile for simulation could be made larger, that set used for practical experiments could not. Indeed for column experiments using only the 44 measured ungrooved bricks and the 20 grooved bricks (Brick pile BP5),  $\lambda_{20}$  only lay in the range 1 to 2.2. With  $\lambda_{20} = 1$  we are effectively only shuffling (changing the order of) the same 20 bricks to form each column: in consequence such a column shows less variation in deflection than one built from a very large brick-set. In fact a scaling factor is needed to

raise any value for  $\sigma_{x20}$  (SD of  $x$ -deviation of top of 20<sup>th</sup> course) obtained from such experiments to a value representative of working with an infinite brick-pile.

Before we simulate the assembly of columns using piles with large number of bricks to generate realistic statistical data there are number of decisions were made.

- This researcher considered that a pile size greater than twenty times the set size would approximate an infinite pile size ( $N \ll M$ ). Thus if  $N = 20$  and  $\lambda = 20$ , then we need to use  $M \geq 400$ ).
- In the physical experiment we used two types of bricks; grooved and ungrooved. With *grooved* bricks we know that brick-to-brick contact can only occur closer to the front and rear edges of the meeting surfaces. This is what the simulation models, in assuming contact is only along lines respectively near the front and near the back. However the *ungrooved* bricks may contact anywhere on their top/bottom surfaces (provided that at least one contact point is in the rear-half of the surfaces and at least one in the front-half).

Thus for the simulation of ungrooved bricks we need to identify a suitable ('average') distance ( $D$  see Figure 6.26) between front and rear contact points. This distance will lie between a minimum of 0 and a maximum of  $W$ . Separate calculations were therefore made to obtain a value for  $D$ .

- From the two methods of determining the brick contact planes considered in the simulation modelling, after trials the statistical data from butting method were found to overestimate the outputs i.e. the wedge-angle  $\gamma$ , the surface merging plane angle  $\omega$  and ultimately the stack inclination angle  $\theta$  Figure 6.25,

which resulted into unrealistic high figures of SD of out-of-plumb deviations ( $\sigma_x$ ).

Therefore this research accepted averaging as a proper contact modelling method.

#### **6.7.4.2 The effective contact-spacing between rear and front contact bands**

We wish to represent all possible combinations of front-half bands and rear-half bands and their corresponding spacing ( $s = b - a$ ) Figure 6.26. However in the determination of experimental brick statistics (Table 6.8), we use the reciprocal of the spacing ( $s$ ) in our calculation of the roll wedge-angles, causing the column to tilt. Therefore we need to average not  $s$  but  $1/s$ .

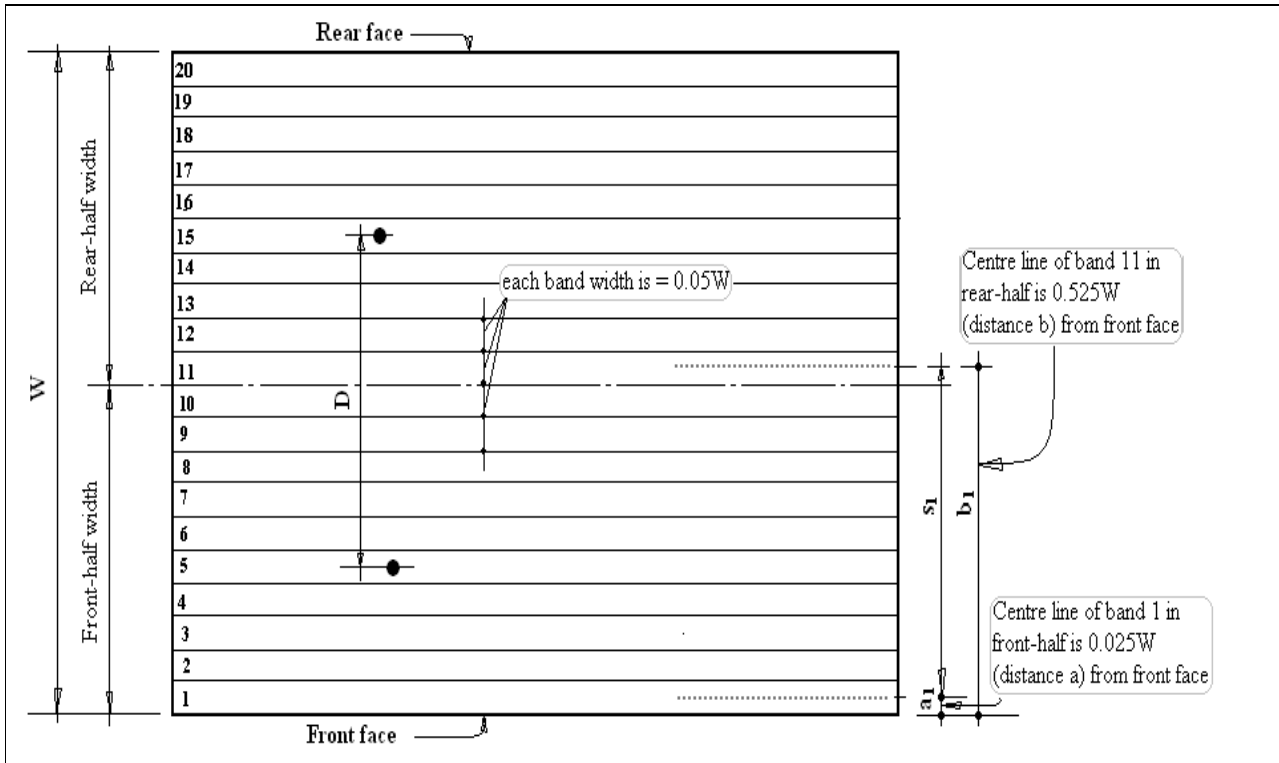
In simulation we use a conversion factor (linear error to angular error) of  $f =$  reciprocal of normalised spacing of contact points. Thus if contacts were only along front and back edges then  $f = W/W = 1$ . Nonetheless contacts are generally closer than this, so if contact spacing is  $s = b - a$  Figure 6.26, then:

$$f = \frac{W}{(b - a)} \quad (6.9)$$

Where:

- $a$  is distance from front face to centre of the relevant front-half band
- $b$  is distance from front face to centre of the relevant rear-half band
- $f$  is a reciprocal of normalised spacing of contact points;
- $W$  is a brick width

**Figure 6.26 Brick surface divided into 20 equal parallel contact bands**



Thus in calculating for example the out-of-square angle between a brick's bottom and front faces:

$$\alpha = \frac{\text{vertical displacement at rear} - \text{vertical displacement at front}}{\text{spacing between front \& rear contact points}}.$$

We could instead use a factor  $f$  i.e.

$$\alpha = f \times (\epsilon_{\text{rear}} - \epsilon_{\text{front}}) / W,$$

where for contact only along back edge and front edge,  $f = 1$ , but normally  $f > 1$ .

To obtain an average value of  $f$  to use in simulation we evaluate:  $f_{Av}$  = average of  $f$  for all possible pairs of contact points, weighted according to their probability of occurring.

For ease of computation we assign possible contact points into a limited number of equal-width bands. Figure 6.26 shows ten such bands for the rear-half and ten for the front-half of the contact surface, 20 bands being a reasonable approximation to the real-world continuum. The centre-lines of these bands (measured from the front face) are at distances  $0.025W$ ,  $0.075W$ , ..., to  $0.975W$  from the front brick face (Table 6.18). Thus (a) is now restricted to the 10 values  $0.025W$  to  $0.475W$  and (b) to the 10 values  $0.525W$  to  $0.975W$ .

With an *ungrooved* brick, we can assume the rear contact points are uniformly distributed over the rear half of brick, the  $b$  values;  $b_1 = 0.525W$ ,  $b_2 = 0.575W$  etc. are equally likely. Similarly the  $a$  values;  $a_1 = 0.025W$ ,  $a_2 = 0.075W$  etc. are equally likely for the front half of brick. For each (of 100) combinations of rear and front bands we calculate  $f$  using Equation 6.9 and then average the 100 values, so obtained, to get  $f_{av}$ .

In the case of *grooved* bricks we remove from the computation the bands corresponding to the groove (as grooving prevents contact in those bands). In this case  $f_{av}$  is the average of values obtained from all combinations of the remaining bands (Table 6.18).

**Table 6.18 Table of  $f^I$  factors,**

$a =$ Normalised distance from front face to front mid-band		$b =$ Normalised distance from front face to rear mid-band										
		Band 11	12	13	14	15	16	17	18	19	20	
		$b = 0.525$	$0.575$	$0.625$	$0.675$	$0.725$	$0.775$	$0.825$	$0.875$	$0.925$	$0.975$	
Band 1	$a = 0.025$	2.00	1.82*	1.67	1.54	1.43	1.33	1.25	1.18	1.11	1.05	
2	$0.075$	2.22	2.00	1.82	1.67	1.54	1.43	1.33	1.25	1.18	1.11	
3	$0.125$	2.50	2.22	2.00	1.82	1.67	1.54	1.43	1.33	1.25	1.18	
4	$0.175$	2.86	2.50	2.22	2.00	1.82	1.67	1.54	1.43	1.33	1.25	
5	$0.225$	3.33	2.86	2.50	2.22	2.00	1.82	1.67	1.54	1.43	1.33	
6	$0.275$	4.00	3.33	2.86	2.50	2.22	2.00	1.82	1.67	1.54	1.43	
7	$0.325$	5.00	4.00	3.33	2.86	2.50	2.22	2.00	1.82	1.67	1.54	
8	$0.375$	6.67	5.00	4.00	3.33	2.86	2.50	2.22	2.00	1.82	1.67	
9	$0.425$	10.00	6.67	5.00	4.00	3.33	2.86	2.50	2.22	2.00	1.82	
10	$0.475$	20.00	10.00	6.67	5.00	4.00	3.33	2.86	2.50	2.22	2.00	
Groove to width ratio, $G/W$		$0.00^2$	<b>0.10</b>	<b>0.20</b>	<b>0.30</b>	<b>0.40</b>	<b>0.50</b>	<b>0.60</b>	<b>0.70</b>	<b>0.80</b>	<b>0.90</b>	$0.7I^3$
Conversion factor = $f_{av}$		<b>2.68</b>	<b>2.10</b>	<b>1.82</b>	<b>1.62</b>	<b>1.47</b>	<b>1.36</b>	<b>1.26</b>	<b>1.18</b>	<b>1.11</b>	<b>1.05</b>	<b>1.17</b>

**Notes** (see note numbers in Table 6.18)

1.  $f$  is the reciprocal of the contact normalised distance between front and rear points of laid bricks, quantised to 5% bands and normalised to brick width.

\* is where  $f = 1.82$  (rear contact point lies in band 12 and front contact point in band 1)

2.  $G/W = 0$  indicates no groove (representing ungrooved brick contact surface)

3. **Highlights** cells represent the grooved bricks actually used in the experiments

The spacing between two strips/bands,  $s$  can be expressed as a function  $s(i,j)$

Where:

- $i$  is the number of the front strips,  $i = 1$  to  $10$
- $j$  is the number of the rear strips,  $j = 11$  to  $20$
- $s$  is a distance between the  $i^{th}$  (front) strip and the  $j^{th}$  (rear) strip

Or for simplicity we define the factor  $f = f(i,j) = W/s(i,j)$

Then,

$f_{Av.} = \text{sum over all functions } i,j \text{ of } \{f(i,j) \times p_i \times p_j\}$

$$f_{Av} = p_i \times p_j \times \sum_i^{n_i} \sum_j^{n_j} f(i, j) \quad (6.10)$$

Where:

- $p_i$  is probability that front contact lies in strip  $i$
- $p_j$  is probability that rear contact lies in strip  $j$

If all allowed contact points are equally likely, then  $p_i = \text{area of strip } i \text{ divide by the area } A \text{ of allowed front half of brick surface, and from different surface conditions i.e. uniform, full grooved and only indented will have various permitted-contact areas.}$

- a)  $A = \frac{1}{2}W\ell$  for a **uniform** surface
- b)  $A = \frac{1}{2}(W-G)\ell$  for a **grooved surface** with groove width  $G$  (Figure 6.20)
- c)  $A = \frac{1}{2}(W\ell - 2t^2)$  for an **indented** surface, assuming two indentations each size  $t \times t$

Moreover as  $\ell = 2W$  and say  $t = \psi W$  ( $\psi$  typically equals 0.7), then for our three cases above become:

- a)  $A = W^2$ ,
- b)  $A = W^2 - WG$
- c)  $A = W^2 (1 - \psi^2)$ .

**Uniform bricks (neither grooved nor indented) of width (W)**

From Table 6.18,  $f_{av} = 2.68$  so effective contact-point spacing is  $D = W / 2.68 = 26 \text{ mm}$

**Indented bricks (Figure 6.20b)**

For the experimental bricks (indent)  $\psi = t/W = 0.7$  and therefore  $A = 0.51W^2$ .

Thus if both halves are split into ten strips, width is split into twenty strips ( $W/20$ ). The probability of contact point occurrences will be;

$$p_i = 0.1 \text{ if } i \leq 3; \quad p_i = 0.03 \text{ if } i > 3$$

$$p_j = 0.1 \text{ if } j \geq 18; \quad p_j = 0.03 \text{ if } j < 18$$

For  $\psi = 0.7$ , where 3 strips are full length and 7 strips are 30% length, we can expect the following cases:

$$(i) \quad i \leq 3, j \geq 18 \quad p_i p_j = 0.1 \frac{wl}{2} / 0.51w^2 \times 0.1 \frac{wl}{2} / 0.51w^2 = 0.0384$$

$$(ii) \quad i > 3, j \geq 18 \quad p_i p_j = 0.03 \frac{wl}{2} / 0.51w^2 \times 0.1 \frac{wl}{2} / 0.51w^2 = 0.0115$$

$$(iii) \quad i \leq 3, j < 18 \quad p_i p_j = 0.1 \frac{wl}{2} / 0.51w^2 \times 0.03 \frac{wl}{2} / 0.51w^2 = 0.0115$$

$$(iv) \quad i > 3, j < 18 \quad p_i p_j = 0.03 \frac{wl}{2} / 0.51w^2 \times 0.03 \frac{wl}{2} / 0.51w^2 = 0.0035$$

So knowing the probability values, we can calculate  $f_{Av}$  using equation 6.10 as the sum of:

$$0.0384 \sum_{i=1}^3 \sum_{j=18}^{20} f(i, j) + 0.0115 \sum_{i=4}^{10} \sum_{j=18}^{20} f(i, j) + 0.0115 \sum_{i=1}^3 \sum_{j=11}^{17} f(i, j) + 0.0035 \sum_{i=4}^{10} \sum_{j=11}^{17} f(i, j)$$

From Table 6.16 we get the sum of the functions i,j:

$$f_{Av} = 0.0384 \times 10.64 + 0.0115 \times 36.22 + 0.0115 \times 36.22 + 0.0035 \times 184.44 = 2.3$$

$$f_{Av} = 2.3 \text{ for } \textit{ungrooved} \text{ bricks (provided with indentations of width of } 70\% W)$$

Thus the effective contact-point spacing is only  $D = W / 2.3$ .



For the ungrooved (indented) bricks used in experiments (width  $W = 70\text{mm}$ ),  $D = 30$  mm.

### **Grooved bricks**

For grooved bricks,  $f_{Av}$  depends on  $G/W$ , the normalised width of the grooving. Thus with 50% grooving,  $f_{av}$  falls to 1.36 and hence  $D = 51$  mm.

