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Interlocking Mortarless Bricks: Column Straightness and Stiffness Testing, Data-set A

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This experimentation was performed on the campus of URDT, Kagai, Uganda

Introduction

Two performance requirements for brick walling are:

- Straightness - accuracy of vertical alignment
- Stiffness – resistance to lateral applied force

In conventional brick laying mortar is used to create bonds between the bricks and ensure each course is level. The absence of mortar in interlocking brick construction is therefore likely to cause a reduction in the straightness and stiffness compared with conventional brick laying. There is a need to test these properties and identify possible strategies for improving performance of this new technology.

Theory

Extensive research has been carried out by Simion Kintingu looking at ways of improving the performance of interlocking bricks[1]. He performed a range of tests using half scale experimental bricks (140x70x100 mm) on both column alignment (straightness) and column stiffness. His research suggests that the performance of mortarless brick structures can be improved by adopting two measures[3]:

i) Modification of brick shape

The positioning of a brick when placed on top of another is determined by the contact between the top and bottom brick faces, not the contact between the interlock protuberances. Any irregularities or biases in either of these faces will cause the column or wall to lean out of plumb. As discussed in section 3.1.1, inaccuracies in brick geometry cause wedge angles on the top and bottom faces. Superposition of wedge angles occurs when the bricks are stacked, meaning that the angle of lean of a column of bricks will be the sum of the wedge angles of the individual bricks. The wedge angles can be either positive or negative, so some wedge angles within a column can cancel each other out. However if there is a bias, for example if the press produces bricks that all have a lean in the same direction the resulting out of plumb displacement will be significant. Brick irregularities therefore have a negative impact on the alignment of columns and also weaken the performance of the wall when subjected to loads.

If the brick shape is modified so that there is a smaller contact area between the top and bottom faces of adjacent bricks it may be possible to improve performance. If the centre portion of the lower face were removed, leaving just two thin edge strips to make contact with the brick below then the effect of any irregularities or biases on the surface will be lessened. Reducing the surface area of the brick interface may increase the likeliness of achieving good contact, and therefore improve performance of the brick in terms of both straightness and stiffness.

ii) Special assembly procedures

Due to the symmetrical nature of the bricks, it is possible to reverse the orientation. In conventional assembly bricks are picked up by the mason and laid randomly. However, if the orientation of each course was chosen such that it created the most level top surface possible, then a straighter wall can be assembled.

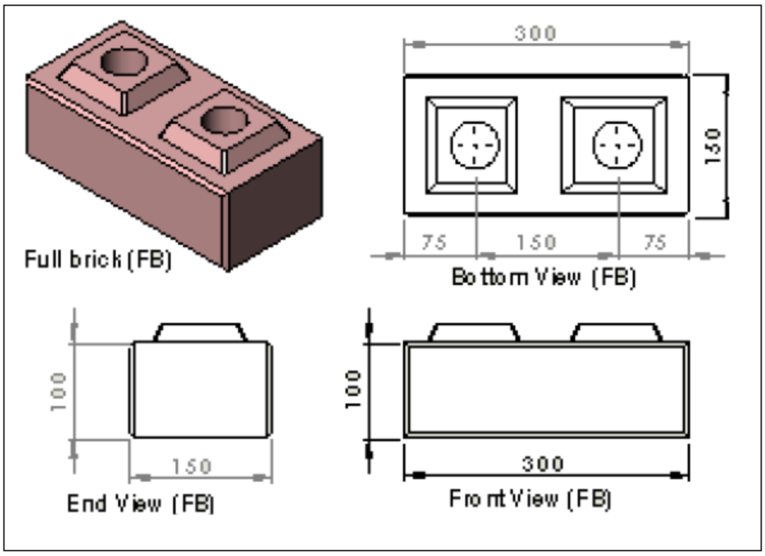

Figure 1 – Full Brick Tanzanian Interlocking Brick (TIB)[1]

Test Column Construction

The objective of this experimental study was to carry out further straightness and stiffness testing on columns made from full size (300x150x100 mm) Tanzanian Interlocking Bricks (see Figure 3).

A sample of 50 stabilised soil interlocking bricks was used in these experiments, selected from a batch made one year ago by the previous field course group. The bricks were manually pressed at URDT in Kagadi using a modification of the CINVA-Ram press machine. The 50 bricks selected from the batch were those that appeared to be in best condition and any that had not been formed correctly or had suffered severe damage were rejected. The bricks were numbered from 1-50 (as shown in figure 4) to aid the process of selecting random brick combinations and also to facilitate repeat stacking of the same tower across the different sets of tests.

