Energy & Low-income Tropical Housing

On Mortarless Masonry Walling

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Abstract

Mortarless masonry walling is potentially cheaper and less energy-intensive than mortared walling and is in use for low-income tropical housing. The saving is because mortar costs more, and entails more CO_2 emissions, per litre than do masonry units (blocks or bricks) and its absence reduces the labour cost of laying. These savings, when using (interlocked) stabilised-soil blocks, lie in the range 10-30%. However mortarless walling has inferior performance with respect to straightness, crushing strength, resistance to lateral loads and lateral stiffness. Moreover to provide a fully sealed building envelope, a mortarless wall needs plastering on at least one side. To achieve satisfactory straightness over a 2.5 meter height, block contact surfaces should be parallel within 0.5 degrees, be cleaned and be grooved to prevent contact close to their centre line. Unless blocks are very precise, the interlock pattern should permit block-reversal during construction. Crushing strength is less (typically by a factor of 5) and lateral stiffness is much less than for a mortared wall: in both cases performance is much improved by the same measures as improve straightness, because these also increase the effective block-to-block contact area from typically 5% to 25% of block plan area. Mortarless walling is quite widely used in Africa, but even with accurate motorised presses, blocks cannot be stacked more than 3 meters high without insertion of mortared courses or ring beams.

Contents

1. Purpose of this article

To identify the advantages and problems associated with mortarless brick or block walling in tropical countries and to identify its scope for reducing the carbon footprint and cost of low-income tropical housing.

2. Masonry and mortar

'Masonry' - building with small, easily handled and interchangeable units – such as bricks or blocks – has several advantages. No large lifting gear, nor complex shuttering or formwork, is needed. The individual units can easily be given treatments prior to their assembly, such as firing or compression, to enhance their strength or durability, treatments hardly possible with a wall formed in situ from raw materials. Interesting patterns can be created using varied bricks styles. Masonry is usually assembled with the aid of mortar.

There is however, in many developing countries, the practice of using mortarless masonry - driven by the belief that omitting mortar in walling reduces both material and labour costs. The omission of mortar however reduces performance in various ways. The purpose of this article is to explore how real are the supposed savings and how easily that reduction in performance can be tolerated or can be ameliorated by other techniques than mortaring. The advantages of masonry itself – i.e. of assembling fairly small units rather than forming large units on site or in factory – will however not be addressed.

A mortar mix – of suitable performance – is generally more expensive per litre than the masonry units it connects, whether the units be mud blocks, fired bricks, hollow cement blocks or stone. (Through the rest of this article the word 'block' will be normally used for a masonry unit regardless of that unit's size or composition: thus 'block' includes both brick and cut stone.) So the materials for dry (= mortarless) assembly will usually cost less per unit of wall volume than the materials of a mortared wall. The cheaper the blocks, the more marked the savings, so cement-mortar is least used in mud building or for field walls assembled from field-gathered uncut stones. In both cases the cheapness of the blocks allows the use of big wall thicknesses and maybe a marked wall taper. Block-laying is a highly developed skill in some cultures and mortaring is done at considerable speed. But there are scenarios such as self-built and community-built housing where mortaring skills and speeds will be low: here there may be substantial *time* savings from employing mortarless construction.

Table 1 lists the functions that mortar normally performs in masonry.

Table 1 The primary functions of mortar in masonry walling

i	Providing adhesion in shear, so preventing deliberate or accidental 'punch-through' of individual units
ii	Allowing adjustment during assembly so that walls can be built plumb, and with straight courses, despite any irregularity in the blocks
iii	Cushioning vertical loads, spreading inter-block contact over a greater area and

	thereby achieve higher crushing strength, Euler buckling strength and lateral stiffness
iv	Sealing the building envelope against penetration of light, sound, dust, wind or water
v	Combatting vermin and plant growth
vi	Improving the appearance of walling

These then are the performance features that mortarless walling must achieve by 'other means' or which must be sacrificed.

Some alternatives to mortaring, several of which are discussed in the following sections, include:

- Interlocking to restrict relative movement of units perpendicular to the wall face (and in some cases movement along the course)
- Using bricks of such accuracy that the airgaps between them are very narrow and their 'dry' assembly produces walls of adequate verticality.
- Injecting a very fine mortar substitute *after* assembling the brick/blocks.
- Using a thin surface render and/or internal plaster to hold the wall together and wind-seal any gaps.
- Designing the brick so its connection to the bricks below and above is so restricted that 'rocking' is prevented
- Having the bricklayer place each brick/block speculatively firstly direct and then reversed, then choosing the orientation giving the straighter wall.
- Periodically inserting a mortar layer, lintel or wall-beam to 'reset' the wall straightness.

3. Advantages of mortarless masonry

Two principal savings from omitting mortar were listed above – cheaper materials and faster assembly. There are also some minor possible savings – for example the omission of mortar in the perpends of engineering bricks allows their use for damp-courses. Where lime-rich mortars are eroded by snails or atmospheric acids, their omission may significantly reduce long-term maintenance costs.

Consider two walls of identical thickness and face area, made of blocks whose individual faces measure *L x H*, one wall without mortar and the other with either 20mm of cementitious mortar ("thick") or 8mm ("thin"). 8 to 25mm represents the typical range for African housing, in Europe the upper bound is only about 16mm. The volumetric unit-cost ratio of mortar material to block material we can call 'μ'. μ=2 is representative of mortar combined with hollow cement blocks; μ=5 of mortar combined with stabilised soil blocks or with low-quality fired 'country' bricks; μ=10 of mortared but unstabilised pressed-earth blocks. Table 2 below shows a range of typical cost savings for 300mm blocks and 200mm bricks. In the table, the fraction of the wall that is mortar ranges from 12% to 33%. (In the field, fractions as high as

50% may be observed in e.g. Uganda.) In every case the saving is significant enough to be worth pursuing and in a few cases the cost of the cement in the mortar totally dominates overall walling costs. Cost reduction is also correlated with reduction in 'embodied carbon' - a label for greenhouse-gas emissions before and during construction – because the production of cement is emissions-intensive.

Neglecting labour-time savings, the fractional cost savings due to omitting mortar from brick (or block) walling equals

S_c = (*cost per unit of wall volume with mortar – cost without mortar*)/*cost with mortar*

$= \lambda_m (\mu-1) / (1 + \lambda_m (\mu-1))$

where μ is defined above and fraction λ_m of the wall face area is mortar. λ_m depends upon the brick-mortar geometry. It can be expressed as

$\lambda_m = A_m / (A_m+A_b)$ where A_m *and* A_b are wall-face areas of mortar and brick respectively

$A_m=(L+h+t).t$ and $A_b= L.h$; where *t* is mortar thickness, *L* and *h* are the face length and height of the brick face.

Table 2 Materials cost savings by omitting mortar

These savings are independent of wall thickness, which would typically be 150mm for a wall of blocks, 100 mm for a single stretcher-bond, fired-brick wall and 200 mm for header-bond or double stretcher-bond brick.

Block length L	Block height H	Mortar thickness t	Mortar fraction of wall vol'm	Assumed volumetric cost ratio mortar:block	Wall cost ratio mortared :	Wall cost saving if no mortar
mm	Mm	mm	λ	μ	unmortared	%
300	100	thick (25)	0.26	2	1.26	21
300	100	thin (10)	0.12	2	1.12	11
200	75	thick	0.33	2	1.33	25
200	75	thin	0.16	2	1.16	14
300	100	thick	0.26	5	2.05	51
300	100	thin	0.12	5	1.48	32
200	75	thick	0.33	5	2.33	57
200	75	thin	0.16	5	1.64	39
300	100	thick	0.26	10	3.35	70
300	100	thin	0.12	10	2.08	52
200	75	thick	0.33	10	4.00	75
200	75	thin	0.16	10	2.44	59

The table immediately suggests that mortar should be kept thin. In practice there are several reasons for not doing so: these include the irregularity of cheap bricks, problems with the poor workability of thin mortar and lack of bricklaying skills.