However the grooving actually made in the *grooved* experimental bricks was 50 mm wide, namely 70% of width, giving  $G/W = 0.71$ ,  $f_{Av} = 1.17$ . Hence  $D = 60$  mm.

### **Comparisons**

Comparing **grooved** with **uniform ungrooved** bricks, the factor  $f_{Av}$  has fallen by 56% (from 2.68 to 1.17), so we should expect grooving to reduce column deviation by the same large percentage.

Comparing **grooved** with **indented** bricks the factor  $f_{av}$  falls by 49% (from 2.30 to 1.17) which is also substantial enough to justify the grooving even of already indented bricks.

### **6.7.4.3 Influence of brick pile size on SD of columns' out-of-plumb deviations (x-variations)**

Using the appropriate value for a contact distance ( $D = 30\text{mm}$ ) between the bumps for indented (experimental ungrooved/normal) bricks, a large number (240) of simulated column assemblies were made to analyse the out-of-plumb deviations variations for each strategy i.e. random (BP1) and alternate wedge angle (BP3) in form of computer working sheets BP1 and BP3 and each was tested using averaging bumps method.

Table 6.19 is a result of computer simulations for twenty-brick high column assemblies using different pile sizes and corresponding scaling factors  $K$  were obtained. From brick-piles of size 20, and  $20 \times \lambda$ , for  $\lambda = 1, \lambda = 2, \lambda = 4, \lambda = 8, \lambda = 16$  and  $\lambda = 25$ .

**Table 6.19 SD of out-of-plumb deviations ( $\sigma_x$  mm) for 1440 simulated column assemblies**

Strategy	Column height at ( $N^{\text{th}}$ - course)	Brick piles size (M)							Mean $\sigma_x$
		M=10	M=20	M=40	M=80	M=160	M=320	M=500	
Random	5	3.5	4.2	4.3	4.7	4.9	4.9	4.9	4.5
	10	7.4	10.8	12.0	13.3	13.8	13.8	14.2	12.2
	20		21.3	29.5	34.9	37.0	37.6	41.1	33.6
Sensitivity $\{S = \ln(\sigma_{x20}/\sigma_{x5})/\ln(N_{20}/N_5)\}$		1.17	1.39	1.45	1.46	1.47	1.53		

From the simulation results (SD of out-of-plumb deviation values) Table 6.19 determined scaling factors  $K$  corresponding to  $\lambda$  – the brick set  $N$  of respective column height (Table 6.20).

**Table 6.20 Scaling factor  $K$**

$\lambda = M/N$	1	2	4	8	16	$\geq 25$
<b>K for N = 5</b>	-	1.40	1.17	1.14	1.04	1.00*
K for N = 10	1.92	1.31	1.18	1.07	1.03	1.00*
K for N = 20	1.93	1.39	1.18	1.11	1.09	1.00*
<b>K - average</b>	<b>1.92</b>	<b>1.37</b>	<b>1.18</b>	<b>1.11</b>	<b>1.05</b>	<b>1.00</b>

\* Definition as  $\lambda \geq 25$  is taken to indicate a very large brick pile, used as a datum for comparing  $\sigma_x$  values for small piles.

**NOTE:**

- These results are from simulations and although the modelling of brick-to-brick may be imperfect, we could expect the ratios to reflect those in experiment.
- $K$  (for any specified values of  $\lambda=M/N$ ) is the ratio of  $\sigma_{xN}$  for  $\lambda$  of very large pile to  $\sigma_{xN}$  for  $\lambda$  of specified value.

- Reassuringly the K values (for a given  $\lambda$ ) are similar whether derived from N=5 data, N=10 data or N=20 data.
- We will now use these K values to upscale those experimental results obtained using low values of  $\lambda$  to what they might have been with  $\lambda > 25$  (brick pile >25 times the set of brick for one column)

However the value of  $K_{20}$  was obtained from simulation result, which using 240 runs were still subject to statistical uncertainty. According to  $\chi^2$  analysis, with 50% certainty,  $K_{20}$  lies within  $\pm 9\%$  of the values 1.9 shown in the Tables 6.20, thus there is this to uncertainty about the ‘corrected’ values Table 6.22 of  $\sigma_{x,20}$ . In addition the practical data is subject to small-sample uncertainty in the raw (experimental) values of  $\sigma_{x,20}$  also of  $\pm 9\%$ . So there is an overall uncertainty of about  $\pm 13\%$  even after ‘K correction’.

#### **6.7.4.4 Effect of brick-laying strategy on out-of-plumb deviations.**

Table 6.21 is a summary of 480 assemblies of simulated columns, from two strategies using higher batch of 500 bricks, from each strategy a total of 240 assemblies were made. Before we compare the data from simulation with theory and practical, we need to check if they obey the expected improvement from random to reverse to alternate wedge-angle signs.

**Table 6.21 Simulations of 480 column assemblies of indented-bricks i.e. using 30mm spacing between the contact points**

<b>SD of out-of-plumb deviations (<math>\sigma_x</math> in mm)</b>			
<b>Contact surface inclination by</b>	<b>N<sup>th</sup> course</b>	<b>Random strategy (BP1)</b>	<b>Alternate wedge-angle strategy (BP3)</b>
<b>Averaging bumps</b>	<b>5</b>	4.9	3.6
	<b>10</b>	14.2	9.8
	<b>20</b>	<b>41.1</b>	<b>28.7</b>

BP1 represents basic assembly; bricks are chosen and assembled at random.

BP3 Is a partial representation of ‘skilled’ brick-laying - the column is built by alternating bricks with positive and negative roll wedge-angles.

Examining the SD of out-of-plumb deviations and considering only the 20<sup>th</sup> course Table 6.21. The “alternate wedge-angle” columns (BP3) display an improvement of 30% over BP1. Comparing the simulation results from BP3/BP1 in comparison with the physical results from strategies C2 and C3 Table 6.14 we found that the improvement in column accuracy due to better laying strategy is less than that observed in physical experiments, only up to half of the experimental results. This confirms that simulation could not model the masons’ intelligent decisions of reversing or replacing appropriately. However the alternate wedge-angle is a better model than random, which requires further improvement to perform intelligent brick-laying.

#### **6.7.4.5 Comparison of simulation, experimental and theoretical data**

Experimental data needs correcting (by scaling factor derived in Table 6.20) for the small size of the brick-pile from which columns were assembled.

**Table 6.22 Correction of experimental data using  $K_\lambda$  factors**

Description	Indented bricks' columns			Grooved bricks' columns		
	5	10	20	5	10	20
Height (course numbers-N)	5	10	20	5	10	20
SD out-of-plumb ( $\sigma_{x,N}$ ) mm	3.3	9.2	19.5	1.9	4.8	9.2
$\lambda$ (pile size-M to set-N ratio)	4	2	1	4	2	1
$K_\lambda$ (correction factor)	1.2	1.4	1.9	1.2	1.4	1.9
$\sigma_{x,N}$ corrected	<b>4.0</b>	<b>12.9</b>	<b>37.0</b>	<b>2.3</b>	<b>6.7</b>	<b>17.5</b>

Table 6.22 show results after the small-brick-set correction factor  $K_\lambda$  had been applied to the experimentally observed SD of x-deviations (Tables 6.15 and 6.16). We can observe a reasonable agreement of 91% in Table 6.23 (i.e. is within  $\pm 13\%$ ) between simulations and the corrected experimental values of the SD of the out-of-plumb deviations at the top of course 20. However various factors may reduce this further in practice i.e. by reversing or select-and-replace for better orientation.

**Table 6.23 the out-of-plumb deviations comparison between practical, simulations and theory for ungrooved-indented bricks**

SD of column out-of-plumb deviations ( $\sigma_{x,20}$ )		
Simulation (using $D = 30\text{mm}$ )	Theory ( $D = 30\text{mm}$ )	Practical (corrected values)
33.6	18.4	37.0

The level of agreement gives confidence that the simulation is realistic and therefore:

- a) The out-of-plumb deviations of columns really are proportional to the roll-wedge-angle deviations in the bricks.
- b) Out-of-plumb rises with the scaling factor and column height

The theoretical value Table 6.23 should be compared with values of indented bricks before corrections because the  $\sigma_\gamma$  obtained from practical data by replacing  $D = 58\text{mm}$  a

practical measured spacing (Figures 6.11), which give results equivalent to grooved bricks, and the derived average  $D = 30\text{mm}$  (Section 6.7.3.2) for indented bricks. However the theoretical values using  $D = 30\text{mm}$  in Table 6.21 is in agreement by 95% with values of indented (NBC) Table 6.16. This confirms that the theoretical assumption and the computations of average contact points spacing give realistic results.

### **6.7.5 SENSITIVITY OF SD OF OUT-OF-PLUMB DEVIATIONS ( $\sigma_x$ ) TO COLUMN HEIGHT**

Theoretical analysis equation 6.6 showed that  $\sigma_x$  rises with column height to the power of 1.5 (i.e.  $N^{1.5}$ ), thus giving a sensitivity  $S$  of 1.5. Table 6.22 shows an increase of  $\sigma_x$  to height as the brick-pile population increases. Theory has been calculated on the assumption that from course 1 to course 20 there is a fixed sensitivity  $S$ , so that  $SD_x$  of deviations at  $N^{\text{th}}$  height<sup>S</sup> is:

$$S = \ln(\sigma_{x-20}/\sigma_{x-5}) / \ln(H_{20}/H_5)$$

Where;

$H_{20}$ and $H_5$	the heights at courses 20 and 5 in course numbers
$S$	is sensitivity of column out-of-plumb deviation to column height
$\sigma_{x-20}$ and $\sigma_{x-5}$	the standard deviations of out-of-plumb deviations at courses 20 and 5 respectively

**Graph 6.2 Influence of brick population on out-of-plumb variations**

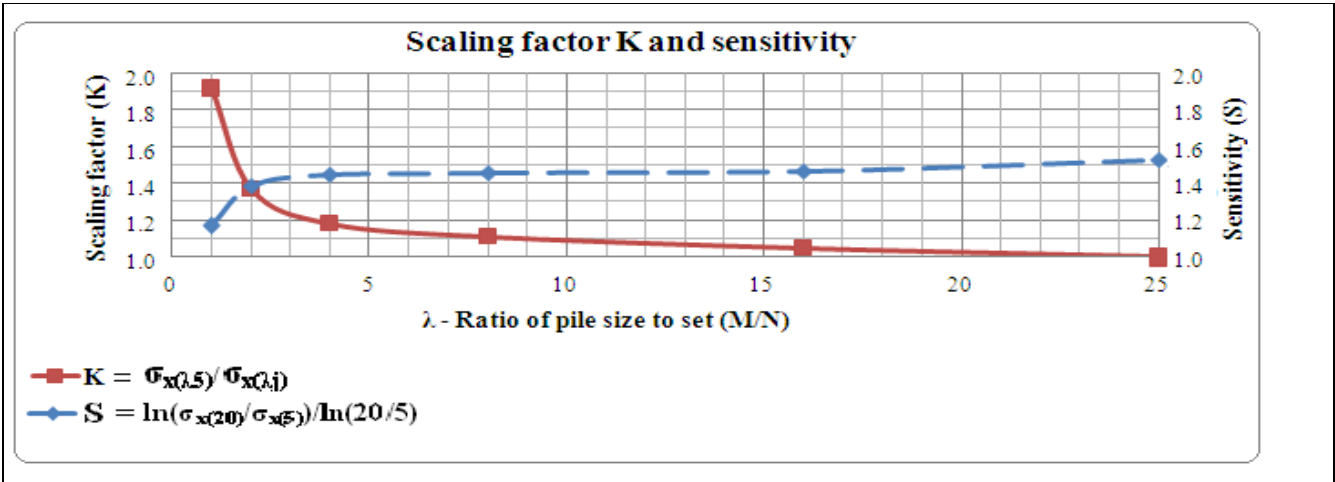


Table 6.22 show the correction for standard deviations at course 5, 10 and 20 to the raw data from Tables 6.15 and 6.16. From the corrected value (Table 6.21), then we can compare the practical and theoretical power (sensitivity) of 20<sup>th</sup> course as;

$$S_{GBC} = \ln(17.5/2.3)/\ln(20/5) = 1.46 \text{ for grooved bricks and}$$

$$S_{NBC} = \ln(37.0/4.0)/\ln(20/5) = 1.6 \text{ for indented (ungrooved) ones}$$

The values for  $S$  so obtained are 1.46 and 1.6 which differ from theoretical value of 1.5. The degree of disagreement between the practical and theoretical is due to double uncertainties mentioned in section 6.7.3.3 ( $\pm 13\%$ ). From the above, the use of K-value reduced the sensitivity difference from 0.3 to 0.03 and 0.07 between physical columns and theoretical computations.

Both scaling factor and sensitivity (Graph 6.2) shows that if the brick pile population is more than four times the brick-set (N) required for an assembly height, there are no remarkable out-of-plumb variations (Table 6.20). In contrary a ratio between brick pile

size and brick-set ( $N$ ) for assembly below four ( $\lambda_4$ ) require higher correcting factor ( $K_\lambda$ ) (Table 6.20).

**Scaling effects**, going from half size bricks to full size will:

- a) Reduce the roll-wedge angle for a given surface roughness/bumpiness (in mm)
- b) Double the height of each brick.

These two effects cancel each other, so the deviation (in mm) expected at a given course (e.g.  $N = 20$ ) for full-size brick will have the same statistics (including SD) as these experimentally observed for half-size bricks.

## **6.8 WALL ALIGNMENT ANALYSIS**

In section 6.6.2.4 it was described the construction procedure of assembling physical/experimental walls in three strategies i.e. random, reverse and replace Table 6.10. In additional walls were provided with end restraints to control vertical alignment (figures 6.27 and 6.28). Simulation successively modelled wall assembly by random brick-stacking without end constraints, which allowed the comparison between physical and simulation in the same condition. However end constraint compared only practical walls.



## 6.8.1 EXPERIMENTAL DATA FOR WALLS

### 6.8.1.1 Physical walls

To generate data for alignment analysis from walls employed three strategies and three end restraint options were provided (Figure 6.27 and 6.28) making total of nine sets (each set equal 5 walls) of test walls to be built.