Figure 2 – Sample of 50 stabilised soil bricks used in tests.

A permanent base brick was labelled zero and fixed to the flat concrete test area using mortar. Brick zero was carefully placed using a spirit level to ensure a level base for the columns. Each test tower was then constructed by stacking ten further bricks on top of brick zero. Of course in reality it is not only the straightness and stiffness of columns that we are concerned with, but that of walls and other structures. However the single brick column demonstrates the worst case, least straight and least stiff scenario in which the out of plumb displacements and horizontal displacement when subjected to lateral load will be greatest. These larger displacements will be easier to measure and less affected by experimental error.

A numbering system was used to ensure that each brick combination was different, allowing 40 unique towers to be constructed and tested using a sample size of just 50 bricks.

Three sets of straightness and stiffness tests were carried out, each set using a different laying strategy as set out in Table 1. After the three sets were completed a single mortared tower was also laid and tested for stiffness to act as a control.

Table 1 – Laying Strategies

SET	**LAYING STRATEGY**	**SIZE OF SET**	
		Straightness Tests	**Stiffness Tests**
Set 1	Unbrushed and randomly laid bricks	40	4
Set 2	Brushed and randomly laid bricks	40	4
Set 3	Brushed and levelled bricks	10	4
Control	Mortared bricks	0	1

Set 1. Unbrushed and randomly laid bricks

Bricks were taken from the sample as found and stacked with random orientations.

Set 2. Brushed and randomly laid bricks

Bricks were taken from the sample and brushed using a wire brush to create a groove along the centre of the bottom surface (see figure 2). This meant that only two thin strips along the edges made contact with the top of the brick below. The bricks were then stacked with random orientations.

Figure 3 – Brushed brick

Set 3. Brushed and levelled bricks

The same brushed bricks were used as in Set 2 but this time a system of optional reversing was employed when stacking. Each brick was first stacked one way and the level of the top surface measured using a spirit level. The orientation was then reversed and the level was measured again. The final orientation of the brick was chosen as the one which created the most level top surface. This process of levelling was repeated as each brick was added to the tower.

Figure 4– Levelling process

Straightness Testing

Introduction

A key function of the mortar used in traditional bricklaying is to ensure good alignment of columns and walls to ensure they are straight. British Standards exist, namely *BS 8000-3:2001 and BS5628-3:2005* which limit the permissible vertical lean and straightness deviation of mortared brick construction[3]. The standards state that the vertical lean of a wall up to 3m in height may not exceed ±10 mm.

The absence of mortar in interlocking brick construction is likely to cause a reduction in the straightness of walls and columns. There are no existing standards for this new mortarless brick laying technique so it is desirable to obtain a measure of the straightness that is achievable.

Methodology

The test towers were constructed in line with the procedures set out in section 4 above. The width of the bottom brick was measured using a ruler, and the centre line of the brick marked on using a thin pen line. The centre of the top brick of each tower was also measured and marked on using a nail to create a narrow groove in the top edge. A plumb line was slowly lowered through a wooden block held in place at the centre of the top brick until the metal weight at the bottom hung just a couple of millimetres from the floor. The plumb line was held in place until any oscillation had died away and the string was as close to stationery as could be achieved in the test conditions. Digital calipers were then placed between the centre line and the string of the hanging plumb line in order to measure the out-of-plumb deviation in millimetres (see Figures 7 & 8 below).