An extreme example of possible savings is standard Ugandan header-bond 200mm-thick walling of clamp-fired 'country' brick for which mortar thickness is typically 30mm, and the unit cost ratio μ (mortar:brick) is about 4. Omitting mortar would save about 57% of materials cost (or 52% in the case of stretcher bond). These huge savings are however unattainable as the irregularity of 'country bricks' rules out interlocked mortarless construction. More feasible is the 20% saving obtainable by reducing mortar thickness from 30 mm to 10mm, which may in turn require higher quality controls in clamp-firing the bricks. In this article we will henceforth focus on masonry that uses not fired bricks but stabilised-soil pressed blocks.

Using pressed stabilised-soil 300mm blocks (sand:cement ratio = 12) and 15mm of mortar costing, per litre, 3 times higher than the blocks (i.e. μ = 3), the materials cost saving would be about 21%. This substantial figure makes mortarless walling worth investigating. The interlocks usually moulded into SS blocks intended for mortarless laying do not affect the materials cost-saving and have little effect on moulding times.

The monetary value of time saving by omitting mortar varies greatly from country to country. Table 3 compares UK with Tanzania.

Table 3 Time and cost savings by omitting mortar in wall construction

Scenario	Mortar used	Units per m^2	Laying speed	Wage rate	Wage	Saving in wages
			m^2/hour	£$^+$/hour	£$^+$/m^2	%
UK bricklayer	Yes	56	1.1	20*	18.1	
"	No	66	6.0	13	2.2	88
Tanzanian self-build (blocks)	Yes	29	2	0.4**	0.20	
" "	No	33	5	0.2	0.04	80
Tanzanian fundi (blocks)	Yes	29	4	0.6*	0.15	
" "	No	33	12	0.4	0.033	80

*Including mate to mix and feed. **For self-build this is an opportunity cost. $^+$Based on TZS 3000 = £1.

Building with compressed but unstabilised earth blocks is a special case. The 'mortar' may be cement-based or may not. In the latter case ('mud mortar') the materials cost difference between 'mortared' and 'unmortared' construction is likely to be negligible and the only extra cost of mortaring would be for labour. Under these circumstances there is little benefit in omitting mortar and incurring all the disadvantages implied in Table 1.

4. The current practice of mortarless masonry

Stone masonry uses rocks either as found, or (ashlar) as found/quarried and then cut. Sometimes no mortar is used in the assembly of ashlar walls but this increases the accuracy of cutting required – and its cost. Mortarless ashlar is generally too costly for housing except for special 'feature' sections.

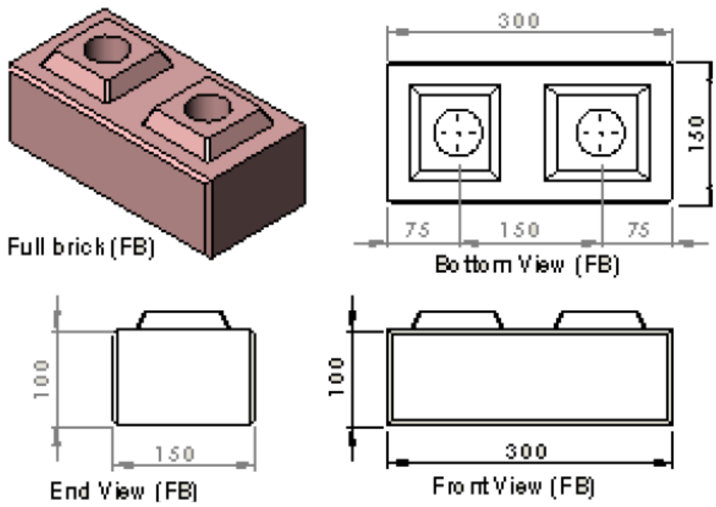
Figure 1 Drystone and ashlar walling.

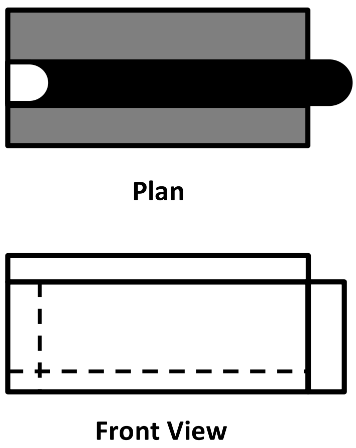
Where rocks are from layered strata and therefore not rounded, they may be heaped fairly stably *without mortar* into walls having a trapezoidal cross-section. This technique is used to construct 'dry stone' boundary walls to fields in mountainous districts. Such walls are thick and so consume much rock which is however often readily available from field-clearance. They are easily dislodged, require considerable maintenance and are for many reasons unsuited to house construction.

Moulded earth blocks have traditionally constituted much walling round the world. In order to get reasonable stability and resistance to surface erosion, the blocks are usually of compressed moist soil, the compression being impulsive or of up to 1 MPa pressure slowly applied. Such blocks have no resistance to standing long in water and therefore earth buildings require a flood-protected environment and a good damp course. Having long been regarded as primitive, earth buildings of various types are slowly returning to popularity and are being promoted by such agencies as CRATerre[craterre@grenoble.archi.fr] in France and producer associations in Europe and the Americas. Some 'welding' of the surfaces of contiguous blocks can be engendered by moistening them immediately prior to laying. Even pressed blocks made with a well-chosen soil mix have poor erosion resistance, are dusty and may harbour vermin (triatomin bugs, cockroaches, mice etc), so mortarless soil-block walling needs either a surface seal or periodic repair. The new attraction of all forms of earth building is its very low carbon footprint.

The most common form of mortarless masonry employs pressed, interlocking, stabilised-soil blocks, 'ISSBs', which are typically 300mm long, 150mm thick and 100mm high. Machines to produce such blocks are available in many countries. Motorised presses give higher pressures, more accurate blocks and somewhat higher labour productivity than manual presses but are too expensive for artisanal builders.

Figure 2a Manual (Makiga) and Motorised (Hydraform) block-making presses





(ii) Tanzanian (NHBRA) manual block **(ii) Hydraform Block**

Figure 2b Interlock designs

A 150mm wall thickness, and hence block-thickness, is that which gives just adequate lateral stiffness during construction (after which a ring beam is added to stabilise the top of a wall). The cement (or occasionally lime) content of the production mix is low, e.g. under 8% and the block hollowness up to 25%. The soil mix must contain some clay (for cohesion during production) and a high moulding pressure must be supplied (1 to 10 MPa). This pressure strengthens the material and permits a fairly dry mix to be used, with a water:cement ration close to the ideal of 0.5. (A dry mix is less vulnerable to uneven drying-shrinkage than a wet one.) Formation pressures of greater than 10 MPa may however drive out so much moisture and cement fines that the interior of blocks is effectively unstabilised and therefore weak.

Table 3 Wet compressive strength after curing (σ_c in MPa) *v* moulding pressure & cement content; from Gooding 1994. **(Figures in brackets show strength increase ratio over datum)**

Formation pressure → Cement fraction ↓	MPa	1.25 (datum pressure)	2.5	5	10
5%		σ_c = 0.86	**1.02** *(1.19)*	**1.22** *(1.42)*	**1.60** *(1.86)*
9%		σ_c = 1.80	**2.20** *(1.22)*	**2.73** *(1.51)*	**3.40** *(1.89)*

For constant cement content, each doubling in compaction pressure produces about a 23% increase in cured compressive strength (as shown by the ratios in brackets). The same increase could alternatively be achieved by increasing absolute cement content by about 1%. There is thus, for a given block strength, the option of trading extra moulding pressure against extra cement.