**Table 6.24 Wall assembling sequence**

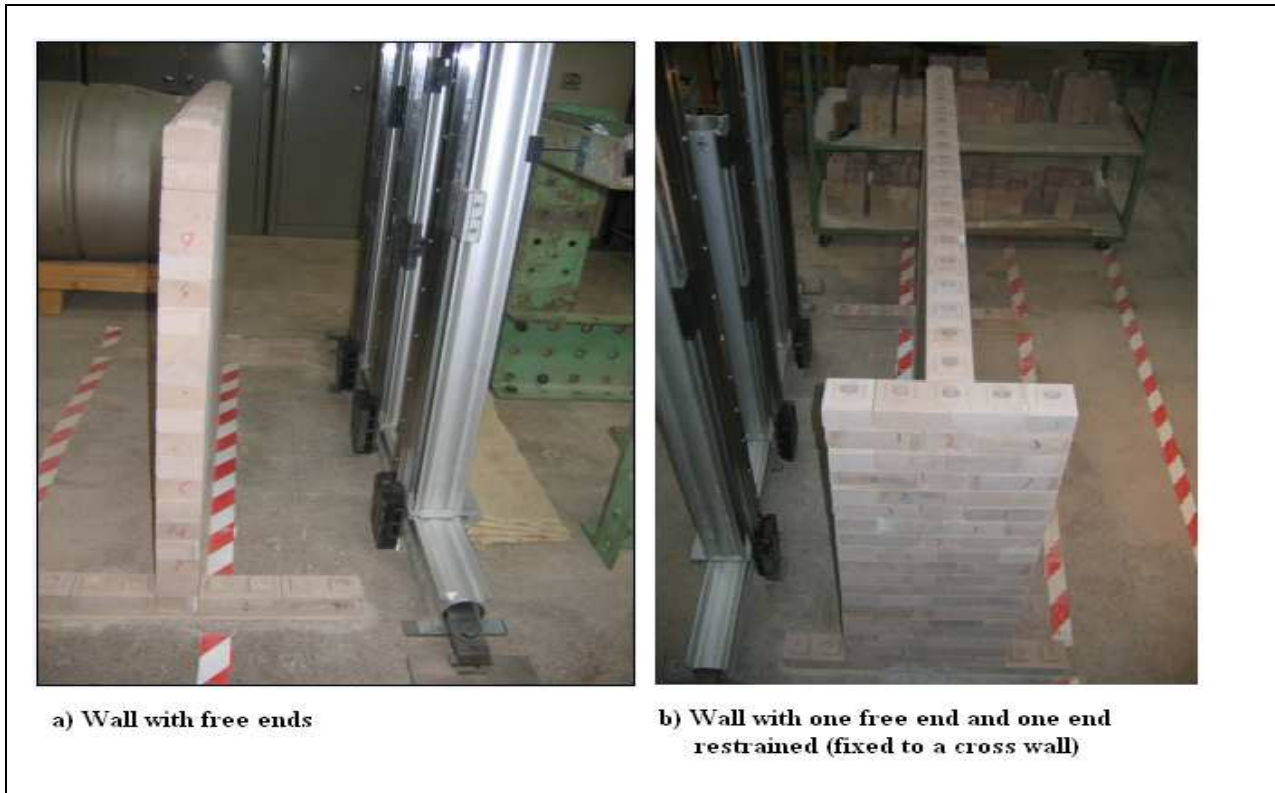
Designation	Method of assembling	End constraints	Size of set
W <sub>A</sub>	Random picking and stacking	None	5
W <sub>B</sub>		One end fixed	5
W <sub>C</sub>		Both ends fixed	5
W <sub>D</sub>	Reverse allowed	None	5
W <sub>E</sub>		One end fixed	5
W <sub>F</sub>		Both ends fixed	5
W <sub>G</sub>	Reversing and replacement allowed	None	5
W <sub>H</sub>		One end fixed	5
W <sub>I</sub>		Both ends fixed	5

The wall assembling sequences summarised in Table 6.24 were constructed in the following order:

**Walls (W<sub>A</sub>, W<sub>D</sub>, W<sub>G</sub>):** are straight with free ends (Figure 6.27a):

- A. The wall assembled using randomly picked bricks from a pile without reversing or selection. As normal the courses were made as straight as possible (relative to a building line or straight-edge).
- D. Randomly stacked bricks as picked from the pile as in A, and each brick were allowed to be reversed to find the best orientation, but no replacement permitted.
- G. The same wall as in A, and both brick reversing and replacement permitted for proper orientation.

**Figure 6.27 Restraining options for experimental walls**



Walls ( $W_B$ ,  $W_E$ ,  $W_H$ ) with one end fixed by a cross wall (Figure 6.27b), and Walls ( $W_C$ ,  $W_F$ ,  $W_I$ ) with both ends fixed (Figure 6.28).

Walls built without end restraint (free ends) used 200 bricks; while one end restrained used 240 bricks and both ends restrained used 280 bricks. After building a wall and taking the necessary measurements as shown in Figure 6.28, the wall disassembled and bricks were thoroughly shuffled and then reassembled into the next wall using the same bricks i.e. pile size  $M$  equals set size  $N$ , thus  $\lambda = M/N = 1$  for all experimental walls assembled.

**Figure 6.28 Test wall with both sides restrained**

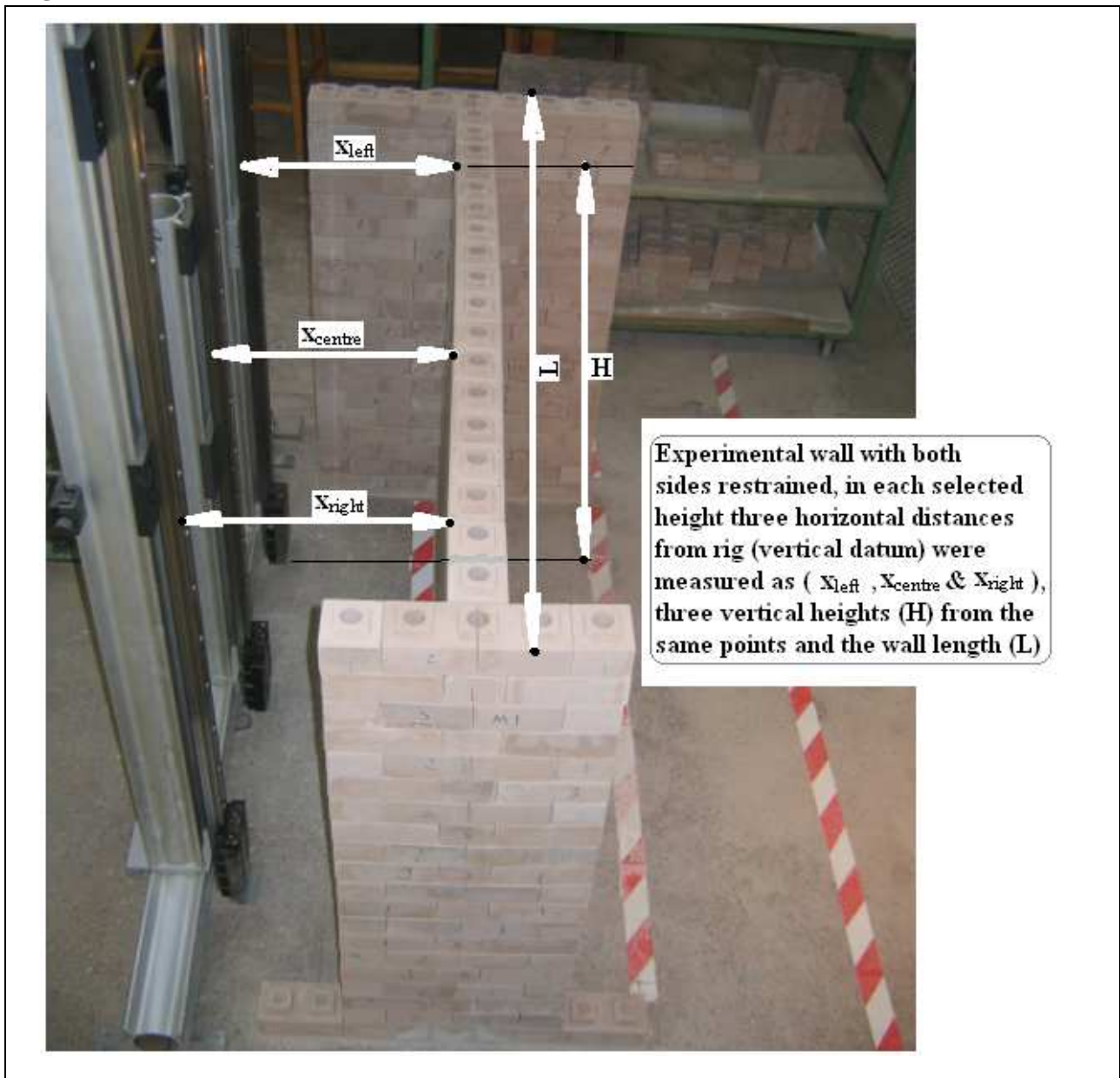


Table 6.25 is a summary of wall measurement results of three assembly strategies, in three restraining options at the selected levels/courses (5, 10, and 20 see figure 6.28). The averages of three measurements along the selected course level are recorded in a single

line like column data. The expectations of the research were that the wall alignment will produce higher accuracy than column because of the following reasons: -

- The overlapping of successive courses act as a correcting measure
- The average of selected courses (at three points) reduce lean error
- The restraints also should add-up the reduction of out-of-plumb deviations

**Table 6.25 SD of out-of-plumb deviations ( $\sigma_x$  mm) of experimental walls for three strategies**

Wall course Nos.	Random strategy			Reverse strategy			Replace strategy		
	None restraint	One end restrained	Both ends restrained	None restraint	One end restrained	Both ends restrained	None restraint	One end restrained	Two end restrained
<b>5</b>	1.01	0.86	0.92	1.10	0.40	0.73	2.28	2.02	0.51
<b>10</b>	1.44	2.82	2.10	2.10	1.66	2.10	3.30	2.67	1.99
<b>20</b>	8.88	8.83	6.90	6.70	4.71	2.99	6.56	4.61	2.80
<b><math>\sigma_x</math> reduction in %</b>		<b>1%</b>	<b>22%</b>	-	<b>30%</b>	<b>55%</b>	-	<b>30%</b>	<b>57%</b>

We can observe a small out-of-plumb deviation reduction in Table 6.25 as you move from random to reverse to replace strategies and from none-restraint to one end restrained to both ends restrained i.e. with a none restraint option from random to reverse to replace realise only a reduction of 25% and 26%. From such a small change in the wall assembly it indicates that skill is less important as unskilled can perform up to 74% of the skill tactics.

The additional restraint in random stacking did not make a substantial alignment improvement in the random strategy. However it shows the same improvement between reverse and replace of which we can recommend to use reverse because ultimately is a cheaper alternative than replace, because the reverse and replace strategies require more skill and hence more time to construct the same volume of work and therefore add more cost of the overall construction.

### 6.8.1.2 Simulated walls

The simulations generated a pile of 500 bricks (Figure 6.23) from where we can pick brick sets for wall assembly. Three pile sizes ( $M = 120, 240$  and  $480$ ) were used and from each 240 wall assemblies were made and results are shown in Table 6.26. The average scaling factor  $K$  for the smallness of sample size is computed from these results.

**Table 6.26 SD of out-of-plumb deviations ( $\sigma_x$  mm) for 720 simulated wall assemblies**

Strategy	Wall height at ( $N^{\text{th}}$ - course)	Brick piles size (M)			Mean $\sigma_x$
		M=120	M=240	M=480	
Random	5	1.29	1.30	1.39	<b>1.33</b>
	10	2.64	2.87	3.06	<b>2.86</b>
	20	9.96	11.11	12.24	<b>11.10</b>
Average scaling factor (K)		<b>1.23</b>	<b>1.13</b>	<b>1.05</b>	

The physical wall assembly data from Table 6.25 (random strategy and none restrained wall) need correction for small-pile-size (Section 6.7.3.3) before comparing with the simulations. Table 6.27 show results after the small-pile-size correction factor ( $K$  - from Table 6.26) had been applied to the experimentally observed SD of x-deviations.

**Table 6.27 the out-of-plumb deviations comparison between practical and simulations for ungrooved-indented brick walls**

Courses	SD of wall out-of-plumb deviations ( $\sigma_x$ mm)	
	Physical (up-scaled using K)	Simulation
5	1.06	1.33
10	2.57	2.86
20	<b>10.92</b>	<b>11.10</b>

We can observe an agreement of 98% in Table 6.27 (i.e. is within  $\pm 13\%$  Section 6.7.3.3) between simulations and the corrected experimental values of the SD of the out-of-plumb deviations at the top of course 20.

If we compare practical results for column assembly Table 6.17 and column simulation Table 6.19 with that of walls, for both practical and simulation Tables 6.25 and 6.26 respectively, it is evident that wall yields less overall out-of-plumb deviations and therefore confirm that wall alignment behaves as expected in the practical wall construction. So we can conclude that mason skill (ability to correctly reverse and replace) is less important in MT as experiment show that random stacking (un-skilled bricklaying) reduces the out-of-plumb deviation up to 74% thus improving the overall alignment performance, and an addition of restraint on both sides reduce further out-of-plumb deviations by 21%, which will increase stability and hence vertical accuracy.

### **6.8.2 BRICK INACCURACY LIMITS FOR ALLOWABLE WALL LEAN**

The column out-of-plumb deviations at any height was analysed theoretically by the use of standard deviation (SD) of roll-wedge angle (Eq. 6.6) for a given brick sample. The British Standards (BS) does not encourage column deflection. However BS 5628-3: 2005 Table A-2 and BS 5606:1990 Table 1 permit the following deviation limits for the wall out-of-plumb deviations: for the height up to 2m the deviation shall not exceed 9mm, and up to 7m shall not exceed  $\pm 14$ mm.

The physical experimental walls built using bricks (results shown in Table 6.25) with standard deviation of surface variations equal to 0.66mm for the top surface and bottom surface 0.3mm giving an average of 0.48mm, resulted in an average wall lean of 8.88mm at the twentieth course (equivalent to 2m height). Although it is in agreement with BS, but such accuracy is a result of under-estimation caused by small brick set available,

which tolerate replication of the same bricks in all assemblies. Simulation investigated for the small brick sample, it generated up to four times the set required for wall assembly i.e. a wall requires 120 bricks and a pile of 500 bricks was generated see Figure 6.23. Results of sample size increase are shown in table 6.26 and compared in Table 6.27 after corrections. Although they agree with simulations but require more accurate bricks to meet standard wall lean limits (not more than 9mm).

Practical could not produce grooved bricks enough for wall assembly. However simulation investigated for the effective contact spacing between rear and front contact bands (Section 6.7.3.2). Using appropriate contact spacing ( $D$ ) i.e.  $D = 30\text{mm}$  for the ungrooved-indented (experimental) bricks and  $D = 60\text{mm}$  for grooved (experimental) bricks, with simulated wall assemblies obtain promising results. As for the expectations from the theoretical analysis moving from contact spacing  $D = 30\text{mm}$  to  $D = 60\text{mm}$  (using  $f_{Av}$  in Table 6.18) would improve alignment accuracy by 49%. Table 6.26 show results for simulated walls using  $D = 30\text{mm}$  and Table 6.28 show results for simulated walls using  $D = 60\text{mm}$ .

Comparing the two set of results and taking into consideration of only 20<sup>th</sup> course for the indented and grooved walls Tables 6.26 and 6.28, we realise an improvement of up to 50%. The author believes that results are realistic within  $\pm 13\%$  coupled with several uncertainties i.e. accuracy of practical data used for simulations, estimate of effective spacing and the appropriateness of modelling the wall assembly.

**Table 6.28 SD of out-of-plumb deviations ( $\sigma_x$  mm) for 720 simulated column assemblies for  $D = 60\text{mm}$  (corresponding to grooved- experimental bricks)**

Strategy	Column height at ( $N^{\text{th}}$ - course)	Brick piles size (M)			Mean $\sigma_x$
		M=120	M=240	M=480	
Random	5	0.67	0.68	0.70	<b>0.68</b>
	10	1.33	1.47	1.52	<b>1.44</b>
	20	4.89	5.59	5.94	<b>5.47</b>

Simulation investigated for the highest brick bump variation that would give allowable wall inclinations; this was possible by changing the SD of brick-bump variations for a given brick set (batch). Various SD of bump variations were investigated using experimental bricks as datum (0.66mm of the top and 0.3 of the bottom from Table 6.8), the variation were increased by 25%, 50%, 75% and 100% respectively see Table 6.29, from each bump assembled 240 walls and determined their out-of-plumb statistics at courses 5, 10 and 20 respectively.