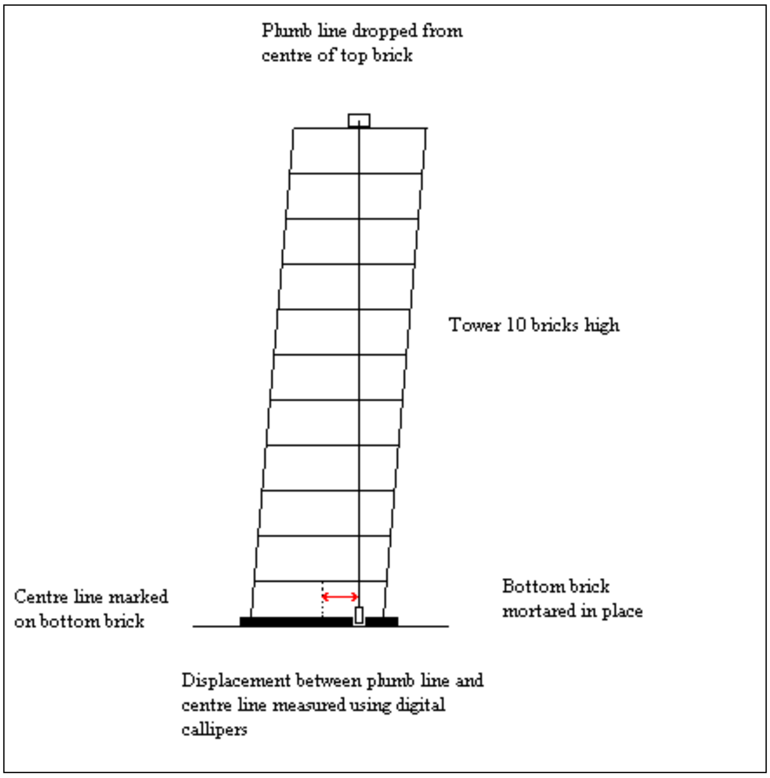

Figure 5 – Diagram showing Straightness test procedure

Figure 6 – Measuring out of plumb displacement using digital calipers

Results

Table 2 – Straightness Test Results

Bricks Used											Out of Plumb Displacement (mm)		
B1	B2	B3	B4	B5	B6	B7	B8	B9	B 10	Tower No.	Set 1 – Unbrushed	Set 2 - Brushed	Set 3- Levelled
1	2	3	4	5	6	7	8	9	10	1	35.49	17.18	-1.16
11	12	13	14	15	16	17	18	19	20	2	10.61	-41.4	-5.39
21	22	23	24	25	26	27	28	29	30	3	47.4	14.63	-4.53
31	32	33	34	35	36	37	38	39	40	4	-21.85	36.19	3.05
41	42	43	44	45	46	47	48	49	50	5	-36.59	-17.93	-3.9
1	3	5	7	9	11	13	15	17	19	6	-10.71	-4.95	3.1
21	23	25	27	29	31	33	35	37	39	7	29.58	33.34	-2.48
41	43	45	47	49	2	4	6	8	10	8	15.39	62.62	-5.34
12	14	16	18	20	22	24	26	28	30	9	29.92	35.26	3.86
32	34	36	38	40	42	44	46	48	50	10	-11.64	43.1	-2.67
3	6	9	12	15	18	21	24	27	30	11	44.49	6.97	
33	36	39	42	45	48	1	4	7	10	12	27.5	30.71	
13	16	19	22	25	28	31	34	37	40	13	24.4	47.38	
42	46	49	2	5	8	11	14	17	20	14	25.46	30.61	
23	26	29	32	35	38	41	44	47	50	15	-7.63	-18.76	
4	8	12	16	20	24	28	32	36	40	16	48.12	12.68	
44	48	2	6	10	14	18	22	26	30	17	-49.4	42.68	
34	38	42	46	50	1	5	9	13	17	18	1.32	40.88	
21	25	29	33	37	41	45	49	3	7	19	7.76	13.69	
11	15	19	23	27	31	35	39	43	47	20	-23.02	-0.85	
5	10	15	20	25	30	35	40	45	50	21	72.1	18.99	
1	11	21	31	41	2	12	22	32	42	22	28.79	-7.82	
3	13	23	33	43	4	14	24	34	44	23	36.19	12.13	
5	15	25	35	45	6	16	26	36	46	24	-3.45	-14.88	
7	17	27	37	47	8	18	28	38	48	25	44.41	32.3	
9	19	29	39	49	10	20	30	40	50	26	-36.93	-14.35	
1	12	23	34	45	2	13	24	35	46	27	-18.76	27.34	
3	14	25	36	47	4	15	26	37	48	28	-35.2	2.97	
5	16	27	38	49	6	17	28	39	50	29	-28.71	-11.57	
7	18	29	40	8	19	30	9	20	10	30	8.21	-8.89	
11	22	33	44	21	32	43	31	42	41	31	1.66	-4.37	
1	11	2	21	12	3	31	22	13	4	32	20.67	6.07	
41	32	23	14	5	42	33	24	15	6	33	17.65	-36.2	
43	34	25	16	7	44	35	20	17	8	34	-4.1	-14.86	
45	36	27	18	19	46	37	28	19	10	35	41.27	42.8	
47	38	29	20	48	39	30	49	40	50	36	33.19	-27.06	
44	12	14	26	7	38	28	24	16	31	37	-38.04	-17.91	
29	13	4	47	16	25	42	22	5	50	38	-52.91	-6.4	
41	32	20	2	18	37	11	42	46	23	39	-2.78	-26.39	
22	1	27	23	8	48	33	16	44	35	40	7.5	3.72	
										Mean	6.93	8.49	-1.55
										S.D	30.46	25.68	3.62

The out of plumb displacements measured across the three sets of tests are presented in Table 6 above. Any displacements that were measured to the right of the centre line were recorded as positive and any that were measured to the left were recorded as negative.