Pressing into a mould, rather than extrusion, is invariably used. The mould therefore initially defines some dimensions of the blocks and these can be made closely repeatable. Unfortunately this definition is least reliable on the critical top and bottom surfaces of a block. Moreover during handling and curing, blocks are often locally damaged, or distorted due to uneven curing and subsequent drying, or acquire small blemishes which prevents them seating properly when laid on the blocks below. Good on-site manual presses – usually based on the 1950s Colombian 'Cinva Ram' and having one moving piston - can generate about 1.5 MPa pressure. Expensive motorised presses in block-yards or on large housing sites often use two opposing hydraulic pistons and exert a moulding pressure up to 15 MPa. Block replicability – which is especially important in mortarless construction – can be improved by weight-batching of the soil used for each block. Control of moulding pressure is achieved by monitoring lever force ('effort') in the case of manual pressing and by hydraulic pressure in the case of mechanical pressing.

Some block-sets are just laterally constrained: their interlock features prevent a block being easily knocked *through* its wall, as that would entail interlock protrusions being sheared off, but sliding *along* a course of bricks is not constrained. Such interlocking is commonly achieved by having the top and bottom faces of blocks longitudinally grooved and ridged to form a 'tongue and groove' joint, as in Fig 2b (ii) above. They may in addition have an end-interlock to close the perpend when they are laid. The widely-marketed 'Hydraform' block, made with a 10 MPa mechanised press is of this type. Unfortunately such blocks do not form neat corners or tee joints, nor can they be 'reversed' during laying

Other block sets, e.g. as illustrated by Fig 2a, are both laterally and longitudinally constrained. Neat strong corners/quoins may be formed and blocks may be reversed, however the perpends are not fully closed. From inside a building daylight chinks can be seen through the walls.

With mortared brickwork, on-site cutting is employed to produce the quarter bricks, half-bricks, three-quarter bricks and closers necessary to create corners, joints and straight-sided openings. Site-cut bricks often look rough, but this roughness can be largely concealed by application of mortar. With mortarless construction it is more desirable to avoid on-site cutting and instead to manufacture half bricks and three-quarter bricks as well as full bricks. Moulds may be adapted so that divider plates can be inserted to create half-bricks. It is general with mortarless masonry to dimension the width of wall-sections as integer multiples of a standard block-length *L* or of *L*/2.

Figure 4 3-bedroom house in Tanzania, one of hundreds made of manually pressed, unmortared, stabilised-soil blocks

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5. Interlocks and resistance to punch-through

'Punch-through' is the penetration of a wall by dislodging an individual block. It can happen by accident (nailing up a shelf, a lurching cow, a colliding car) or as a means of criminal 'breaking and entering'. The force required to punch-through a single block is usually less than that to create a larger hole spanning several blocks, so our primary interest is to identify and increase the former.

Mortar between two masonry courses acts partly as an adhesive able to resist shear failure. Its effectiveness can be increased by such partial interlock features as the 'frogs' (mortar-locating indentations) moulded into the top of some fired bricks. Widely-used hollow 'cement' blocks are commonly laid so that their cavities act as such frogs but on their undersides. There is a tradition in e.g. parts of Latin America and Asia of incorporating barbed wire within mortar layers to better resist deliberate punch through. In Tanzania illegal entry using a battering ram has its own term ('faduma'). In most countries however, forced (criminal) entry is usually via windows or doors rather than through masonry.

Without mortar or interlock features, the primary resistance to shear failure in a wall is the friction created by the vertical pressure across a horizontal joint. The coefficient of friction between blocks or bricks is typically about 0.7 http://www.supercivilcd.com/FRICTION.htm and the vertical pressure in a single-storey wall ranges from near zero at the top course to about 50 kPa at the lowest course, giving a shear strength in the range 0 to 35 kPa. Relying only on this friction is likely to result in punch-through when large out-of-plane forces are applied high up in a wall. Since walling is quite rigid, such large forces can readily be generated via impulsive blows. In consequence of this vulnerability, most mortarless walling systems employ interlocking blocks, whose top and bottom surfaces carry matching protrusions and depressions.

Table 4 10 desirable features that interlocks should allow

a	Clearance sufficient to accommodate production tolerances, but kept low enough that the interlock can be relied on to correctly (within say 1 mm) locate a block relative to the blocks below it in the direction perpendicular to the wall face. Some 'double-constraint' interlock designs also locate blocks correctly *along* a course;
b	No intrusion into the block-to-block bearing surfaces (which should ideally be near the front and to the back of each block. (Actually – as discussed later - it is useful if the interlock actually *prevents* block-to-block contact close to the blocks' centrelines.);
c	Adequate vertical overlap and vertical contact area such that to punch a block through the wall entails shearing off a significant area of interlock material;
d	No light, or much wind or sound, allowed to pass through the wall;
e	Production of neat strong corners, openings and tee joints without on-site cutting of blocks (this may need the block-set to include ½ blocks, ¾ blocks, corners);
f	Some – say at least 10% - block hollowness, located close to the block centreline, to save material;
g	Creation of vertical passages through blocks to permit electrical wiring or reinforcement bars to be placed within walls;
h	Relative rotation of adjacent blocks along a course by at least 5^0 and preferably 8^0 to enable the construction of curved walls
i	Block reversal (via suitable symmetry) as this may aid production of plumb walls;
j	Production by extrusion.

Features (a) to (c) we may consider essential, (d) to (j) 'desirable'. No current, commercially available, block-set geometries satisfy all these desiderata. Requirement (d) = sealed envelope can be obtained by other means – for example by plastering the wall. Requirements (d) and (e) are normally in conflict with each other, as are (e) and (j).

Incorporation of 'block-end' interlocks enhances (d) but conflicts with (i). Indeed is lack of feature (v) – e.g. ability to form neat strong corners – that is the most obvious defect of some block-sets.
To date, suitability for extrusion (j), has not been considered necessary as interlocking blocks have never been extruded, even when the interlock design would permit it.

To date the mortarless laying of 215mm *fired* bricks is very rarely practiced, although Table 2 indicates that the materials advantages of mortarless assembly would be greatest with these smaller units. Clay bricks can be extruded with a tolerance of 0.1mm, but the subsequent operations of drying and firing cause additional size-variations that result in manufacturing height tolerances increasing to at least 1mm. Bricks are intended for being placed with one hand and therefore are weight limited. In UK a standard brick (65 x 102.5 x 215mm) occupies 1.4 litres, much less than a typical 'cement' or stabilised-soil block which occupies 3.5 to 4.5 litres. The number of bricks required per square meter of walling is typically 60, increasing to 72 in the absence of mortar; the corresponding block count is 30 increasing to 33.

Lack of negative field reports suggest that current ISSB interlocks are adequate to prevent 'punch-through'. However little numerical data is available to compare the forces (or the energy in blows) needed to punch through (a) interlocked unmortared blocks, (b) smooth-topped unmortared blocks and (c) smooth-topped mortared blocks of the same size. Including interlock features in block design incurs only a minor production cost; however if done as badly as it is in a few commercial cases, the interlock itself may interfere with accurate assembly. Moreover the penultimate of the desiderata listed in Table 4 – namely (ix) block reversibility - which is *not* available when using some widely used block presses – is significant for achieving verticality (plumb) of walls as discussed below. The lack of desideratum (x) – compatibility with block formation by extrusion – is likely to seriously discourage the application of mortarlessness to fired-brick walling.

An ideal block form

Table 4 lists desirable features of the block-to-block interlock and hence of the block form. Fig 2b shows two block forms, each with its own advantages. Both variants (i) and (ii) satisfy criterion (a) in Table 4; both fail the curved wall criterion (h) and extrudability criterion (j).
The ridged form of 2b(ii) , with its additional end interlock satisfies criteria (b), (c) and (d) whereas the form of 2b(i) satisfies criteria (e), (f), (g), and (i).
It will not be possible to combine the merits of each form if we are limited to a single block shape, so we should be considering block SETs comprising multiple shapes.