**Table 6.29 The effect of brick bump variation on allowable wall lean limits using grooved bricks ( $D = 60\text{mm}$ )**

Average SD of bump variations of the top and bottom surfaces (mm) increased from the measured by 25% up to 100%		0.48	0.6	0.72	0.84	0.96
SD of out-of-plumb deviations at respective course levels	5	0.70	0.82	1.03	1.18	1.29
	10	1.52	1.73	2.25	2.41	2.73
	20	5.94	6.65	8.08	9.93	10.63

The brick variations that passed the BS wall lean limits are those under 0.5mm SD of bumps variations using ungrooved bricks Table 6.26. However the use of grooved bricks Table 6.29 show that brick accuracy requirements may be reduced by more than 75% and hence achieve the limits of wall vertical alignment in accordance with the BS 5606:1990



Table 1. This reduction in brick accuracy will have construction cost impact as it will allow less expensive machinery and less-skilled labour.

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# CHAPTER 7

## 7.0 STIFFNESS OF DRY-STACKED BRICK COLUMNS

### 7.1 INTRODUCTION

In the proceeding Chapter we examined the inaccuracies (out-of-plumb deviations) of columns and walls built with dry-stacked bricks. These deviations were solely attributable to imperfections in brick geometry and no account was taken of additional deviations caused by lateral forces. Lateral forces may occur, due to wind, earthquakes, collisions etc. Additional lateral displacements can also result from moments that are themselves the result of gravity acting on a leaning wall.

In this Chapter, the response of dry-stacked (i.e. mortarless) walling to lateral forces is explored. Three responses are of interest, namely: The stiffness of a wall to forces perpendicular to its face, extra deflection due to application of such forces, and overturning due to a hinge forming somewhere in the wall, following applications of such forces See figure 7.2.

Secondary experiments were set up to test the stiffness of dry-stacked, single-brick, mortarless columns, loaded transversally at the top (20<sup>th</sup>) course. Half-size bricks were used to build two types of columns; those built with normal bricks (NBC), and those built using grooved bricks (GBC). The grooved bricks (see figure 6.23) forced brick-to-brick contacts to lie in two bands (see Figure 6.28) extending respectively 10mm from the front

and back edges. Thus only 28% (20mm/70mm) of the brick surface was available for contact.

The tests were designed to explore the capacity of columns to withstand transversal loading, and methods of improving stability and control of their vertical position.

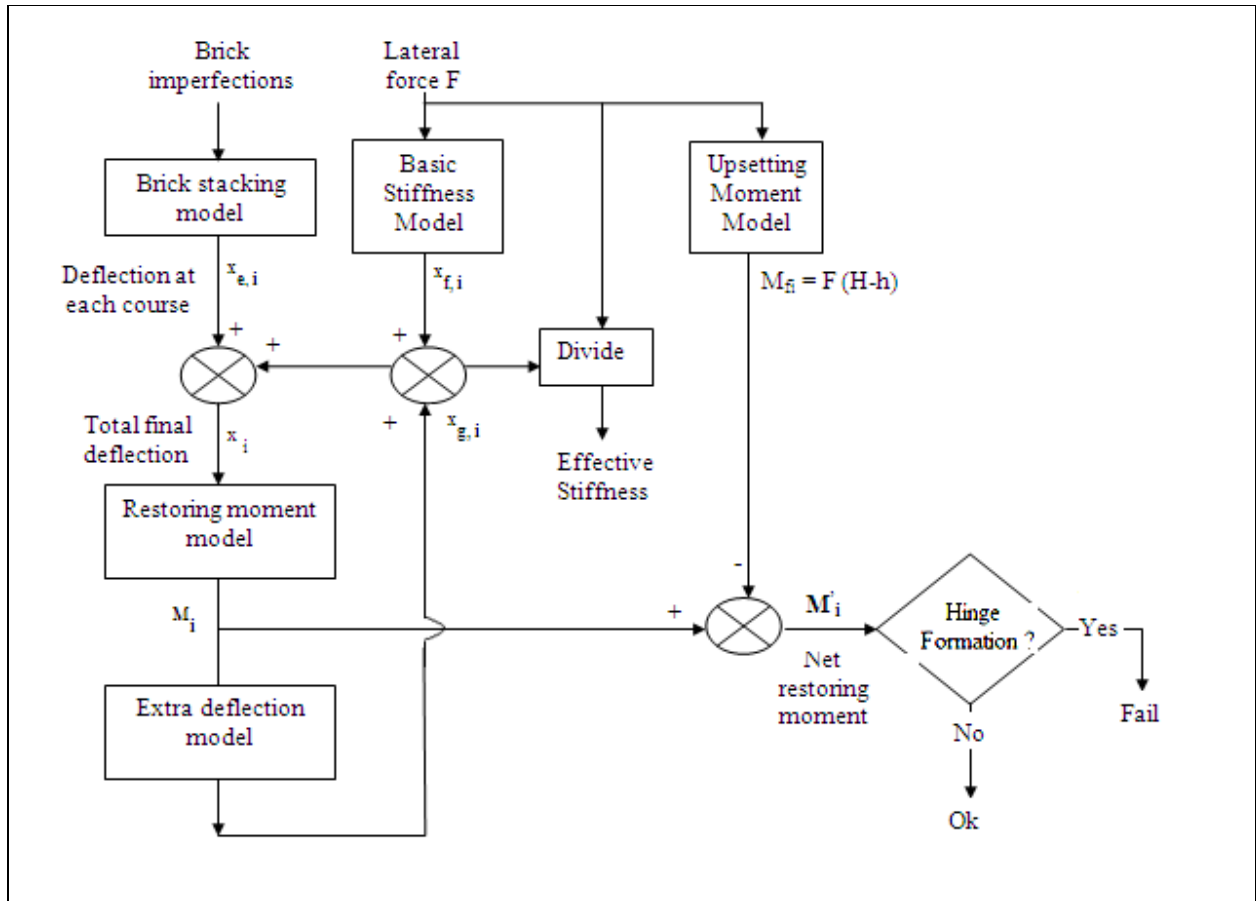
It has been observed during construction of dry-stacked columns is that they can easily sway under application of small transversal forces. This flexibility can cause difficulties in maintaining alignment accuracy and may result in accidental structural collapsing before a wall is secured with a ring beam. Slender and hence flexible walls in practice are inevitable: they appear between windows or between doors and windows. They have typically a thickness of half-brick and width less than two brick-lengths. The vertical position of a column assembled using irregular bricks is difficult to control, poor surface contact causes pliable behaviour that magnifies as the height increases, and column become less stable; even wind pressure can make the column to easily sway.

The test objectives were to identify means of improving the stiffness and alignment accuracy of dry-stacked brick column.

Before physical testing of dry-stacked brick columns, a theoretical analysis was made for a columns' resistance to lateral forces. To guide the analysis a theoretical model was designed Figure 7.1.

Figure 7.1 is a flow diagram modelling the sequence of a loaded dry-stacked column. We can observe three types of deflection (due to respectively brick imperfections, forces and gravity). In response to forces and brick surface characteristics, the column will deflect. Model shows also the sequence leading to net restoring moment that may cause a hinge at any point of interface.

**Figure 7.1 Moment and Deflection Model to examine hinging formation for a dry-stacked column**



Where;

- $x_{e,i}$  for all  $i$ , are deflections from plumb in the absence of any forces
- $x_{f,i}$  for all  $i$ , are deflections just due to forces
- $x_{g,i}$  are extra deflections due to gravity acting on column (“2<sup>nd</sup> order affects”)
- $M_i$  is restoring moment at interface  $i$
- $M_{fi}$  is upsetting moment at interface  $i$  - due to applied force  $F$
- $M_i = M_i - M_{fi}$  ( $M_i = 0$  at onset of hinging at  $i$ )

## 7.2 THEORETICAL ANALYSIS FOR A COLUMNS' RESISTANCE TO LATERAL FORCES

Starting with a perfect column i.e. vertical to plumb, the application of a lateral force at its top causes a displacement in the direction of line of action of force. With different characteristics of bricks used to assemble column, the effects of resistance to lateral forces take various stages of displacement to finally may result into overturning.

For example if the top of a column height H, is subjected to lateral force (F), the total displacement of the column top will be;  $x_N = x_i + x_{fi} + x_{gi}$

Where:

$x_N$  is final (total) displacement at the N<sup>th</sup> course

$x_i$  is a displacement due to brick irregularity, and

$x_{fi}$  is a displacement due to applied force.

$x_{gi}$  is a second order effect displacement due to weight of leaning column above interface

In the analysis of a vertical brick column subject to lateral force (Figure 7.2) at its top, we may consider three cases: -

- All bricks are glued together (full continuity where jointing is ignored and the column is of the brick material throughout)
- Dry-stacked bricks with perfect surfaces

- Dry-stacked bricks with irregular surfaces causing some of the contact points between successive bricks to lie not at front and back of bricks but near their centre line (Figure 7.4)

### Symbols

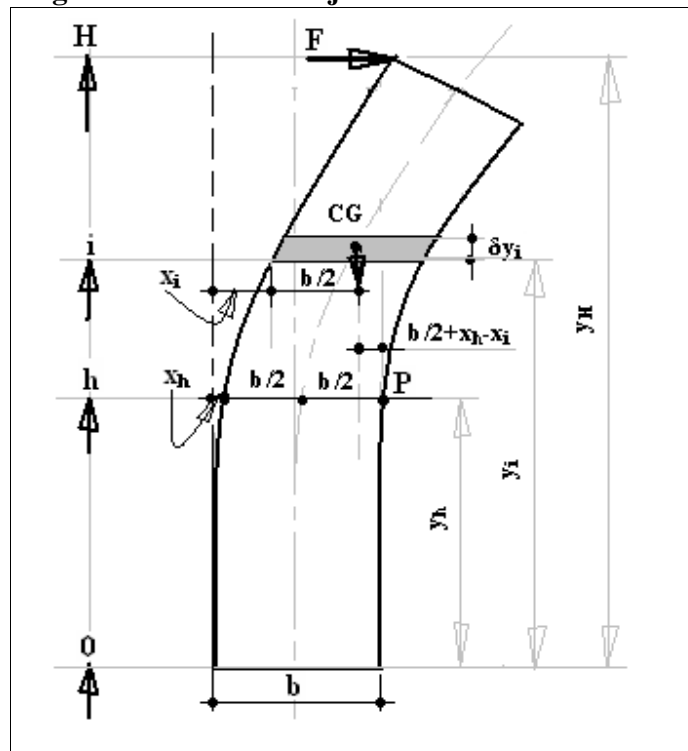
The brick (Figure 2.20) placed on a column has plan area  $A = L \times W$ .

Young's Modulus for brick material is  $E$ ,

Second moment of area of brick surface about a lengthwise axis is  $I = L \times W^3/12$ ,

Column weight pressing on any interface is  $w = K(H - h)$ , where  $K = A\rho g$  and  $(H - h)$  is a distance (height) from interface up to the top of the column (Figure 7.2). The column's bottom interface we can call '0', and its top interface (underside of top brick) 'N - 1'.

**Figure 7.2 Column subject to lateral force**



## 7.2.1 A VERTICAL COLUMN WITH ALL BRICKS GLUED TOGETHER

The column acts as one solid beam, before the displacement takes place it will develop areas of tension and compression. Considering a free-standing column fixed at its base (Figure 7.2), the front side from the direction of applied force will develop tensions and the back compression.

A force applied at the top of a column Figure 7.2 will initiate a moment ( $M_{fo} = FH$ ) at the columns base, and at the  $i^{\text{th}}$  interface a moment  $M_{fi} = F(H-h)$ . Where  $h$  is the height of at this interface.

The behaviour of a mortared column and of a dry-stacked column will be the same until hinges form in the latter (onset of toppling). So for analysing the force to initiate hinging we need not distinguish between mortared and dry-stacked columns.

From the glued column we can calculate initial displacement caused by the applied lateral force;

$$x_f = F(H^3/6EI) \quad (7.1)$$

So we have elastic deformation ( $x$  is proportional to force), where stiffness ( $= 3EI/H^3$ ) falls rapidly with increase in wall height ( $H$ ).

If the direction of the applied force (Figure 7.2) is from front to back so the column will be forced to lean backwards. From the above information, maximum compressive stress at height  $h$  within the column and at the back edge will be;

$$\sigma_{back} = (H-h)\rho g + \frac{F(H-h)\frac{W}{2}}{I}$$

$$\sigma_{back} = (H-h)\left(\rho g + \frac{6F}{LW^2}\right)$$

The compressive stress at the front edge will be less than at the back (negative) due to the force applied forcing the joints to open-up and lean backwards.

$$\sigma_{front} = (H-h)\left(\rho g - \frac{6F}{LW^2}\right) \quad (7.2)$$

As the force ( $F$ ) increased, displacement will also increase; and so will the overturning moment applied to lower courses. When force reaches some value  $F = F_h$  (and the corresponding displacement is  $x = x_h$  the front compressive stress  $\sigma_{front}$  falls to zero, thus;

From (7.2)  $F_h = \frac{LW^2\rho g}{6}$ , and as  $I = \frac{lW^3}{12}$  so;

$$x_H = \frac{F_h H^3}{6EI} = \frac{\rho g}{3EW} H^3 \quad (7.3)$$

Note that the toppling force  $F_h$  is not dependent on column height, but that  $x_H$  – the top deflection at onset of toppling is highly dependent on height  $H$ .

With a glued column, lateral force  $F$  may be increased beyond  $F_h$ , putting the front face into tension.

## 7.2.2 DRY-STACKED BRICKS WITH PERFECT SURFACES

For dry-stacked bricks, as soon as front face compressive stress falls to zero at  $F = F_h$ , ‘hinging’ will take place at any or all of the interfaces. After this, deflection  $x$  will increase indefinitely but  $F$  will stay at  $F_h$ .



The movement of the column pushed by lateral force can be represented in diagram form Figure 7.3; line A (Force -  $F$  against displacement  $x_f = F((H-h)^3/6EI)$ ) with the slope of the inclined solid line representing stiffness/rigidity of a column requiring more force to attain further displacement.

**Figure 7.3 The displacement behaviour of dry-stacked column built from perfect and imperfect bricks**

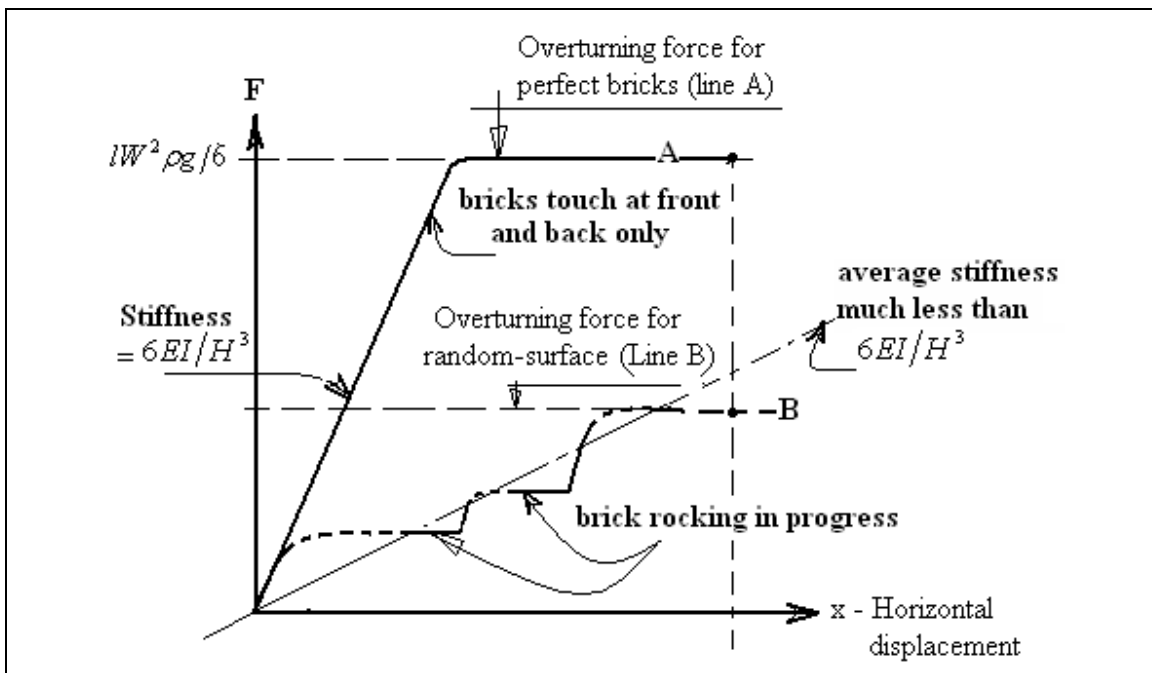


Figure 7.3 compares the displacement behaviour of a perfect brick column (line A) represented by solid inclined line of an irregular brick column (line B). For the latter, sloping solid short lines show stiffness before starting displacement, followed by spiralling dashed lines representing softness of a column easy to push with a small force, and finally the horizontal short lines representing balancing points where the column rocks from one seating to another.