Analysis and Discussion

The mean out of plumb displacement and standard deviation for each laying strategy was calculated (as shown in the bottom two rows of Table 6). These values were used to calculate the normal distribution function for each set using Equation 1 below, where μ = mean and σ= standard deviation.

$$f_x(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$

Equation 1 - Normal Probability Density Function

The calculated functions were then used to plot the normal distribution curves for the three sets of tests: unbrushed, brushed and levelled (see Figure 9).

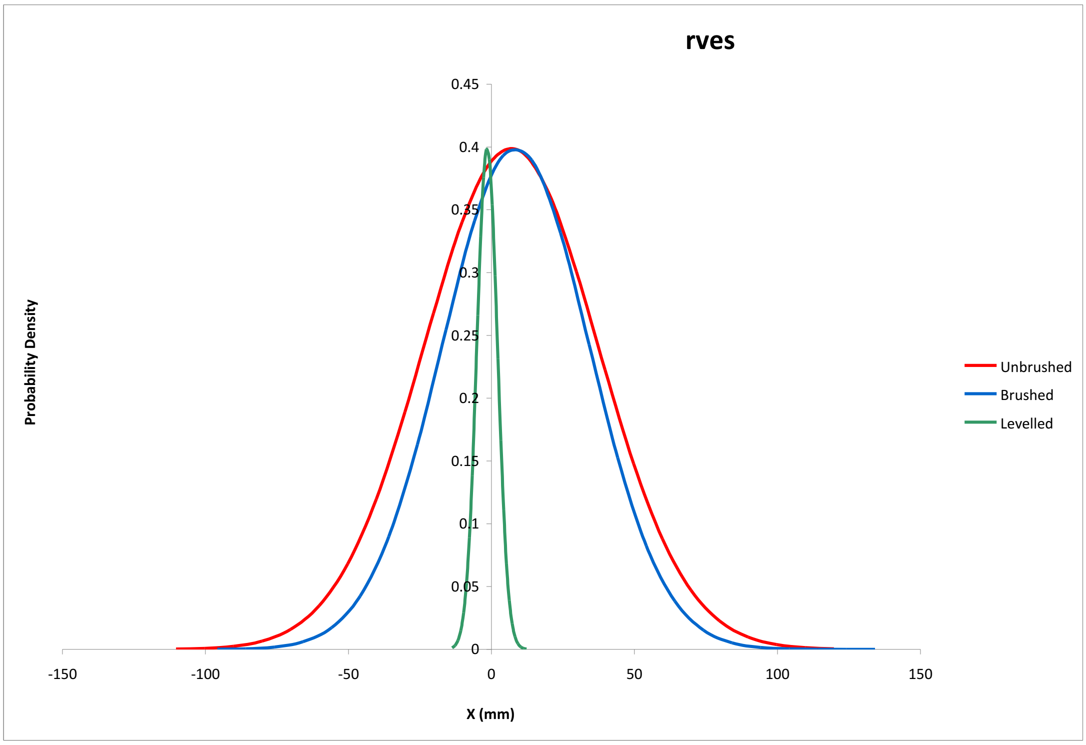

Figure 7 – Normal Distribution Curves for Straightness Results

<u>Set 1: Unbrushed Bricks</u>

The largest displacement measured was approximately 52 mm which is very large for a tower of only 1.2 m in height. In fact when constructing the ten storey towers for Set 1 it was observed that it would not have been possible to make them any taller as they would have become too unstable to stand up. The mean out of plumb displacement for the unbrushed bricks was 6.93 mm, however this figure does not reflect the average straightness as the measurements were recorded as both positive and negative. Theoretically the mean for all three sets of tests should have been zero as you would expect 50% of towers to lean to the left and 50% to lean to the right. In the unbrushed set of tests the mean is positive which would suggest there is a small bias for the towers to lean to the right rather than left. The standard deviation for this set was 30.46 mm which shows that there is a high variability in the straightness of towers. This is reflected by the wide spread of the normal distribution curve, shown by the red line in Figure 9. This agrees with the prediction that the poor dimensional accuracy of interlocking bricks creates a high level of variability in the straightness of columns and walls.