Taking the 'tongue-and-groove' form 2b(ii) as a starting point we need to

- Create ½ blocks and ¾ blocks for edging openings and joining cross walls

- Create a corner unit that will give a full corner interlock with no voids – for example a block that for half its length has a longitudinal tongue-and-groove and for its second half has a lateral tongue-and-groove.
- Remove the end interlock or replace it by a symmetric form (such as an 'S' shaped end) so that only one version of ½ and ¾ and corner blocks are needed and in addition the reversibility criterion (i) is satisfied at least for full blocks. Note however that without end interlocks the perpends are no longer completely sealed against light or wind penetration. This may be acceptable or may require perpend pointing. If blocks are very accurate, reversal during assembly is not required and criterion (i) no longer applies.
- Create two symmetric voids (e.g. with centres at ¼ and ¾ of the block length) within the tongue and groove swathe in order to satisfy the material saving criteria (f) and the presence of vertical passages for wiring or reinforcement (g). The cross sectional area of each passage is however unlikely to exceed 5% of the block's plan area so maximum material saving is 10%.

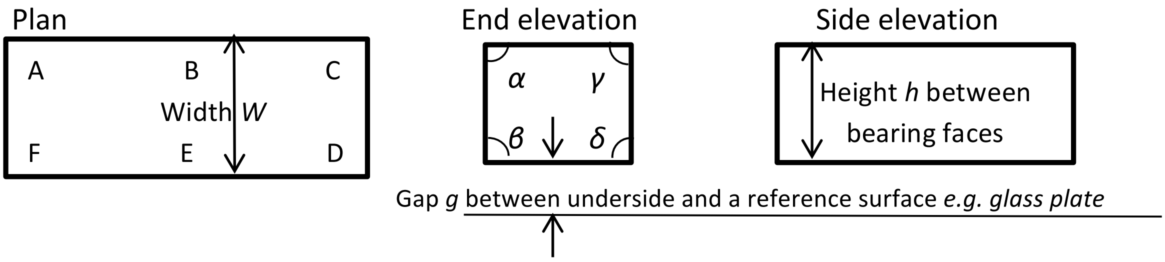
We now have a block SET that largely satisfies all criteria except rotatability (h) and extrudability (j).

6. **Achieving good vertical alignment** (See also Appendix A)

A column assembled from unmortared and inaccurate blocks will rapidly become out-of-plumb as it rises. In the worst cases the top of columns only 10 blocks high will overhang by so much that they topple. This is clearly an unacceptable failing. Ideally the (standard deviation of the) overhang X of a single-storey (e.g. 2.5 meter) wall should be acceptably small – this height corresponds to 25 courses of 100mm-high blocks. However under some circumstances a wall's straightness can be reset every say 8 courses by introduction of an intermittent mortar layer at for example windowsill and lintel heights. Ring-beams and floor slabs are commonly used in conjunction with mortarless masonry walls. These effectively 'reset' a wall's straightness at each floor, so the inability of such walls to keep within overhang limits over *two* storeys is generally not a problem. Fortunately ISSB walls lean less than columns do, and some are so flexible that they can be pulled into verticality before the casting of a ring beam on top of them. Nevertheless, restricting overhang to an acceptable value is the most challenging of the problems facing the builder of a mortarless wall.

Block imperfections include variation in height, lateral taper, longitudinal taper, twist and bowing. These are caused by variability in the moulding process and by block distortion during drying, curing or firing. Wall imperfections that follow are lack of 'plumb', rocking, wavy courses, uneven stresses leading to stress amplification and loss of crushing strength, reduced Euler-load capacity, much reduced stiffness etc. We might distinguish between small-scale 'blemishes' that reduce the effective contact area between adjacent blocks, and overall geometric inaccuracy. To completely describe such inaccuracy would require an infinity of data, whereas any practical classification of the geometric 'quality' or accuracy of a block must employ only a few data. As the front and rear of a block are not normally in contact with other blocks, their imperfection is rarely of importance – it is the mating top and bottom surfaces that matter.

Fig 6 Simplified description of a parallelepiped block



In practice the block heights and the gaps between the block's underside and a reference plane will vary slightly at the different plan-points *A* to *F*. A perfect prism would have *uniform height* ($h_A = h_B = h_C = h_D = h_F = h_G = \mathbf{h_0}$, where h_0 is the nominal height and height variation $\sigma_h = 0$), *equal gaps* ($g_A = g_B = g_C = g_D = g_F = g_G$ and $\sigma_g = 0$) and *right angles between faces* ($\alpha = \beta = \gamma = \delta = 90^0$).

From the point of view of assembling blocks (on a level base) into a vertical wall, we want the top and bottom bearing faces of the blocks to be parallel ($\alpha+\beta = 180^0$); however we have only a weak requirement for either α or β to be close to 90^0 (e.g. $87^o<\alpha<93^0$ would suffice) Our best estimate of the 'out-of-parallel' angle of these bearing faces is

'Roll taper angle' $\theta = \alpha+\beta-180^0 = ((h_A+h_B+h_C) - (h_D+h_F+h_G))/3W$ (in radians)

whose calculation therefore requires the measurement of 7 data points.

However even this measure gives an under-estimate of the imperfection in roll because neither the block being considered, nor that supposedly mating with it, have an absolutely plane top and bottom surfaces. There may be bowing/hogging (by a distance *b*) and twisting (by an angle ϕ) that do not show up as differences in the block heights h_A to h_G. For the bottom face these may be estimated as respectively

bowing: $b = (g_{B+}g_F)/2 - (g_A+g_D+g_F+g_G)/4$

twist: $\phi = (g_A+g_D-g_C-g_G)/2L$ where *L* is the block length.

The main impact of bowing and twist is to increase the instability of the wall units – as manifest by rocking during assembly.

Appendix A contains analysis that relates the variability of a column's overhang (i.e. out-of-plumb) distance *X* to the variability of the blocks' small but random roll-taper angle θ and to column height *H*. However the analysis neglects bowing and twist, so that it underestimates likely overhang *X*. It predicts that the standard deviation σ_x of *X* is proportional to the standard deviation σ_θ of the blocks' roll-taper angle θ (provided θ has a zero mean) and to $H^{1.5}$. (See Eq A2b: $\sigma_X \approx 0.58\, H^{1.5}\, \sigma_\theta / h^{0.5}$) .

Several experiments have been undertaken to test this relationship.

2016 experiments at NHBRA, Dar es Salaam, 140 poor quality ISSB blocks were measured to establish their *SD* of roll-taper angle as being σ_θ = 0.0102 radians and their *mean* roll-taper angle as m_θ = 0.0013 radians. The latter was reduced to .0005 radians by reversing alternate blocks which operation however had negligible effect on their SD (σ_θ). 1.5m (i.e. 15-course) *columns* were built with these blocks and their overhangs *X* were measured to yield the column statistics (SD = σ_X and mean = m_X of overhang) below:

- for 20 columns built with raw blocks (but brushed): σ_X = 22 mm, m_X = 83mm
- for 30 columns built with raw blocks (50% reversed): σ_{XR} = 19 mm, m_{XR} = 14mm

and for the best case:

- 30 columns with blocks reversed & grooved σ_{XG} = 14 mm, m_{XG} = 8mm

So for 50% reversing, σ_{XR}/σ_X = 0.86; for also grooving, σ_{XG}/σ_X = 0.64
for 50% reversing, m_{XR}/m_X = 0.17; for also grooving, m_{XG}/m_X = 0.10
Thus reversing and grooving markedly reduce the mean overhang but only modestly reduce the SD of overhand. Grooving was to prevent blocks contacting each other close to their longitudinal centrelines. Reversing is only possible with some interlock designs.

Note that even the best case above (blocks 50% reversed and grooved) was barely satisfactory, as the overhang reached 50mm in some columns. Extrapolating the limit (X < 9mm for a *wall* of H = 2m) mentioned in Appendix A, we might adopt the acceptability criterion:

σ_X should be less than say 6mm for an H = 2.5 m *column*.

In that case these columns are unacceptable even when made of grooved bricks. Walls would however have a lower overhang variability (σ_X) than columns. Some will argue that for low-cost, low-rise, tropical housing, wall-accuracy standards could be relaxed.

Theory (using Eq A2b) – based on assuming planar top and bottom surfaces and (using the measured block data σ_θ = 0.0102rad, H = 1.5m, h = 0.1m and assuming m_θ = 0) predicted a high σ_{XG} value of 34mm.