### 7.2.3 DRY-STACKED BRICKS WITH IRREGULAR SURFACES

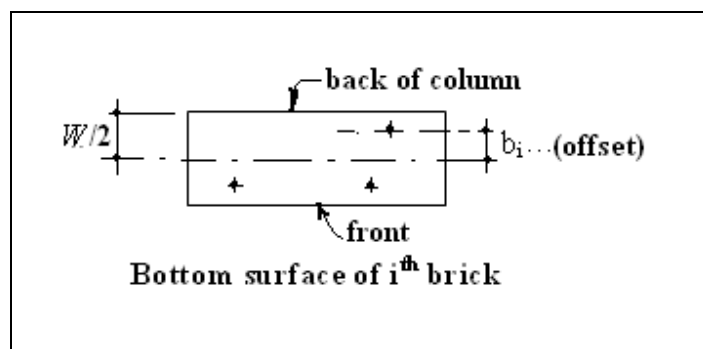
The geometric imperfections have produced some lean even before force is applied (Figure 6.16). Then hinging will occur at lower value of  $F$  than  $F_H$  and toppling will occur. Moreover due to surface irregularities, the actual contact area will be less than the brick face area  $A$ , so local stresses will be higher and displacements a little bigger than Section 7.2.2 The irregular bricks interface on points rather than surfaces, when lateral forces applied form rocking movement as represented schematic Figure 7.2 line B.

We can observe a rocking movement when brick contacts initially lie between the centre line and the edges:  $x_i$

#### Brick contact points between the centre line and the edges

Let the distance from the central axis to initial contact point (Figure 7.4) at  $i^{\text{th}}$  interface be  $b_i$  ( $i = 1, 2, 3 \dots N$ ), rocking of the interface  $i$  will occur when moment about contact point falls to zero  $\{M_i = F_i(H - h) - A\rho g(H - h)b_i = 0\}$

**Figure 7.4 Brick interface contact points**



Thus as long as  $F < \min(F_1, F_2 \dots F_N)$ , the column will act like a glued beam.

When  $F = \min (F_1, F_2 \dots F_N) = K \min (b_1, b_2 \dots b_N) = F_{\text{first}}$ , rocking will occur at the interface for which  $b_i$  is the lowest.

The wall top will move (displacement  $x_N$  increases) until the interface rocks onto a new seating. We assume  $b_i$  becomes  $b/2$ . The column now again acts as a glued column, and  $F$  increases with small increase in  $x$ -displacement until some other interface reaches the rocking point at  $F = F_{\text{second}} = Kb_j$ , where  $b_j$  is second smallest offset (Figure 7.3 line B represent such stepped column movement). Again the column top will move at a constant force ( $F = F_{\text{second}}$ ) until interface  $j$  reseats at its back edge. This continues (with rising applied force  $F$ ) until all interface contact at their back edges (point P Figure 7.2). The interfaces to develop into a hinge will depend on the combination of moments caused by applied force to that interface, namely;

- An overturning moment directly due to  $F$  [ $M_{fi} = F(H-h)$ ]
- A restoring moment  $M_i$  due to the part of the column supported by the interface whose its centre of gravity is distance  $(\frac{w}{2} - b_i) + x_h - x_i$  from the contact point.

Rocking take place (Figure 7.2) when;  $M_{fi} \geq M_i$  (see Figure 7.1) thus,

$$M_i = \rho g (H - h) A \left\{ \left( \frac{w}{2} - b_i \right) + (x_h - x_i) \right\}.$$

If  $M_{fi} = M_i$

$$F(H - h) = \rho g (H - h) A \left\{ \left( \frac{w}{2} - b_i \right) + (x_h - x_i) \right\}$$

$$F = A \rho g \left\{ \left( \frac{w}{2} - b_i \right) + (x_h - x_i) \right\} \quad (7.4)$$

## 7.2.4 THE COLUMN OVERTURNING POINT ANALYSIS

We are interested in under what circumstances a 'leaning' column will fall over and at what height 'hinging' (the start of falling over) begins. The analysis is unfortunately, too complex attempt a 'general algebraic solution', since lateral forces (or imperfect brick geometry) produces leaning and leaning gravity results in increased bending moments causing an increase in leaning.

We consider 2 scenarios

- i) Leaning due to imperfect brick geometry (non-zero roll-wedge angle) and no lateral forces are applied.
- ii) Force  $F$  is applied to an initially straight column, resulting in leaning and combination of lean plus applied force causes toppling.

The shape of leaning column is expressed by some function ( $f$ ) when deviation from plumb at height  $y$  ( $= H_i$ ; where  $H$  is a small height but not less than one brick) is

$$x_i = f(y)$$

If we express  $f(y)$  as a Binomial theorem

$x = f(y) = a_0 + a_1y + a_2y^2 + a_3y^3 + a_4y^4 + \dots$  And we know the column is vertical at its base, then  $a_0 = a_1 = 0$

To keep the analysis practical we will neglect high order terms so that:

$$f(y) \cong a_2y^2 + a_3y^3 \quad (7.5)$$

## CASE 1

Analysis of a column leaning because all bricks have a fixed wedge-angle  $\gamma = \gamma_0$  yields

$$x = f(y) \approx a_2 y^2, \text{ where } a_2 = \frac{\gamma_0}{2H} \dots \text{ See the derivation below}$$

[To check the value of  $x$  will consider the  $i^{\text{th}}$  course in Figure 6.16, the centre line is an arc with top and bottom points forming an angle ( $i\gamma$ ) between two radiuses from the striking point 0, thus;

$$R - x = R \cos(i\gamma)$$

$$x = R - R \cos(i\gamma) = R[1 - \cos(i\gamma)]$$

$$x = R[1 - \cos(i\gamma)] \tag{7.6}$$

From trigonometry,  $R = \frac{H}{\gamma}$ , substituting the value of  $R$  in equation 7.6, using Maclaurin

series which observes conditions of small angles that,

$$\cos(i\gamma) = 1 + \frac{(i\gamma)^2}{2!} - \frac{(i\gamma)^4}{4!} \dots \text{ (Neglecting high order terms)}$$

$$x = \frac{H}{\gamma} \left\{ 1 - \left( 1 - \frac{(i\gamma)^2}{2} \right) \right\} = \frac{H}{\gamma} \frac{(i\gamma)^2}{2} = \frac{H}{2\gamma} (i\gamma)^2$$

From Figure 6.16,  $i \times H = y$ , a column height composed of  $i$  small parts; thus  $i = \frac{y}{H}$ .

And therefore:

$$x = \frac{H}{2\gamma} \left( \frac{y}{H} \right)^2 = \frac{H}{2\gamma} \left( \frac{\gamma^2 y^2}{H^2} \right) = \frac{\gamma}{2H} y^2$$

$$x = \frac{\gamma}{2H} y^2 \quad (7.7)$$

The basic assumption is that the lowest course is laid perpendicular to the ideal horizontal line Figure 7.2. Formation of a hinge in a dry-stacked column of bricks due to the applied lateral force  $F$  at its top. Hinging will occur at any brick-edge point such as  $P$  at height  $h$ , if the direction of net moment is clockwise. The net moment is  $M_f + M_w$  (equals 0 at the onset of hinging), where  $M_f$  is due to the applied force,  $M_f = F(H - h)$  and  $M_w$  is due to the weight of the bricks in the column above  $P$ .

The weight of the element from height  $y_i$  to height  $y_i + \delta y_i$  is

$$\delta_{weight} = A\rho g \delta y_i \quad (7.8)$$

Where  $A$  is top face area of brick, its contribution to moment about  $P$  is

$$\delta_{M_w} = \delta_{weight} \left( \frac{w}{2} + x_h - x_i \right) dx \quad (7.9)$$

Thus;  $M_{w,h} = -K \int_{x=h}^H \left( \frac{w}{2} + x_h - x_i \right) d(x)$  where  $K = A\rho g$ . For hinging at  $y = h$  (7.10)

$$M_{w,h} = -M_f = -F_h (H - h),$$

So;

$$F_h = -\frac{M_{w,h}}{(H - h)} \quad (7.11)$$

For this case the column lean due to non-zero roll-wedge angle is  $x_i = Ki^2$

Now,

$$M_{w,h} = -K \int_{i=h}^H \left( \frac{W}{2} + kh^2 - kx^2 \right) dx = -K \left[ \frac{Wx}{2} + kh^2x - \frac{k}{3}x^3 \right]_h^H$$

$$M_{w,h} = -\frac{KW}{2}(H-h) + Kk \left( \frac{H^3}{3} - \frac{h^3}{3} \right) - Kkh^2(H-h)$$

So;

$$F_h = -\frac{M_{w,h}}{H-h} = \frac{KW}{2} + \frac{Kk}{3} \left( \frac{H^3 - h^3}{H-h} \right) + kh^2 = \frac{KW}{2} + \frac{Kk}{3} (H^2 + hH - 2h^2)$$

$$F_h = \frac{Kb}{2} + \frac{Kk}{3} (H^2 + hH - 2h^2) \quad (7.12)$$

From case 1;  $Kb/2 = 0$ , so hinging will occur at height  $h$  for which  $F_h$  is a minimum i.e.

where  $\frac{dF_h}{dh} = H^2 + hH - 2h^2 = 0$ ; then  $H - 4h = 0$ , hinging occurs at quarter height;

(  $h = H/4$ ).

## CASE 2

Analysis of a column acting as a vertical cantilever beam with force  $F$  applied laterally to its top.

$$x = f(y) = a_2y^2 + a_3y^3, \text{ where } a_2 = \frac{3Hw}{EI}; a_3 = -\frac{W}{EI}$$

We can determine the overturning column point by using the cantilever beam theory

$x_i = Ci^2 + Ci^3$  from *Cartwright (2006)* data book.

Now;

$$M_{w,h} = -k \int_{i=h}^H \left( \frac{W}{2} + Ch^3 - Cx^3 \right) dx = -\frac{KW}{2}(H-h) + \frac{KC}{4}(H^4 - h^4) - KC(H-h)h^3$$

From equation 7.11 we get;

$$F_h = -\frac{M_{w,h}}{H-h} = \frac{KW}{2} - \frac{KC}{4} \left( \frac{H^4 - h^4}{H-h} - 4h^3 \right) = F_0 - \frac{KC}{4} (H^3 + H^2h + Hh^2 - 3h^3)$$

$$F_h = F_0 - \frac{KC}{4} (H^3 + H^2h + Hh^2 - 3h^3) \quad (7.13)$$

In this case  $F_w$  minimum when  $\frac{dF_h}{dh} = H^2 + 2Hh - 9h^2 = 0$

$$\text{Therefore; } h = \frac{2H \pm \sqrt{4H^2 + 36H^2}}{18} = H \left( \frac{2 \pm \sqrt{40}}{18} \right) = 0.46H$$

So hinging occurs just below mid height; at  $h = 0.46H$

## 7.1.5 SUMMARY OF THEORETICAL ANALYSIS

### 7.1.5.1 Resistance to lateral force

The theoretical analysis for dry-stacked column when subject to lateral forces looked at three variants: - when all bricks glued together, dry-stacked bricks with perfect surfaces, dry-stacked bricks with irregular surfaces making contact points some of which are near the centre line. The dry-stack column forms a rocking movement induced by the contact points shifting the equilibrium position as force changes. This phenomenon is represented by a stepped diagram (Figure7.3) showing phases of stiffness interspaced by phases of softness (during rocking).



### **7.1.5.2 Columns' overturning point**

In practice we superimpose two mechanisms, namely lean due to brick imperfections and lean due to applied forces. If the force is large enough, a hinge will form at one of the brick-to-brick contacts in the column, causing collapse. This force is lower for a column of imperfect bricks than for an initially vertical column of perfect bricks.

Depending on brick surface imperfection this hinging occurs at a height between 25% and 46% of column height.

## **7.3 EXPERIMENTAL APPLICATION OF LATERAL FORCE TO THE TOP OF COLUMNS**

The column's stiffness and stability were also investigated see the test setup Figure 7.5: - each time columns were assembled via the "random" strategy C1, using normal bricks and grooved bricks respectively. Column was subjected to increasing transverse force applied to the 20<sup>th</sup> course by adding weight cells in the plastic bag see figure 7.5 extreme left. Through the line cord the column is pulled perpendicular to the direction of force see Figure 7.5 top arrow. The force measured through spring balance and deflection measured as horizontal distance ( $x_i$  minus the starting point  $x_0$  of the assembled column) from rig vertical member was recorded at intervals until overturning occurred.