Set 2: Brushed Bricks

The mean of Set 2 was 8.21 mm which shows that again results were slightly biased towards leaning to the right. The maximum displacement measured in this set was approximately 62 mm which is actually greater than the maximum from the unbrushed set. This is likely to be due to the high level of variability that was present in both Set 1 and Set 2 and not due to the fact that the straightness was actually reduced by the brushing process. In fact the variability of straightness, which is the most important factor, was slightly improved. This is shown by the lower Standard Deviation of 25.56 mm and the resulting slightly narrower normal distribution spread as shown by the blue line in Figure 9. This indicates that straightness variability can be improved by approximately 10% by brushing the bricks before laying them.

Set 3: Brushed and Levelled Bricks

Drastic improvements in straightness were made by levelling the bricks as they were added. The mean was reduced to -1.55 mm which is much closer to the theoretical zero value that was expected, suggesting that there was very little bias. The maximum displacement measured was -5.39 mm which is approximately a 90% improvement from the unlevelled tests. The Standard Deviation was significantly reduced to just 3.62 mm, showing that the levelling process greatly reduces the straightness variability. The improvement is shown by the very narrow spread of the distribution curve (see the green line in Figure 9). If the assumption of a normal distribution is valid, this would suggest that the out of plumb displacement of any ten-storey single brick tower is likely to be within the limit of ±10 mm. If the levelling process were adopted in the construction of more stable structures such as walls the alignment accuracy is likely to be well within the acceptable limit set by British Standards of ±10 mm for a 3 m high wall.

Stiffness Testing

Introduction

For the safe construction of buildings it must be ensured that the vertical walls and columns can withstand lateral forces that may occur due to applied loads such as earthquakes, wind or an impact. It was observed during preliminary stacking that the columns would often sway due to external lateral forces, mainly wind, and in some cases caused the tower to collapse prematurely.

This testing aims to explore the loading capacity of ten-storey single brick towers and investigate ways to increase the stiffness. The results obtained may be useful in improving the safety of this new technology.)

Methodology

Test Setup and Procedure

As testing was taking place in Uganda, typical testing procedure could not be followed as the apparatus available was limited. Therefore a test setup comprising of a bucket and hook was arranged in order to allow for a gradual increment of load (Figure 2). A frame was constructed by driving two wooden poles into the soil in front of the test tower and fixing a horizontal pole between the two at a height of 1.2m, the same height as the test towers (See Figure 11). Before it was fixed in place the horizontal pole was carefully levelled using a spirit level. A length of string was tied to the handle of a plastic bucket and hung over the horizontal pole. A right angle hook was fabricated by bending a strip of sheet metal and drilling a hole in one end. This was attached to the other end of the string and was hooked over the top of the 10 storey tower in order to act out the worst case scenario of a lateral load applied at the top. This will produce failure at the lowest loading, thus giving an indication of the lower bound load limit. Load was increased by adding water to the bucket at fixed volumes using a measuring cylinder. The actual load acting on the wall could then be determined using Equation 2:

$$F_H = [m_b + (v_w \times \rho_{water})] \times g \times (F_{90/}F_0)$$

where F_H = Applied lateral load (N)

v_w = Volume of water in bucket (ml)

ρ_{water} = *Density of water (kg litre^{-1})* = 1kgl^{-1}

g = *Acceleration due to gravity (m s^{-2})* = 9.81 m s^{-2}

(F_{90} / F_0) = Friction Factor (no units, (See Friction Factor section below)

The load was added at known increments up to failure of the tower, or up to a displacement of 20 mm if the tower was still standing. At this point the load was removed to see if the tower could return from failure. Situated between the test tower and the bucket, a safety tower was constructed using old bricks to prevent the tower from falling down and potentially damaging the bricks.