2009 Experiments at URDT Campus, Kagadi, Uganda by Warwick University Students: 10-block columns (i.e. 1.0m high) of poor quality ISSB blocks (each 300 x 150 x 100mm high) were assembled and their overhangs measured. Three variants of assembly were compared.

- for 40 columns built with raw blocks, σ_X = 30.5 mm, m_X = 6.9mm
- for 40 columns built with grooved blocks, σ_{XG} = 25.7 mm, m_{XG} = 8.5mm

However when blocks were 'bespoke reversed' so as to best fit a builder's level test for verticality

- σ_{XL} = 3.6 mm, m_{XL} = 1.6mm for 10 columns built

So for grooving alone, σ_{XG}/σ_X = 0.84; for bespoke reversing & also grooving, σ_{XL}/σ_X = 0.12
for grooving alone, m_{XG}/m_X = 1.23; for bespoke reversing & also grooving, m_{XL}/m_X = 0.23

Thus whilst grooving produced only a minor reduction in overhang variability σ_{XG}, 'bespoke reversing' of individual blocks produced a major (88%) reduction.

A ready, if crude, indicator of the poor precision of these blocks is that the SD of their heights, measured at points A…F for every NHBRA block, was large at 1.6mm. It is suggested that a height variation within a block of more than 0.5mm should be taken as it being unsuitable for use in unmortared walling unless it is to be 'bespoke reversed' by the mason.

If we were to analyse the overhang of a *wall* built of randomly variable blocks, we would expect it to be less than that of a *column* by a factor of at least 2: unfortunately such analysis is impractically complex.

Clearly we should be looking for ways of manufacturing blocks with low SD values (σ_θ) for lateral taper and very low values for mean taper m_θ. It is unlikely that blocks with a lateral taper exceeding 0.5^o can be used to construct a mortarless wall exceeding 1 meter in height. Achieving low values for σ_θ requires accurate press-moulds and well-maintained presses. Achieving low values for m_θ can be assisted by reversing alternate blocks (between manufacture and use in a wall).

Measures to achieve straighter walls, also explored in Appendix A, thus include:

- Brushing blocks to remove small blemishes and bumps
- 'Grooving' blocks along their centre-lines to prevent 'rocking' block-to-block contact in the central region. This reduces σ_x by 15-30% but at a cost of somewhat reducing the bearing surface area on the top of each block.
- Bespoke reversing of individual blocks during their assembly to best conform to a builder's level. This slows down wall or column assembly but reduces σ_x massively as shown by the Kagadi data above.
- Identifying and rejecting blocks whose roll-taper angle θ exceeds say 0.5^o or which display other major blemishes. This identification would require a 'go – nogo' gauge into which each block is dropped for testing – a procedure currently unknown in ISSB construction but not unacceptably costly.

The maximum overhang X_{max} acceptable during single-storey mortared brickwork is about 10mm (see Appendix A). Without applying some of the four measures just listed, this quality is difficult to achieve with unmortared blockwork. A less exacting standard (e.g. X_{max} < 25mm) is apparently acceptable in those countries currently practicing mortarless masonry. There is also evidence that mechanised block-pressing produces more accurate blocks than manual pressing.

7. Achieving vertical strength

Column failure under a balanced vertical load *F* can be by crushing or by Euler instability. Respectively:

$F_{\text{crush}} = \sigma_c A_c$ where σ_c is the compressive strength of the wall material and A_c is the block-to-block contact area; for a non-centred vertical load $F_{\text{crush}} < \sigma_c A_c$

$F_{Euler} = 4EI\,\pi^2/H^2$ for a wall of height H made of material of Young's Modulus E

Both F values are reduced by reducing the wall thickness or by reducing A_c.

Because of imperfect contact ($A_c < LW$) the 2nd moment at the block-to-block contact plane, (I_c = approx. $A_cW^2/12$), has a lower value than within blocks ($I_b = L\,W^3/12$). Due to absence of cushioning, in mortarless walls the 2nd moment I varies through the wall's height in a very complex way dependent on flux paths.

In a straight wall of height H, subject to only its own weight, the vertical crushing pressure at its base will be $p_{base} = \rho g H$. However we should apply a loading factor f, where $f > 1$, to account for the transmitted weight of suspended floors and roofing. Moreover any eccentricity of vertical loading, or out-of-plumb or application of wind loading will result in uneven pressure (vertical stress) through the wall. Taking as a limiting case the situation that the minimum pressure is zero on one wall face, then at the base of the wall the maximum pressure near the opposite face will be

$p_{base,\,max} = 2\,f\,\rho g H$

which, to avoid crushing failure *within* blocks, should be less than the compressive strength σ_c of the walling material.

However at the block-to-block interface the only-partial contact ($A_c/LW = \gamma$, where $\gamma < 1$) effectively increases the pressure at actual contact points even further – by the factor $1/\gamma$.

Thus to avoid crushing failure we require:

$p_{lowest\ interface,\,max} = 2\,\lambda\,\rho g H\,/\gamma$

to be less than the wall material's compressive strength σ_c.

For a two-storey brick walling, typical values for the various parameters are:

H = 5m; ρ = 1800 kg m^{-3}; λ =1.5; γ = (very approximately) 0.2, giving

$p_{interface,\,max}$ = 1.35 MPa

So to avoid crushing failure the material compressive strength σ_c should exceed 1.35 MPa, or higher, as a safety factor is required. In fact a compressive strength σ_c of 1.35 MPa is representive of a low-quality fired brick, a block of dried pressed earth or a weakly stabilised soil-cement block, so *unmortared* block walling is barely suitable for 2-storey buildings or for 5m-high gable-end walls. The distinctive negative feature of mortarless walling is its low contact-area factor $\gamma = A_c/LW$ due to

- imperfect contact even over the nominal bearing surfaces
- bearing surfaces being reduced (by chamfers, interlocks and deliberate grooving), to about 60% of the plan area $L \times W$

We need to raise γ to at least 0.5 to have confidence in 2-storey mortarless walling of low-quality masonry. Fortunately in practice very localised crushing of small bumps on the bearing surfaces has the effect of increasing γ as critical loading is approached, thereby increasing the crushing strength of a column.

It is difficult to measure γ directly, but we can infer its value from experiments that compare the crushing strength, σ_{column}, of short mortarless columns with that, σ_{block}, of individual blocks tested with good load-cushioning. We assume $\gamma = \sigma_{column}/\sigma_{block}$. We do have some limited data (see EWP IIB-8-5) for 2x2 ISSB prisms compared with single ISSB blocks which indicate a value for γ of ca 0.54.

Table 5 Strength of 3-block unmortared column compared with block strength

Data to Follow However we do not yet possess the data for the table below. Some experiments at Warwick in 2016-7 may provide extra data**.**

Blocks are 300mm x 150 mm, *pressed at ca 1 MPa. Burnt bricks are 200mm x 100mm. Both are strength-tested with top and bottom cushioning.

Columns are unmortared 'prisms' 3 blocks high and 2 blocks deep but topped and bottomed with mortar cushioning.

All strength values are the average for a sample of 5 tests.

	Unit	Pressed* soil block	'Country brick'	Kiln-fired brick	Pressed* Stabilised soil
Column strength σ_{column}	MPa				
Block strength σ_{block}	MPa				
$\gamma= \sigma_{column}/ \sigma_{block}$	Ratio				

8. Achieving lateral stiffness and strength (see also Appendix B)

For all walling, but especially boundary walling, wall-thickness is chosen to give adequate lateral stiffness and strength under wind-loading, seismic loading and casual impacts. Thickness can be reduced if buttressing, closely-spaced 'returns' or stepped (or wavy) wall plans are employed. 150-200 mm is the normal range for the thickness of domestic masonry walling, although 100mm may suffice for internal walls.