**Figure 7.5 Application of lateral load to the top of dry-stacked brick column**

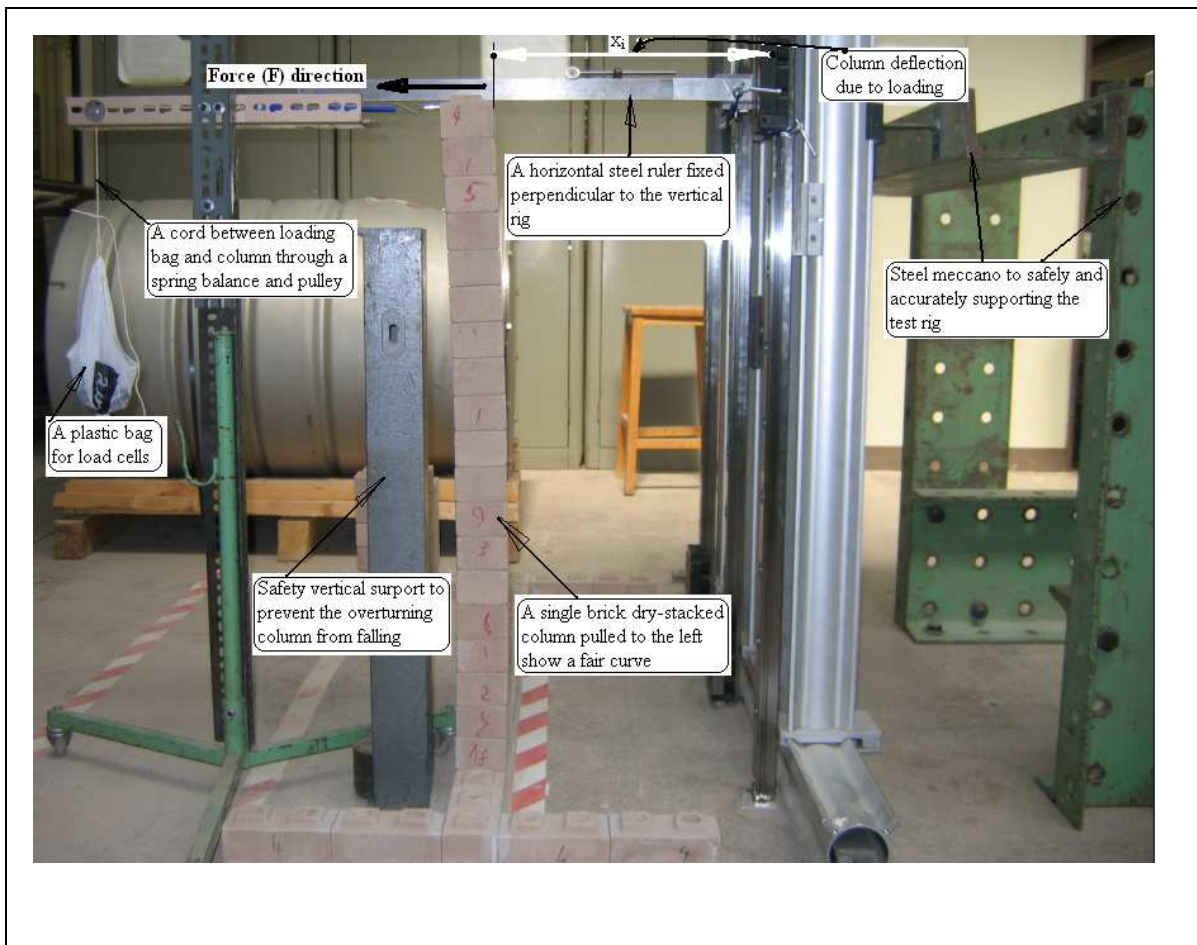


Table 7.1 and Graph 7.1 show the displacement-force versus  $x_i$  for five normal-brick columns. Table 7.2 and Graph 7.2 show the displacement-force versus  $x_i$  for grooved-brick columns.

The physical experiment and theory are in good agreement as concerns the shape of these  $k_{xi}$ . Figure 7.3 in section 7.2.2 and Graphs 7.1 and 7.2 show similar steps on increasing lateral forces.

The column makes rocking movement as the imperfect bricks roll and take up new balancing position, it stiffens and then makes another movement. The overturning hinge

occurs between 20% and 65% of the height of the column (theory predicted between 25 and 46%, which is within the range of physical experiment).

An expected consequence of the 'contact area fraction'  $f_{cA}$  being very small is that at each brick interface of a column of bricks, the second moment of area  $I$  about a longitudinal axis will be much less than its (mortared brickwork) full face value  $I_0$ .

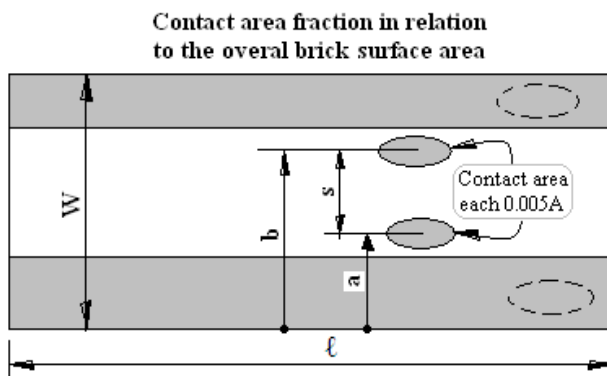
$$I_0 = W^3 L / 12, \text{ where } W \text{ is brick width and } L \text{ is brick length}$$

The higher the value of  $I$  the higher the column stiffness – for example for a column height  $H$ , the stiffness to lateral forces applied at the top of the column is

$$k = 3EI / H^3$$

Suppose (see diagram) that  $f_{cA}$  has the value 0.01 and brick-to-brick contact is limited to two small zones each of area  $WL / 200$  whose centres are a distance  $s$  apart; then the 2<sup>nd</sup> moment for the unmortared brick interface is:

$$I_U = 0.01 L W s^2 / 4, \text{ where } s = b - a$$



And if the two contact zones are randomly located, then the expected value of  $s^2$  is  $W^2 / 6$ , giving

$$I_U = 0.01 L W W^2 / 24 = 0.01 I_0$$

If however, in order to increase  $I_U$ , the two zones are constrained to lie in opposite deciles of the brick surface, namely, as shown dotted, one in each of the light shaded areas in the diagram, then the expected value of  $s^2$  increases to  $0.811 W^2$  and

$$I_U = 0.00811 L W W^2 / 24 = 0.024 I_0$$

Both these values for  $I_U$  are much less than  $I_0$ . Unfortunately, even if  $I$  is known it is too difficult to calculate the stiffness of a column whose value of  $I$  fluctuates greatly with height – falling by a factor of a hundred or more at each brick joint. So we can only predict that an unmortared column will be much less stiff - maybe 100 times less stiff - than a mortared one.

Response to the application of lateral forces to the top of a 20-course column was measured for 5 columns of indented bricks and 5 of grooved bricks. The average force to initiate toppling and the corresponding average of displacements  $x_{20}$  were calculated and their ratio was deemed to be the stiffness of the column.

**Table 7.1 Stiffness comparison between mortarless and mortared columns**

	Unit	Indented bricks	Grooved bricks	Ratio grooved/indented	Mortared bricks
Average force at failure	N	3.6	4.1	1.15	
Av deflection $x_{20}$ at failure	mm	12.3	7.2	0.58	
Stiffness	kN/m	0.29	0.57	2.0	255*

**NOTE:** \*Stiffness =  $3EI/H^3$  calculated using  $L=140$  mm;  $B=70$  mm; height  $H=980$  mm;  $E=10$  GPa (measured from experimental bricks);

Although grooved brick column demonstrates higher stiffness by a factor of 2 than indented brick column, but in general the unmortared column is less stiff compared with

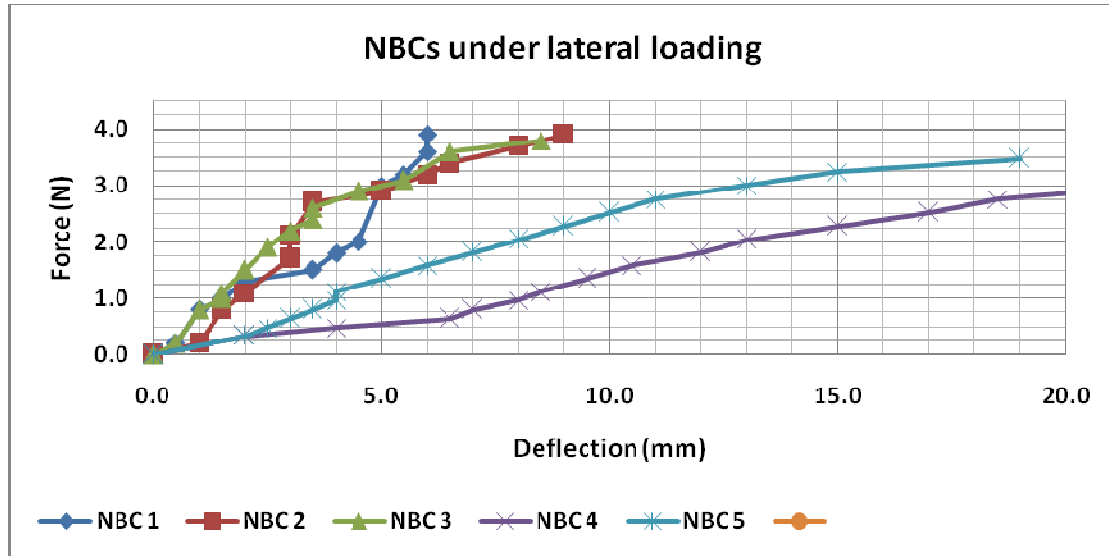
mortared by a factor of more than hundred times. This requires means of strengthening during construction as their vulnerable to very small lateral forces.

**Table 7.2 Normal brick column (NBC) stiffness test results**

S/No	NBC 1		NBC 2		NBC 3		NBC 4		NBC 5	
	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.5	0.2	1.0	0.2	0.5	0.2	2.0	0.3	2.0	0.3
3	1.0	0.8	1.5	0.8	1.0	0.8	4.0	0.5	2.5	0.5
4	1.5	1.0	2.0	1.1	1.5	1.0	6.5	0.6	3.0	0.6
5	2.0	1.3	3.0	1.7	1.5	1.1	7.0	0.8	3.5	0.8
6	3.5	1.5	3.0	2.1	2.0	1.5	8.0	1.0	4.0	1.0
7	4.0	1.8	3.5	2.7	2.5	1.9	8.5	1.1	4.0	1.1
8	4.5	2.0	5.0	2.9	3.0	2.2	9.5	1.4	5.0	1.4
9	5.0	3.0	6.0	3.2	3.5	2.4	10.5	1.6	6.0	1.6
10	5.5	3.2	6.5	3.4	3.5	2.6	12.0	1.8	7.0	1.8
11	6.0	3.6	8.0	3.7	4.5	2.9	13.0	2.0	8.0	2.0
12	6.0	3.9	9.0	3.9	5.5	3.1	15.0	2.3	9.0	2.3
13					6.5	3.6	17.0	2.5	10.0	2.5
14			Average at collapse		8.5	3.8	18.5	2.8	11.0	2.8
15			Deflection	Force			22.0	3.0	13.0	3.0
16			12.3	3.6					15.0	3.2
17			Stiffness	0.29N/mm					19.0	3.5

**NOTE:** Average deflection (at start of overturning) = 12.3mm; Average of corresponding lateral forces = 3.6N, so effective lateral stiffness of NBC at top of column = 290 kN/m (ranging widely from 136 kN/m to 650 kN/m) and Force to give 6mm deflection – see highlights table entries - for NBC (average of 5 columns = 2.5N)

**Graph 7.1 NBC stiffness test**



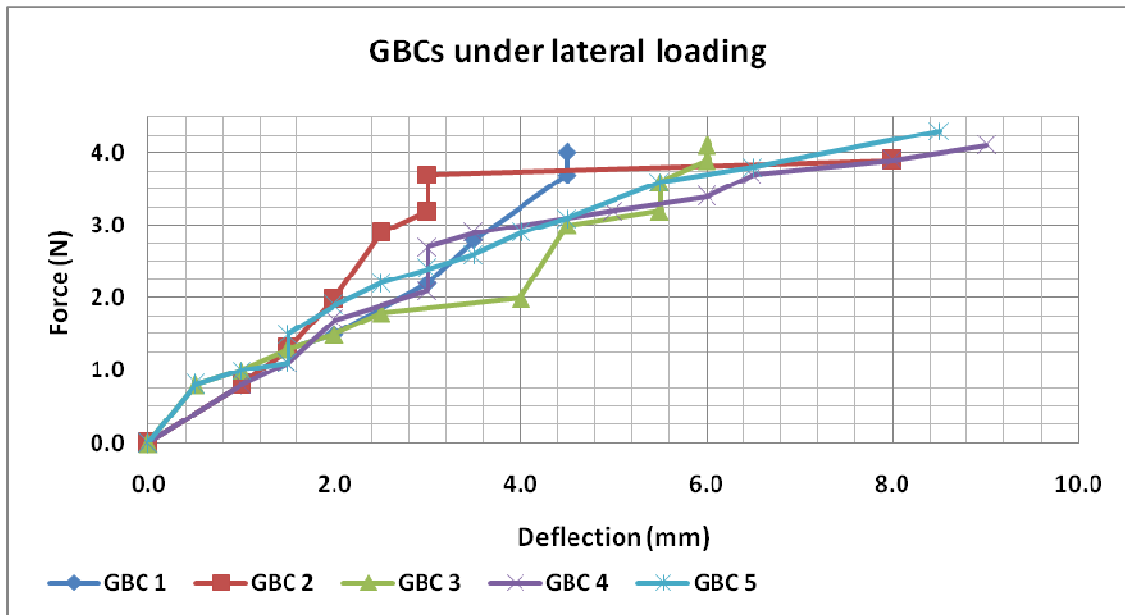
*NOTE: Normal brick columns (NBC) 1, 2, 3, 4 and 5*

**Table 7.3 Grooved brick columns (GBC) stiffness test results**

S/No	GBC 1		GBC 2		GBC 3		GBC 4		GBC 5	
	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)	Deflection mm	Force (N)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.0	0.8	1.0	0.8	0.5	0.8	1.0	0.8	0.5	0.8
3	1.5	1.3	1.5	1.3	1.0	1.0	1.5	1.1	1.0	1.0
4	2.0	1.5	2.0	2.0	1.5	1.3	2.0	1.7	1.5	1.1
5	3.0	2.2	2.5	2.9	2.0	1.5	3.0	2.1	1.5	1.5
6	3.5	2.8	3.0	3.2	2.5	1.8	3.0	2.7	2.0	1.9
7	4.5	3.7	3.0	3.7	4.0	2.0	3.5	2.9	2.5	2.2
8	4.5	4.0	8.0	3.9	4.5	3.0	5.0	3.2	3.0	2.4
9					5.5	3.2	6.0	3.4	3.5	2.6
10					5.5	3.6	6.5	3.7	4.0	2.9
11					6.0	3.9	8.0	3.9	4.5	3.1
12			Average at collapse		6.0	4.1	9.0	4.1	5.5	3.6
13			Deflection	Force					6.5	3.8
14			7.2	4.1					8.5	4.3
15			Stiffness	0.57N/mm						

*NOTE: Stiffness at threshold of tipping = 4.1N/7.2mm = 570 KN/m (ranging from 455 KN/m to 950 KN/m)*

Graph 7.2 GBC stiffness test



NOTE: Grooved brick columns (GBC) 1, 2, 3, 4 and 5

# CHAPTER 8

## 8.0 CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study were to; i) examine the performance of interlock bricks for the construction of walls, ii) identify patterns/bonds, joints and configurations, iii) develop remedial measures to reduce the effect of brick irregularities, iv) measure how brick imperfections affect dry-stack wall/column alignment accuracy and stability during construction. Below are the findings of the study.

### 8.1 INTERLOCK BRICKS' OPPORTUNITIES ENHANCED

A major weakness of Mortarless Technology (MT) using interlocking dry-stack bricks before this research began was its poor architectural and construction flexibility. MT could only be used for stretcher-bond walling with right-angled corners. The introduction of the developed new brick shapes has much improved the flexibility of interlock construction. A summary comparison of performance improvements for few major wall construction operations are shown in Table 4.3 and Figure 4.22 demonstrate level of performances between new development and available practice.



The development of the new part-bricks (centre-half bat - C $\frac{1}{2}$ B and closer - CL), enable the construction of most masonry wall joints. From Table 4.3 it is evident that the TIB system offers higher flexibility in the wall construction.

This study have demonstrated the increase in flexibility obtained by using a new part-brick (C $\frac{1}{2}$ B) and identified interlock specials (*tee and angle bricks*) with the potential to further increase the flexibility of interlock bricklaying. The contribution of the C $\frac{1}{2}$ B and CL to MT includes the formation of two new bonds (*Shokse and Lijuja Figures 4.9 and 4.14*). With these two bonds, it is now possible to build one-brick thick (e.g. 300mm) walls that can be used for foundations and other load-bearing structures like retaining walls. It is also possible to attach different sizes (*from 1-brick to 2-brick*) of piers to walls and build-isolated piers more than 1 $\frac{1}{2}$ -brick wide, which was not possible before. The uses of the two new brick shapes C $\frac{1}{2}$ B and CL will improve the craftsmanship quality of masons and simplify interlock bricklaying for most masonry joints.