The importance of lateral stiffness and strength is debatable. There is little doubt that boundary walls do fail during wind-storms or earthquakes due to insufficient lateral strength. House walls however are stiffened by both the 'returns' that occur at every room corner and by any ring-beam holding together the top edge of the wall. The importance of the ring beam (or ceiling slab) is illustrated by the African construction practice of avoiding completing the upper parts of mortarless walls on windy days. High lateral stiffness is clearly desirable in seismic areas because it raises the natural frequency of walls above that of the shaking motion – resonance is to be clearly avoided. Stiffness also has a security function as a wall of low lateral stiffness can be manually broken down by rocking it and thereby incrementally building up large movements.

A column or wall of *perfect* blocks of a pre-specified height *H* would have an *initial* stiffness (to out-of-plane forces) that depended on the Young's modulus of the material *E* and the second moment of area *I* of the column's plan. This stiffness would be the same for an unmortared as for a mortared wall. For a wall or column *of unit width*, subject to a lateral force *F* spread along its top edge causing a displacement δ, we would expect an elastic stiffness $F/\delta = 3\ EI/H^3$ where I = thickness^3/12. However when applied force *F,* and hence the overturning moment, reaches a sufficient ('yield') value F_y, parts of one wall face will go into tension. A mortared or plastered wall may be able to sustain some tensile stress but an unmortared wall cannot. For the latter therefore at $F = F_y$ block separation would begin on the face under tension and the incremental stiffness would reduce. What follows may be 'peeling', cracking & sliding or cracking & hinging – as is analysed in Appendix B. However sliding – after taking up any slack in the block-to-block interlocks - is usually then prevented by such interlocks.

In the case of *actual*, i.e. imperfect, mortarless blocks, surface irregularity significantly reduce the effective 2nd moment of area *I* and hence the elastic stiffness. Indeed if inter-block contact is limited to a zone close to the blocks' centreline, this reduction can be massive: a displacement versus force graph for such a scenario may include horizontal sections of zero incremental stiffness during which one block rocks on the block below. Thus preventing (by grooving) contact occurring in this central zone, already noted above as improving wall straightness, also enhances column stiffness. Indeed, in general, measures to improve straightness also improve lateral stiffness.

Experimental data concerning lateral stiffness (and comparison with theory of unmortared masonry and of continuously cast columns) as recorded in ELITH Working Papers EWP IIB-8-1, -2, -3, -4. Indicate:

- Lack of ISSB stiffness compared with theoretical continuous & actual mortared columns.
- Benefits of plastering

9. Plastering and partial mortaring

'Full mortaring' is the filling of all horizontal and vertical (perpend) gaps between units with a workable plastic solid, that subsequently hardens, and whose thickness is adjustable. There are however several forms of 'partial mortaring' that include dusting with sand, use of non-setting mastics, application of pointing, use of thin fluid adhesives, and injection of a grout *after* assembly etc. For the purposes of this paper we count all these techniques as 'mortarless'. None of them offers any means of adjusting the straightness of a wall, indeed they may worsen it if their thickness is significant (e.g. more than 1mm), but they can improve those masonry properties that depend upon block-to-block cushioning.

There is also the option of alternating mortared and unmortared masonry, for example by mortaring every 5th or 10th course, or using ring beams and lintel beams to periodically reset the wall's plane.
Plastering, or even just pointing a wall, undoubtedly improves its lateral strength and stiffness. The plaster thickens the wall by typically 10% and thereby increases its 2nd moment of area *I* by over 30%. It also provides a layer with *some* tensile strength exactly where (i.e. furthest from the wall's neutral axis) it can most contribute to lateral strength. Plastering provides sealing of the walling envelope that some block sets don't provide, so that its omission can reduce privacy and resistance to rain penetration. Indeed it is usual to use mortarless masonry only where roofing overhangs walls by 50 cm or more, such overhangs (intended to improve shading) reducing the incidence of driving rain.

10. The geometric accuracy of masonry elements

In the paragraphs following Figure 6 in Section 6 above, several forms of inaccuracy were mentioned – e.g. unacceptably high values for roll-taper angle θ, twist ϕ and bowing *b*. These are 'within block' defects. There is also an important 'between blocks' defect, namely excessive variation in the average heights of adjacent blocks in a course. Such variation exceeding about 0.5mm will result in some blocks being 'unsupported', i.e. having no contact with the block below for half of their length and hence being liable to crack under the load from above. Such height variation is also often visible because when looking along a course the block lines are seen to be wavy.

The causes of inaccuracies in fired bricks are well known – uneven drying and uneven firing. For stabilised soil or for 'cement' blocks moulded from a firm mix, the cause lies mainly in the moulding process prior to curing, although post-ejection handling can also cause distortion and accumulation of micro-debris on bearing surfaces.

For ISSB masonry we require not just higher geometric accuracy than for mortared masonry, we also require adequate material quality which is dependent on the mix used, the moulding pressure achieved and the thoroughness of curing. Geometric and material properties interact. Depending on the design of a block press we can *either* tightly control size *or* tightly control material strength but not both. Fixed-geometry presses produce a nearly-fixed block size but uncertain block quality.

Conventionally a block is formed within a rigid 5-sided steel mould by moving a piston forming the 6th side (usually the block's bottom face) under a high force. Later, during block ejection the mechanism has to be altered. The piston's movement is fixed by the press's geometry, however this restraint can be compromised by wear in bearings and by failure of the piston face to remain exactly perpendicular to the sidewalls of the mould. Research has also shown that such 'single-sided' pressing results in considerable variation in material formation pressure from one part of a block to another. The block face next to the moving piston is more compressed (and therefore is more dense and strong) than the opposite face. Block material quality will vary with the applied pressure (which in turn is affected by the soil-cement mix used), the water content of the mix and most critically by the quantity of the mix put into the mould. Thus material quality control requires accurate batching.

Fixed-force presses allow the operator to set the pressure applied during moulding but thereby lose control over block size. As however maintaining geometric accuracy is more important (and much easier to gauge) than maintaining material strength, fixed-geometry presses are to be preferred to fixed-force ones.

A compromise between the two press designs is one that has two opposing moving pistons, one geometrically limited and the other pressure limited. This can give more uniform pressure than a one-piston press, but of course compromised geometrical accuracy.

Presses have parts moving in a very abrasive environment and are therefore liable to wear that leads to block variability. Greasing of bearings is essential but often neglected. Some designs of manual press can only deliver about 10,000 blocks (i.e. enough to build only 2 houses) before their wear results in unacceptable block-geometry variation.

11. High-tech versus low-tech versions of mortarless masonry.

There are two forms of mortarless masonry in common use, employing respectively mechanised and manual block presses. As mechanised presses typically cost over $10,000 but deliver higher pressures and more tightly controlled mix-batching: we can regard them as the ‘high tech’ option. Artisanal builders in the tropics, who generally do not have access to so much capital, employ manual presses, the low-tech option, costing around $1000. Production rates with motorised presses can exceed 800 blocks per day with a work-gang of 5, with manual presses only 400 blocks per day can be made with a work gang of 3, so mechanisation does increase labour productivity as well as block quality. In practice, mechanisation suits production in a permanent block-yard, (especially where there is also some mechanisation of block-handling and mixing) or in a temporary yard serving construction of an estate of new housing. Manual production better suits the construction of a single dwelling (say with 2000 blocks) and where sloping land permits much of the soil to be stabilised to be dug from the site of the dwelling.

12. Conclusions and the likely future of mortarless construction

The material, energy and cost savings from using mortarless construction are significant, but the quality of that construction is often poor. Quality control, especially in block production, requires more attention than it is currently receiving. Improvement requires better press design, regular press maintenance, measurement of block dimensions and block-hardness, care in curing and batching. Blocks from mechanised presses set a standard (e.g. of crispness) that manual pressing should be able to match but do not match at present.

Interlock designs that allow neat corners without on-site cutting are highly desirable, as are designs that permit block reversal before or during construction.

Mortarless masonry is suitable for internal walls, somewhat suitable for external walls and largely unsuitable for boundary walling. Unplastered mortarless masonry should not be used in actively seismic areas.

Plastering of at least one surface is desirable for sealing and for wall stiffness. It may be that block thickness could be reduced from 150mm to 120mm if compensated by use of 15 mm of plaster. Outdoor faces, if not rendered, need protection, by overhanging roofs, from water streaming down them; otherwise water will penetrate the wall. Some tongue-and-groove interlock designs do provide some internal sealing. Unfortunately this is at the expense of preventing block-reversal during construction and so requires a high level of geometric accuracy.

Acceptably straight (i.e. vertical) single-storey walls can only be built with close-tolerance blocks – for example those that, after removal of the most inaccurate blocks, have within-block and between-block height variations of under 0.5mm. Less accurate blocks require one of the following procedures:

- That the wall be reset to vertical using a mortar joint every say 8 courses
- That 'bespoke reversing' and a builder's level is used during construction
- Straightness standards are relaxed for single-storey tropical housing.

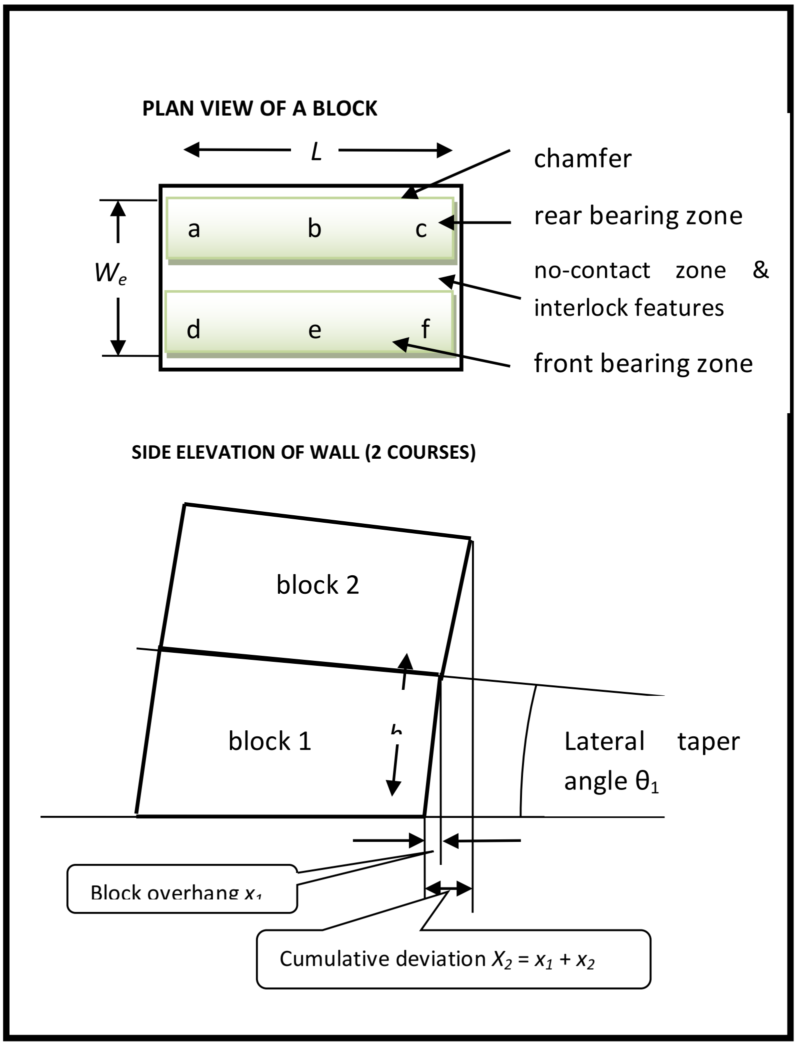
Blocks should be chamfered (to facilitate adhesion of thin plaster) and 'centre-grooved' to prevent block to block contact close to the blocks' centreline. Grooving improves both wall straightness and wall stiffness. Both processes however reduce the fraction of block-plan are that is available as load-bearing surface. If this fraction falls below say 50% there is a possibility of block crushing at the bottom of walls over 5m high. Mortarless masonry seems unsuited to multi-storey construction even where straightness is reset at each floor by the presence of a (concrete) floor slab.

Mortarless masonry has a low stiffness (under 20% of that of mortared brickwork) to out-of-plane forces such as wind pressure, seismic accelerations or roof out-thrust. Stiffness is much enhanced by plastering. Lateral strength is also very low and in seismic zones mortarless walls should be plastered, close-buttressed or crenelated to enhance their strength.

The need to press, rather than extrude, interlocking blocks gives an opportunity to include through-holes close to the block's centreline. These have little effect on crushing strength or lateral strength but save up to 15% of material and facilitate the placement of electrical wiring in walling without having to chase surface grooves.

Experiments should be pursued to investigate the feasibility of injecting a thin (e.g. 1mm) layer of mortar between blocks *after* construction.

Appendix A Relationship between out-of-plumb (overhang) *X* of a masonry column and the roll-wedge angle θ of its constituent blocks



An ideal brick is a rectangular parallelepiped of uniform height and with parallel top and bottom bearing surfaces. These two surfaces are indeed the critical ones and especially so for mortarless construction. However no artefact has perfect dimensions, all will deviate within specified tolerance limits from some ideal.

The simplest of models is a two dimensional one in which we treat the contact surfaces (i.e. those parts of the top and bottom faces that touch other bricks) as planes with some taper both longitudinally and laterally. The latter, which we might measure by a 'roll-taper' angle θ is the more critical as it affects the wall being 'out-of-plumb'.

Uniform blocks: The simplest case is that θ is the same (= θ_0) for every brick, for which the offset (out-of-plumb) distance x_n for the top of *n* courses may be very large, as the wall centre describes a circular arc of radius *R.*

$$x_n = R\,(1 - \cos(n\,\theta_0)) = \text{approx } R\,n^2\,\theta_0^2/2 = n^2 h\,\theta_0/2. \qquad \text{(A1)}$$

For example if $\theta_0 = 0.01$rad (= 0.6^0) and h = 0.1m and wall height = 2.5m (thus n = 25 courses) then the overhang would be a quite unacceptable 0.31m.

However this simple form of brick distortion can be easily compensated by reversing every second brick to remove any bias due to press-mould inaccuracy.

Variable blocks: More generally the angle θ is a random variable whose average θ_m and standard deviation σ_θ may be measured. By randomly reversing bricks we can make θ_m close to zero, but this has no effect on σ_θ. In this case x_n will also be a random variable.

For block 1, see Fig.A1, the front face leans forward at angle β_1 (assume = $\theta_1/2$) and the top of block 1 overhangs its base by

$$x_1 = h \sin(\beta_1) \approx h\,\beta_1 \quad \text{(as } \beta_1 \text{ is very small)}$$

By accumulation, the lean angle of the top block will be $\beta_n = \theta_1/2 + \theta_2 + \ldots + \theta_n$

The top of the wall will overhang the wall's base by:

$$X_n = x_1 + x_2 + \ldots + x_n = h\,\{\beta_1 + \beta_2 + \ldots + \beta_n\} = h\,\{n\,\theta_1/2 + (n-1)\,\theta_2 + \ldots + \theta_n\}$$

We may regard the taper angles $\theta_1 \ldots \theta_n$ of the individual blocks as being independent random variables with a mean value (α_m) of zero and a variance of σ_θ^2. We should like to be able to calculate the variance σ_{Xn}^2 of the deviation of the top of the wall.

variance $\sigma_{Xn}^2 = h^2$ times the expected value of $\{n\,\theta_1/2 + (n-1)\,\theta_2 + \ldots + \theta_n\}^2$

From the properties of such variables, we can say that

the expected value of each of $\theta_1^2, \theta_2^2, \ldots \theta_n^2$ is σ_θ^2

the expected value of $\theta_i\,\theta_j$, = 0 for $i \neq j$ because the errors are uncorrelated.