The new interlock brick type examined in this study is of simple shape, designed to minimize weight yet maintain adequate web thickness/strength.

Although throughout this research the use of stabilised soil has been assumed, the main focus of the study was on brick shape design for the purpose of flexibility improvement. The proposed shapes may in fact be produced using any available and affordable material like burnt clay and sand-cement.

The bricks produced (at half scale) were used to physically test the applications of new centre-half bat, tee brick and closer units in the construction of various walls. The use of these three new bricks in unison with full bricks, half bats and three-quarter bats allowed construction of most joints, much faster, and more accurately than when using traditional

(mortared) bricks. The formation these two new bonds (Shokse and Lijuja) and therefore for the first time in the history of interlock bricks, it is possible to construct a double wall (full-brick thick wall). After the new developments, MT can be used for special load-bearing structures like retaining walls (to hold earth or rock etc.).

The introduction of angle bricks further extends the prospects for interlocking bricks in the building industry. Three types of angle bricks were proposed in the course of this research i.e. with 30, 45 and 60 degrees. The assemblies and fittings of angle bricks to assess the resemblance to other units were evaluated using SolidWorks programme (Figure 4.20).

We can conclude that the flexibility requirements on MT for wall construction can be fully met, which will further boost market opportunities of interlock bricks. The self-aligning characteristic of interlock bricks eases brick-laying, encourage the use of less-skilled manpower and realizing higher productivity. Apart from savings of material, MT saves time due to higher productivity resulting in an ultimate cost saving of around 50% *Whelan (1989), Hines (1993), Anand and Ramamurthy (2003)*.

## **8.2 MEASURES TO REDUCE BRICK IRREGULARITIES**

It is evident that the major cause of brick irregularities is poor curing. Curing conditions require proper control and close monitoring for effective performance. The types of physical brick irregularity analysed are warping and curvature of the faces. It was argued that irregularity can be reduced if proper curing (under a roof and or under the covering of plastic sheets, grass or any other materials) is performed. Further it was recommended

that brick producers should change their habit of placing bricks on end or face, however the bottom or top surfaces are the proper to be placed on curing floors for further improvement of brick surface flatness, and it is insisted that the curing floors shall be straight and flat, impermeable and clean.

### **8.3 DEFLECTION PREDICTIONS FOR WALLS & COLUMNS**

The investigation on the effect of brick imperfections on column alignment accuracy required three research methods namely theory, physical testing and simulation.

#### **Theory**

Theory analysed three cases: bricks (a) with parallel top and bottom surfaces but not square front/back and (b) with square front/back surfaces but non-parallel top and bottom surfaces were compared. The former were found to generate much straighter walls, so during manufacture concentration on minimizing 'roll wedge angle' is strongly recommended (roll wedge angle is the angle between top and bottom surfaces as measured perpendicular to the brick front face).

Bricks with randomly varying surfaces were given particular attention throughout this research. The theoretical analysis used probability relations to formulate an equation ( $\sigma_{xN} = 0.577 * H * \sigma_{\gamma} * N^{1.5}$ ) that allows prediction of column lean (standard deviation of column deflections at any height -  $N^{\text{th}}$  course) from the statistics of brick imperfection (standard deviation of displacement of top and bottom surfaces in relation with a perfect cuboids).

### **Confirmation of theory**

Theory indicated that for a randomly laid column, the SD of out-of-plumb deviations of a particular course  $\sigma_{x,N}$  is proportional to the SD of roll wedge angle  $\sigma_\gamma$  and rises with column height to the power 1.5. Experiments with grooved bricks (which interface roughly in the manner assumed in the theory) showed  $\sigma_{x,N}$  rising with  $N$  to the power 1.46 and thereby confirmed the theory. Computer simulations confirmed that this relationship extends to columns higher than could practically be built. However for a given course number  $N$ , the practical columns showed a 54% higher out-of-plumb deviations (as computed by  $\sigma_{x,N}$ ) than theory predicted, indicating that the model of brick-to-brick contact used in the theory was oversimplified. Remodelling this contact (effectively by changing the way in which roll wedge angle is to be measured by determining average spacing  $D$  for grooved and ungrooved) brought the practical and theoretical results in closer agreement. In addition,  $\chi^2$  analysis also showed that the small sample size (30) for practical columns would give estimates for  $\sigma_{x,N}$  with considerable statistical uncertainty. The simulations confirmed the proportionality between deflection and roll-wedge SDs (respectively  $\sigma_{x,N}$  and  $\sigma_\gamma$ ).

### **Corrections for small brick-pile population**

It was observed that when the brick pile size (from which the brick set to build sample columns was selected) were small, the deviations  $\sigma_{x,N}$  were reduced. A correction factor  $K_\lambda$  was developed, by randomized simulation studies, to convert deviations measured for small brick pile into deviations expected when bricks are drawn from a large brick pile.

Defining  $\lambda$  as the ratio of brick-pile size to column brick-set enough to assemble one column (height),  $K_z$  was found to fall from 1.9 at  $\lambda = 1$  to unity for  $\lambda > 20$ .

### **Effect of laying strategy (and brick-laying skill)**

This research demonstrated various possible ways of improving column/wall alignment from the inferior bricklaying ('random' strategy) related to unskilled bricklaying, through 'reverse' and 'replace' strategies (skilled way of bricklaying) and the use of modified (grooved) bricks.

Using 'reverse' strategy reduced the column out-of-plumb deviation to only 62% of that observed with 'random' laying. Using a more attentive but slower 'replace' strategy, that allowed the replacing of any brick with a better second choice from the stock, further reduced the column deflection to 35% of the random value.

Another improvement from a different method other than laying strategy was the provision of a groove to prevent bricks making contact near their centre lines. Although with grooved bricks only assemblies using the random brick-laying strategy were built, it demonstrated that the out-of-plumb deviation was reduced to 49% of the value obtained with un-grooved bricks laid using the same "random" strategy.

Assuming the benefit of more-skilled bricklaying and grooving can be superimposed, then the best (grooving and replacing) would give column deviations of only 49% x 35% = 17% of the worst case (un-grooved, random-laid column). This is an improvement of 83%.

Moving from column to wall assemblies was a step further to enhance alignment using the same bricks. Walls of ten un-grooved bricks long and twenty courses high were

constructed using the ‘random’ laying strategy. The longitudinal overlapping of the walls’ bricks was found to produce a reduction in wall out-of-plumb deviation to 45% of that of columns assembled using the same laying strategy.

So if a superior strategy (‘reverse’) were combined with grooving of bricks and applied to a *wall* assembly; we could expect the wall deflection to fall to 14% ( $62\% \times 49\% \times 45\%$ ), of the random-un-grooved-column deflections taken as our datum (worst case). This is an overall improvement of 86%.

### **Lateral stiffness of columns**

Dry-stack columns demonstrate hinging and rocking mechanisms. Observations showed improvements to lateral stiffness by factor of 2 are obtainable by grooving to prevent inter-brick contact near the roll centreline. The out-of-plumb deviations were reduced by the factor of 2. From the benefits of grooving both on stiffness and on accuracy, we can recommend that all MT brick designs should be designed to prevent rocking contacts by at least groove  $G = 70\% W$ .

### **Extension from column to wall**

The factor by which walls are less variable than columns of the same height (reduction factor for  $\sigma_{x,N}$ ) – and the dependence of that factor on *distance* to constraints (cross walls, reinforced columns or corners) and *type* of constraint were all examined. All wall data is derived from experiments with un-grooved bricks, but we expect similar column-to-wall improvement factors to apply to grooved bricks. The specification of brick tolerances needed to meet defined out-of-plumb tolerances (BS 5628-3:2005;

BS5606:1990) for walls was calculated. It was found that with grooved bricks we may accept a surface (bumps) standard deviation of up to 0.8mm. With un-grooved bricks we require greater brick uniformity, namely a surface SD of under 0.5mm.

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## **8.4 AREAS FOR FURTHER RESEARCH**

Most experiments in this research were performed for the first time, therefore resulted into primary findings which necessitate more practical for perfections. These verdicts however enlightened a number of prospective matters for future research. The following are the areas for further research that were not possible to undertake within this study.

- A feasibility study to be performed for practical implementation of the research findings, to extend and perfect the construction flexibility performance described in this thesis.
- Further work required to incorporate special interlock bricks for mortarless technology to ease building of complicated wall configurations as suggested by this research.
- Investigations of the appropriate and simple methods for measuring surface imperfections of dry-stack interlock bricks as a quality control measure.
- Burglar resistance test for dry-stack interlocking brick wall is necessary to enhance trust of most clients not believing in mortarless technology.
- A long term study for interlock wall strength following lifetime disturbances to be performed on the local movements: of foundations, mechanical shocks (due to door slamming) and major shocks (caused by earthquakes).

# REFERENCES

**ACI-ASCE Committee 530 (1988)** “*Building Code Requirements for Masonry Structures (ACI 530-88/ASCE 5-88)*”, ACI, Michigan, U.S.A., 18pages.

**Adam, E.A. and Agib, A.R.A., (2001).** “*Compressed Stabilised Earth Blocks manufactured in Sudan.*” United Nations Education Scientific and Cultural Organization (UNESCO). 7 Place de fontenoy, 75352 Paris 07 SP, France.

**Adamus, L. and Spevak, V. (1986)** “*Dry stone walling technology-manufacturing and using building blocks without mortar*”. Proc., 10<sup>th</sup> Triennial Congress of Int. Council for building Research, Studies and Documentation, Washington, D.C., 27090-2716.

**Anand KB & Ramamurthy K. (2003).** *Laboratory-based productivity study on alternative masonry systems.* ASCE Journal of Construction Engineering and Management: 129(3): 237–242.

**ASTM C90-75 (1975).** *Standard Specification for hollow load-bearing concrete masonry.*

**Basu, A.R., (1988),** *Urban Housing in third World,* Delhi, India: Mittal Publications.

**BCA (2007)** British Cement Association, *Cement Industry Sets out its Work to help Climate Change,* Thursday, 12 April, 12:34



**Beall C. (2000).** *New masonry products, materials.* Progress in Structural Engineering and Materials 2: 296–303.

**BRU-B2 (1974)** *Soil-Stabilizations*, building Research Unit data sheet, Ministry of Lands, Housing and Urban Development's. Dar Es Salaam, Tanzania.

**British Standards Institution. (1971).** BS 12: 1971: *Specifications for Portland cement (ordinary and rapid hardening)* BSI, London, England.

**British Standards Institution. (1981).** BS 6073: 1981: *Precast concrete masonry units – Part 1: Specification for precast concrete masonry units.* BSI. London, England. ISBN 0 580 121895

**British Standards Institution. (1985).** BS 6649: 1985: *Specification for Clay and calcium silicate modular bricks.* BSI. London, England. ISBN 0 580 14641 3.

**British Standards Institution. (1990).** BS 1377: Part 2: 1990: *Method of test for soils for civil engineering purposes. Part 2 Classification test.* BSI. London, England

**British Standards Institution. (1990).** BS1924: Part 1: 1990. *Stabilised materials for civil engineering purposes. Part 1. General requirements, sampling, sample preparation and tests on materials before stabilization.* BSI. London, England.

**British Standards Institution. (1990).** BS 4729: 1990. *Specification for 'Dimensions of bricks of special shapes and sizes'* BSI. London, England. ISBN 0 580 17952 2.

**British Standards Institution. (1990).** BS 5606: 1990: *Guide to Accuracy in Building*. BSI. London, England. ISBN 0 580 18657 1.

**British Standards Institution. (1990).** BS 7307-1: 1990 (ISO 7976-1: 1989): *Building tolerances- measurement of buildings and building products*. BSI. London, England. ISBN 0 580 18490 0.

**British Standards Institution. (1997).** BS 5328-1: 1997: *Concrete – Part 1: Guide to specifying concrete*. British Standard Institution, BSI. London, England. ISBN 0 580 26722 9.

**British Standards Institution. (1997).** BS ISO 1803: 1997: *Building construction. Tolerances. Expression of dimensional accuracy Principales and Technology*. British Standard/International Organization Standardization/15-Feb-1998/16pages. ISBN 0 580 29203 7.

**British Standards Institution. (2000).** BS EN 206-1: 2000: *Concrete: Part 1: Specifications, Performance, Production and Conformity*. BSI. London, England.

**British Standards Institution. (2000).** BS EN 772-1: 2000: *Methods of test for masonry units- Part 1: Determination of compressive strength*. BSI. London, England. ISBN 0.580 32726 4.

**BS EN 772-20:2000.** *Methods of tests for Masonry Units. Determination of flatness of faces of masonry units*. BSI. London, England.

**British Standards Institution. (2001).** BS 8000-3: 2001: *Workmanship on building sites – Part 3: Code of practice for masonry*. BSI. London, England. ISBN 0 580 33301 9.

**British Standards Institution. (2003).** BS EN 771-3: 2003: *Specification for masonry units- Part 3: Aggregate masonry units (dense and light-weight aggregates)*. BSI. London, England. ISBN 0580 43559 8.

**British Standards Institution. (2005).** BS 4729: 2005: *Clay and calcium silicate bricks of special shapes and sizes – recommendations*. BSI. London, England. ISBN 0 580 46694 9.

**British Standards Institution. (2005).** BS 5628-1: 2005: *Code of practice for the use of masonry – Part 1: Structural use of unreinforced masonry*. BSI. London, England. ISBN 0 580 46718 X.

**British Standards Institution. (2005).** BS 5628-3: 2005: *Code of practice for the use of masonry – Part 3: Materials and components, design and workmanship*. BSI. London, England. ISBN 0 580 46682 5.

**British Standards Institution. (2005).** BS 8103-2: 2005: *Structural design of low rise buildings – Part 2: Code of practice for masonry wall for housing*. BSI. London, England. BSI 14 March 2005 Second edition, ISBN 0 580 45463 0.

**British Standards Institution. (2006).** BS 8500-1: 2006: *Concrete: Complementary British Standard to BS EN 206-1 Specification for Constituent Materials and Concrete*. British Standard Institution 30-Nov-2006, 146 pages. ISBN 058 0482529.

**Burroughs, V.S. (2001).** *Quantitative criteria for the selection of soils for rammed earth wall construction*. Thesis presented at the Faculty of built environment, University of New South Wales, Australia.

**California Test 228 (2000).** *Method of test for linear shrinkage of soils (bar method).* Department of transportation, Engineering service centre. Transportation Laboratory, P.O.Box 19128, Sacramento, California 95819.

**CAN3-S304-M84, (1984)** Canadian Standard Association, “*Masonry Design for Buildings*, CSA, Ontario, Canada, 69pages.

**CML - TLM1999, (2000).** Central Material Laboratory, *Testing Laboratory Manual*, Ministry of Works (MoW), Dar Es Salaam, Tanzania

**Co-Create working document (2004).** *Protocol on Appropriate Technologies for Water and Sanitation a definition of the basic characteristics*, Co-Create international business development, The Hague, Netherlands ([www.co.create.nl](http://www.co.create.nl))

**Collins (1995),** *Paperback English Dictionary, Major New Edition.* HarperCollins Publisher, Caledonian International Book Manufacturing Ltd. Glasgow G64, Great Britain. ISBN 0 00 470780-X

**Craig, R.F., (1997)** *Soil Mechanics*, E & FN Spon, London, England.

**Crofts FS. (1993)** State of the art of mortarless concrete masonry in South Africa. *Proceedings of the 6th North American Masonry Conference*, Pennsylvania Philadelphia, June 6-9, vl.1 or 2, pp. 875–884. ISSN/ISSN 1053-2366.