So $\sigma_{Xn}^2 = h^2\,\{n^2/4\ \sigma_\theta^2 + (n-1)^2\,\sigma_\theta^2 + \ldots\ \sigma_\theta^2\} = h^2\,\sigma_\theta^2\{2n^3+3n^2+n - 4.5n^2\}/6$

$$= n^3 h^2\,\sigma_\theta^2\,(1 - 0.75n^{-1} + 0.5n^{-2})/3 \qquad \text{[A2a]}$$

and for large values of *n* (typically $n > 20$) we can simplify this to

$$\sigma_{Xn}^2 \approx n^3 h^2\,\sigma_\theta^2/3 = n\,H^2\,\sigma_\theta^2/3 \qquad \text{giving} \quad \sigma_{Xn} \approx 0.58\,n^{1.5}\,h\,\sigma_\theta \qquad \text{[A2b]}$$

As expected, high variation (σ_θ) in the lateral taper of the bricks gives high deflections in any wall built with them: standard deviation σ_{Xn} of the wall-top overhang is proportional to the taper angle's standard deviation σ_θ. Also if, for a given wall height, the bricks are individually thinner (*h* is smaller and so *n* is larger) then the wall top deflection will be more variable.

More interestingly, the overhang's standard deviation σ_{Xn} is proportional to $H^{1.5}$ where *H* is wall height; in general, for a particular block set, doubling a wall's height will increase maximum overhang (for example taken as 2 σ_{Xn} , i.e. 2 x standard deviation of *X*) by a factor of about 3. This relation was borne out by laboratory experiments with 30 columns of half-size blocks for which it was found that σ_{Xn} was proportional to $H^{1.46}$ Kintingu, (2009). However in these experiments, formula [A1b] was found to under-estimate σ_{Xn} by the large factor of 3, indicating that warping or bowing of the contact zones were also contributing to the variations in overhang. Unfortunately these defects are less easy to measure than the lateral taper angle and much more difficult to model than equation [A1a] above.

A full formulaic approach to assessing whether blocks are acceptably accurate seems unlikely. Only by field experiments can criteria for block-error acceptability be developed. Walling standards BS 5628-3: 2005 Table A-2 and BS 5606: 1990 Table 1 specify that the maximum overhang for a 2m wall shall not exceed 9mm, and up to 14m high wall the overhang shall not exceed ±14mm (this corresponds to $\sigma_{Xn} < 20$mm). This might be experimentally tied to a test on blocks such as "When a block is placed on a glass plate, at no point around its perimeter should the height of its top surface deviate by more than 1mm from its intended value (of e.g. 100mm)". The practical objective is *either* to be able to decide if a set of blocks can be assembled to a specified height without exceeding a specified deflection limit *or* to indicate how many courses can be built with that brick set before 'relevelling' (using mortar) is required.

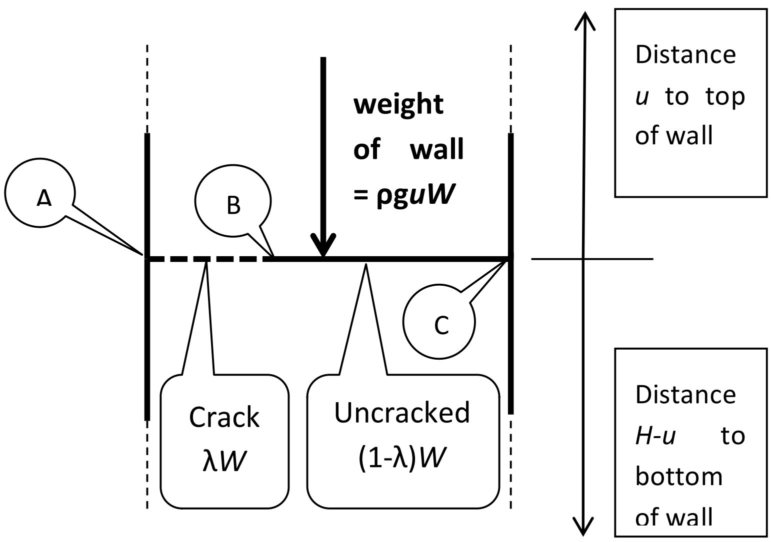
So for a given wall (i.e. given n and h) and a given brick taper (θ_0), we could decide if the offset from vertical X is acceptable or not. When it is NOT acceptable, then we must improve brick accuracy or limit n by introducing a mortar layer every say 10 courses.

Unfortunately the measured standard deviation of offset X is usually found to substantially exceed the value predicted by this formula – see Section 7 below - indicating that the model underlying the formula is too simple. The top and bottom faces cannot be assumed to be planes but instead display sagging/hogging and twisting.

Appendix B Behaviour of an unmortared column under lateral force.

Although the mode of failure of a column subject to a large lateral force F may be quite complex, we will consider the most likely – namely initiation of 'peeling' (progressive separation) at some block-to-block joint. To simplify the analysis without disqualifying its validity, we consider a column of unit width (e.g. 1 meter) of height H, thickness W and density ρ, subject to an out-of-plane force F applied to its top edge. We assume the height of the joint at which separation occurs is at a height u ($0<u<H$). The height of that part of the column that is above the assumed failure plane is therefore $H – u$.
We also assume that a separation ('crack') has already progressed distance λW through the wall – following a mortarless joint. So the uncracked section B-C is carrying the weight $\rho g u W$ of the wall above and in the absence of any applied moments would be subject to compressive stress $\sigma_c = \rho g u W/(1-\lambda)W = \rho g u/(1-\lambda)$.

The section B-C is also however subject to both a clockwise couple $M_1 = F.u$ (due to the lateral top loading) and an anti-clockwise couple M_2 (because the wall's weight is acting distance $\lambda W/2$ to the left of the centre of section B-C). So the total clockwise moment is



$M = M_1 - M_2$
$= F\,u - \lambda W\,\rho g u/2(1-\lambda)$.

This moment acting alone would create a tensile stress at B of $\sigma_T = M\,y_{max}/I$ where both y_{max} and I apply to section B-C. For this B-C section,

$y_{max} = 0.5\,(1-\lambda)W$

$I = ((1-\lambda)W)^3/12$,

so $y_{max}/I = 6/((1-\lambda)W)^2$.

For a mortarless column in which tensile stresses cannot be borne, the maximum load F will be that which reduces the compressive stress at point B to zero. i.e. makes $\sigma_T = \sigma_c$.
Thus

$$\rho g u/(1-\lambda) = [F\,u - \lambda W\,\rho g u/2(1-\lambda)].[6/((1-\lambda)^2 W)^2] \qquad \text{(B1)}$$

As dimension u cancels out, it transpires that the size of force F to progress the crack beyond fraction λ of the wall's thickness is the same for all potential crack locations (successive course joints): hinging failure does not always occur at the base of a wall.

$$F = (1-\lambda)\,\rho g W^2/6 + \lambda\,\rho g W^2/2 = (\rho g W^2/6).(1+2\,\lambda) \qquad \text{(B2)}$$

Thus as the peel/crack progresses from point A (where λ=0) to point C (where λ=1) the applied lateral force rises three-fold from

$F_y = (\rho g W^2/6)$ at initiation of peeling ('yielding')

to $F_f = (\rho g W^2/2)$ at hinging failure about point C..

In practice as peeling progresses and λ tends to 1, i.e. the zone B-C shrinks, compressive stresses become very high and local crushing or sliding may occur. It is therefore prudent to consider F_y as the design strength of the wall against lateral loading of its top.

Wind-loading or quake-loading is distributed fairly evenly across the whole of a wall's face and failure values for total force will be about twice those applicable with top-edge loading. For quake-loading the applied forces will be proportional to wall mass, so there is an incentive to make walls thinner – yet still laterally strong and stiff.

Up to load $F = F_y$ the elastic stiffness of the load application point should stay constant at least during unloading. (During loading there may have been instances of rocking contact and localised crushing of surface blemishes. Beyond load force $F = F_y$ (in theory up to failure at $F = F_f = 3F_y$) the incremental stiffness is erratic, very low and hard to estimate.