**Drysdale R. G. and Gazzola E. A. (1991).** Strength and deformation properties of a grouted, dry-stacked, Interlocking Concrete Block System. *Proceedings of the 9th International Brick/Block Masonry Conference, Berlin*, pp. 164–171.

**Dyskin, A.V. Estrin, Y. Pasternak, E. Khor H.C. and Kanel-Belov, A.J. (2003).** *Fracture resistant structures based on topological interlocking with non-planar contacts*, *Advanced Engineering Materials* 5 (3), pp. 116–119.

**Dyskin, A.V. Estrin, Y. Pasternak, E. Khor H.C. and Kanel-Belov, A.J. (2005).** *The principle of topological interlocking in extraterrestrial construction*, *Acta Astronautica* 57, 10-21

**Eco-towns (2008)** *Living a green future, Communities and Local Government Eland House, Bressenden Place, London SW1E 5DU. Tel. 020 7944 4400, Website: [www.communities.go.uk](http://www.communities.go.uk)* © Queens Printer and Controller her Majesty's Stationary Office.

**Estrin, Y., Dyskin, A.V., Kanel-Belov A.J. and Pasternak, E. (2002).** *Materials with novel architectonics assemblies of interlocked elements*. B. L. Karihaloo (Ed), *IUTAM Symposium on Analytical and Computational Fracture Mechanics of Non-homogeneous Materials*, 51-55 Kluwer Academic Publishers, Dordrecht, pp. 51–56. ISBN/ISSN 1402005105

**Etherington BA. (1983)** *Interlocking cement and concrete components for low cost house construction: The building together experience in Thailand. Proceedings of the Symposium on Appropriate Building Materials for Low-cost Housing*, Nairobi, 236–243. ISBN/ISSN: 0419132805

- Gallegos, H. (1988).** *Mortarless masonry: the Mecano system*. International Journal of Housing Science and its Applications V12, No. 2, 145–157.  
ISBN/ISSN: 0146-6518
- Gazzola EA & Drysdale RG. (1989).** Strength and deformation properties of dry-stacked surface bonded low density block masonry. *Proceedings of the 5<sup>th</sup> Canadian Masonry Symposium, Vancouver 5-7* Vol. 5, pp. 609–618.
- Gilbert A, & Gugler, J. (1992).** *Cities, Poverty, and Development: Urbanization in the third World*, Oxford: Oxford University Press.
- Gilroy, D. Goffi, E.D. (2001).** *Modular interlocking brick system in wide use at BHP*, AISE Steel Technology, January.
- Gooding, D.E.M. (1993).** *Soil Testing for Soil-Cement Block Preparation*. Working Paper No. 38. Development Technology Unit, University of Warwick. Coventry. England.
- Gooding, D.E.M. (1994).** *Improved Processes for Production Soil-Cement Building Blocks*. Development Technology Unit, University of Warwick. Coventry. England.
- Grimm, C.T., (1974)** *Masonry Construction Operations*, Journal of the Construction divisions, ASCE Vol. 100, No. CO2 – pgs 71-185
- Haener. (1984).** *Stacking mortarless block system*. In Engineering Design Manual, Atkinson Engineering, Inc., Hamilton, Ontario, 1984.
- Hamdi, N. (1995).** *Housing without Houses: Participation, Flexibility, and Enablement*. Intermediate Technology Publications. London, England.

**Harlae, M. and Marten, M. (1990).** *New Ideas for Housing: The experience of three countries.* London, Shelter.

**Harris H. G., Oh K. and Hamid A. A. (1992).** Development of new interlocking and mortarless block masonry units for efficient building systems. *Proceedings of the 6th Canadian Masonry Symposium, Saskatoon Saskatchewan, Canada*, pp. 15–17.

**Hendry, A. W., Sinha, B. P., Davis, S. R. (1997).** *Design of Masonry Structures.* London: E & F.N. Spon

**Hines, T (1992).** The use of mortarless, dry-stack, concrete masonry as a contributor to affordable construction. *Proceedings of the 4th International Seminar on Structural Masonry for Developing Countries, Madras*, 176–186.

**Hines, T (1993).** Benefits of dry-stack interlocking concrete masonry as a component of cost effective construction. *Proceedings of the 6th North American Masonry Conference, Philadelphia*, 849–861.

**Houben, H. Guillaud, H. (1994).** *Earth Construction: A Comprehensive Guide.* CRATerre – EAG. Intermediate Technology Publications. London, England.

**Housing Forum, (2001),** *The Green Guide to Housing Specification – Six Guiding Principles to Improve the Sustainability of the Housing Construction Industry.* July Issue

**Hydraform (1988).** *Illustrations of the Hydraform Building System,* Hydraform Africa (Pty) Limited, Johannesburg, South Africa.

**Hydraform, (2004).** *Hydraform Training Manual*. Johannesburg 220  
Rondebult road, Libradene boksburt. P.O.Box 17570, Sunward park 1470.  
([www.hydraform.com](http://www.hydraform.com))

**IGPCC (2001).** Intergovernmental Panel on Climate Change: *Special report on Emissions*. <http://www.grida.no/climate>

**ILO, (1987).** *Small - Scale Manufacture of Stabilised Soil Blocks*. International Labour Organization Office, Geneva, Switzerland.

**International Labour Organization, (1990).** *Small-scale Brick Making*: Technical Memorandum No. 6. Technology Series, International Labour Office. Geneva, Switzerland.

**Jaafar M. S., Thanoon W. A., Najm A. M., Abdulkadir M. R. and ALI A. A. (2006).** *Strength correlation between individual block, prism and basic wall panel for load bearing interlocking mortarless hollow block masonry*. *Construction and Building Materials*, 20, No. 7, 492–498.

**Jaafar, M.S. Alwathaf, A.H Thanoon, W.A Noorzai, J. Abdulkadir, M.R.(2006)** *Behaviour of interlocking mortarless block masonry, Proceedings of Institute of Engineering*, *Construction Materials* 159 August, Issue CM3 pp. 111-117.

**Keef L. (2005)** *Earth Building “Methods and Materials, Repair and Conservation”*. Taylor and Francis, 2 Park Square, Milton, Abington, Oxon OX14 4RN. ISBN 0-415-32322-3.

**Kerali, A.G., (2001),** *Durability of Compressed and Cement-Stabilised Building Blocks*. PhD. Thesis, University of Warwick – School of Engineering.



**Kintingu, S.H. (2003).** *Interlocking Bricks Presser Machine an Appropriate Technology for Brick Production.* Construction Industry Forum proceedings pgs. 51 - 67. – Dar es Salaam. Tanzania.

**Knight, T. (1997).** On behalf of the Brick Development Association. *Creative Brick work.* By Arnold, 338 Euston Road, London NW1 3BH. ISBN 0 340 67643 4.

**Kruse, C. (2004)** International Investors Group on Climate Change (IIGCC) *Brief Note, Climate Change and the Construction Sector,* ISIS Asset Management.

**Kua, H., Lee, S., (2001),** *Demonstration Intelligent Building – A methodology for the Promotion of Total Sustainability in the built Environment.* Building and Environment

**Laquian, A, A. (1983).** *Basic Housing: Policies for Urban sites, Services and shelter in Developing Countries.* IDRC–708C. Ottawa, Canada

**Lea, F.M. (1976).** *The chemistry of cement and concrete.* 3<sup>rd</sup> Edition. Edward Anorld (Pblishers) Limited. London, England.

**Love, B and Gamble, J. (1985).** *The Meccano System and the Special Purpose Meccano sets,* New Cvendish books, London.

**Lynch, G. (1994).** *Brickwork Volume 1; History, Technology and Practice, Vol.1.* London, Donhead Publishing ltd. 28 Southdean Garden, Wimbledon, London SW19 6NU. ISBN 1 8733 940 20.

- Maasdorp, G.G. and Humphreys, A.S.B. (1975).** *From Shantytown to township: an economic study of African poverty and rehousing in a South African City*, Cape Town: Juta.
- Maniatidis, V. & Walker, P. (2003).** *A Review of Rammed Earth Construction for DTI Partners in Innovation Project 'Developing Rammed Earth for UK Housing'*. Natural Building Technology Group, Department of Architecture & Civil Engineering, University of Bath, Bath BA2 7AY.
- Marchal, G. (2001).** 'Decreasing Pollution,' cement and Building Materials Review 3, (AUCBM).
- Marzahn G. (1998).** *The shear strength of dry-stacked masonry walls*. Leipzig Annual Civil Engineering Report, (3), 247–262.
- Marzahn G. (1999).** *Investigation on the initial settlement of dry-stacked masonry under compression*. Leipzig Annual Civil Engineering Report: 4: 253–269. ISBN/ISSN: 1432-6590
- Marzahn, G. and G. König (2002).** *Experimental Investigation of Long-Term Behavior of Dry-Stacked Masonry*, Journal of the Masonry Society, December, pp. 9-21.
- McAuslan, P., (1985),** *Urban Land and Shelter for the Poor*. London: Earthscan.
- McGinley. (1995)** *Development of dry stacked clay masonry wall systems*. Proceedings of the 7th Canadian Masonry Symposium, Hamilton, 147–159.
- McKusick, M. (1997).** *Discavaring Late Erector 1963-1988*, Ashton Press, Iowa City.

- Montgomery, D.E., (2002).** *Dynamically Compacted Cement-Stabilised Soil Blocks for Low-cost Walling*. PhD. Thesis, University of Warwick – School of Engineering.
- Morris, J. Booyesen, Q. (2000).** Earth Construction in Africa. *Proceedings: Strategies for a Sustainable Built Environment, Pretoria, 23-25 August 2000*.
- Moustafa, M.E. (1990).** *Management of technology transfer*. International Labour Organization, Geneva, Switzerland.
- Nash, W.G. (1983).** *Brickwork 1*, Third Edition reprinted 2001 by Nelson Thornes Ltd, Delta Place 27 Bath Road, Cheltenham GL53 7TH United Kingdom. ISBN 0 7487 0266 0.
- Nash, W.G. (1991).** *Construction Competences for NVQ level 2, Bricklaying*. Nelson Thornes Ltd, Delta Place 27 Bath Road, Cheltenham GL53 7TH, United Kingdom. ISBN 0 7487 1292 5.
- NCMA TEK 14-22 Structural (2003).** “*Design and construction of dry-stack masonry walls*”, National Concrete Masonry Association 2302 Horse Pen Road, Herndon, Virginia 20171 – 3499 ([www.ncma.org](http://www.ncma.org)).
- Norton, J., (1997).** *Building with Earth: A handbook*. London: Intermediate Technology.
- Odul, (1984).** *Case Studies on Earth Construction: Synthesis*. PDC-HS. Katholieke Universiteit Leuven, Belgium.
- Ophoven, P. (1977).** *Compressive strength of walls built up of mud-blocks and soil cement-blocks*. Building Research Unit, Ministry of Lands, Housing and Urban Development, Dar Es Salaam, Tanzania.

**Racodi, C. (1997).** *The urban challenge in Africa – Growth and management of its large Cities* – UNUP – 952.

**Ramamurthy, K. and Nambiar, E.K. (2004).** *Accelerated masonry construction: Review and future prospects.* Proceedings of Structural Engineering materials (2004); 6:1-9 (DOI: 10.1002/pse.162)

**Ruth, M., Price, L., Worrell, E. (2000).** *Evaluating Clean Development Mechanism Projects in the Cement Industry using Process-Step Benchmarking Approach*, Report No. LBNL 45346 Lawrence Berkeley National Laboratory US.

**SAA (1977)** “*Methods of testing soils for engineering purposes*”, Standard Association of Australia, Australian Standard 1289.

**Sanders, S.R. Thomas, R.H. (1991).** *Factors affecting masonry labor productivity*, Journal of construction Engineering Management 1991, Vol.117 N4, pp.626-644. ISBN/ISSN: 0733-9364.

**Shrive, N. Bakay, R. Scholefield, B. (2003).** *AB fence executive summary for structural testing.* University of Galgarry (alanblock.com).

**Spence, R.J.S, Cook, D.J. (1983).** *Building Materials in Developing Countries.* John Wiley & Sons Ltd. Chichester, England.

**Stewart, F. (1987).** *Macro-policies for Appropriate Technology in Developing Countries.* Westview Press, Boulder, CO, USA.

**Stulz, R., Mukerji, R. (1993).** *Appropriate Building Materials: a catalogue of potential solutions.* St. Gallen: Skat.

**Thanoon W. A., Jaafar M. S., Abdulkadir M. R., Ali A. A., Trikha D. N. and Najm A. M. (2004).** *Development of an innovative interlocking load bearing hollow block system in Malaysia.* *Construction and Building Materials*, 18, No. 6, 445–454.

**The BDA Guide, (2000).** *The Brick Development Association Guide to successful brickwork*, second edition. Elsevier Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford OX2 8DP, 30 Corporate Drive, Burlington, MA 01803. ISBN 0 340 75899 6.

**The Guardian (2006).** Article History, June 11. The Guardian.co.uk

**UN. (1992).** “*Earth Construction Technology*” United Nations Centre for Human Settlements, Nairobi.

**URT – NHSDP (2000).** United Republic of Tanzania, National Human Settlements Development Policy. Ministry of Lands and Human Settlements Developments (MLHSD), Dar es Salaam, Tanzania.

**VanderBorgh, B. and Brodman, U. (2001).** *The Cement CO<sub>2</sub> Protocol: CO<sub>2</sub> Emission Monitoring and Reporting, Protocol for the Cement Industry, Guide to the Protocol, Version 1.6.* WBCSD Working Group Cement.

**VanderWerf P., Munsel, W. (1999).** *Concrete Home Building Systems*, the Portland Cement Associations Guide.

**Vasco Costa, F. (1993)** Plea for placement armour blocks in orderly patterns, *Proceedings of the 23rd International Conference on Coastal Engineering* October 4–9, 1992, Venice, Italy pp. 1091–1100. ISBN/ISSN: 0872-62933

**VITA (1975).** *“Making building blocks with the CINVA-Ram block press”*, Volunteers in Technical Assistance, Intermediate Technology Publications, London.

**Walker, P. (1995).** *Performance of Stabilised Soil Block Masonry under Uniform and Concentrated Compressive Loading*. Proceedings British Masonry Society Vol. 7 pgs 49-57 ISBN/ISSN 0950-9615.

**Webb, D.T.J. (1983).** *Stabilised Soil Construction in Kenya*. Proceedings of the International Conference on Economic Housing in Developing Countries, UNESCO/RILEM, 25-27 January 1983, Paris, France.

**Webb, D.T.J., Lockwood, A.J. (1987).** *BREPAK Operators Manual*. Overseas Development Administration. Building Research Establishment Client Report. Department of the Environment. Garston, England.

**Weinhuber, K., (1995).** *Building with Interlocking Blocks*. Published by GATE.

**Whelan M.L. (1985).** *Hollow concrete masonry unit shape modification to improve productivity of placement: results of the preliminary research effort*. Proceedings of the 3rd North American Masonry Conference, Arlington, Texas, 1985, Vol.9.1–9. ISBN/ISSN: 1053-2366.

**Wolfskill, L.A., Dunlap, W., & Gallaway, B.M. (1963).** *“Handbook for building homes of earth”* , Texas Transportation Institute, Report for the Agency for International Development, Bulletin 21, E 14-63, Texas A&M University, College Station, Texas.

**World Bank, (1995).** *Labor and growth Crisis in Sub-Sahara Africa,*  
Washington, D.C.