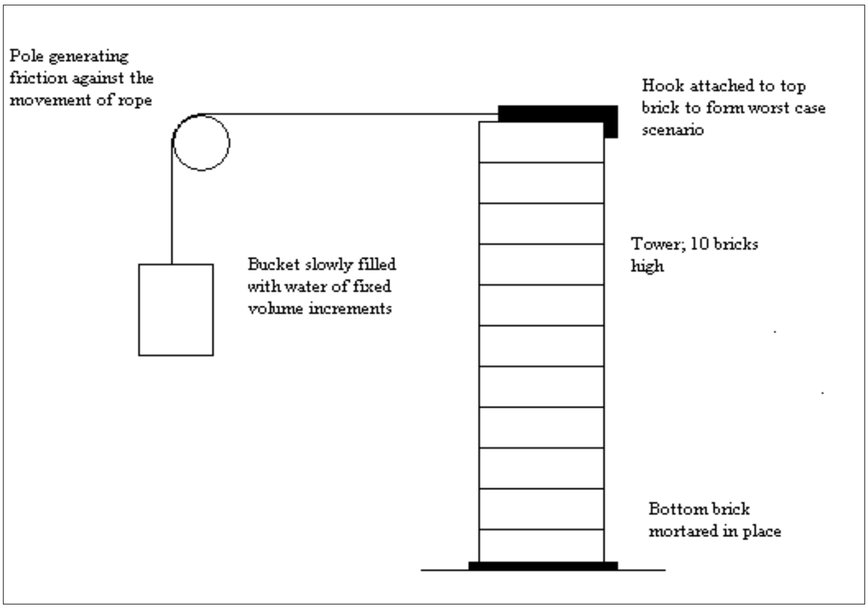

Figure 8 – Stiffness Test Set Up

Figure 9 - Photograph of Stiffness Test Rig

Friction Factor

Before testing could begin the friction acting between the string and the wood had to be taken into consideration. This meant that a friction factor had to be determined in order to calculate the actual force that was acting on the tower. This was achieved by hanging two buckets by a length of string resting over the top of the pole. The mass of the buckets was measured and recorded before testing began. Two litres of water was initially added to each bucket so the system was in equilibrium. Water was then slowly added to one bucket until sliding began. The volume of water in each bucket at the point of sliding was recorded and converted to a mass by multiplying it by the density. The total mass could then be calculated by summing the mass of the bucket and water. The final masses were 2.388 kg in one bucket and 5.388 kg in the other. The ratio of these masses is equal to the ratio of the forces on either side of the string (F_{180} / F_0). This represents the friction factor of a string passing 180° over the surface. In our test rig the string passes 90° over the surface of the wooden pole, so the ratio we require for the friction factor is F_{90} / $F_{0.}$ This can be calculated using trigonometry:

$$(F_{90} / F_0) = \sqrt{(F_{180} / F_0)} = \sqrt{2388/5388} = 0.666$$

This factor can be used to convert the known vertical load that is applied to the test rig to the lateral load that is applied to the top of the tower.

Testing

A total of 17 tests were undertaken. Using towers 1-4 (see Table 6 for the brick combinations used) the load test was performed on each tower using the 3 test setups, Sets1-3 (see Table 5) A final test was performed using tower 2, mortared in place to allow for comparison with the stiffness achieved using the traditional brick laying technique.

Observations and Results

Table 3 – Summary of Stiffness Test Results

Tower	Set up	Max Load (N) (± 1)	Displacement (mm) (± 0.5)
1	1	5159.4	FAIL
1	2	29963.7	24.82
1	3	25402.1	24.79
2	1	10253.5	FAIL
2	2	32576.1	21.82
2	3	30628.9	27.16
3	1	4049.2	FAIL
3	2	25392.1	21.06
3	3	18215.3	35.47
4	1	5812.5	FAIL
4	2	34535.3	18.12
4	3	26708.8	17.96
2	Mortared	31935.5	2.69

By looking at the results in Table 7 the following observations can be made:

There is a large variation in the stiffness of towers as there was a wide range of failure loads under similar conditions:

The failure loads in Set 1 ranged from approximately 4 kN to 10 kN
The failure loads in Set 2 ranged from approximately 25 kN to 35 kN.
The failure loads in Set 3 ranged from approximately 18 kN to 36 kN.

Brushing the bricks (Set 2) dramatically increases the lateral load the tower is capable of holding, supporting the hypothesis that reducing? the contact area between bricks increases stiffness.

Levelling the bricks by selective reversing (Set 3) doesn't have such an effect, if anything the maximum load appeared to be slightly reduced.

Towers under Set 2 and Set 3 conditions are capable of relatively large displacements before failure.

The mortared tower failed at a similar load to sets 2 and 3, however the previous displacement before failure was reduced greatly (i.e. stiffness much increased).

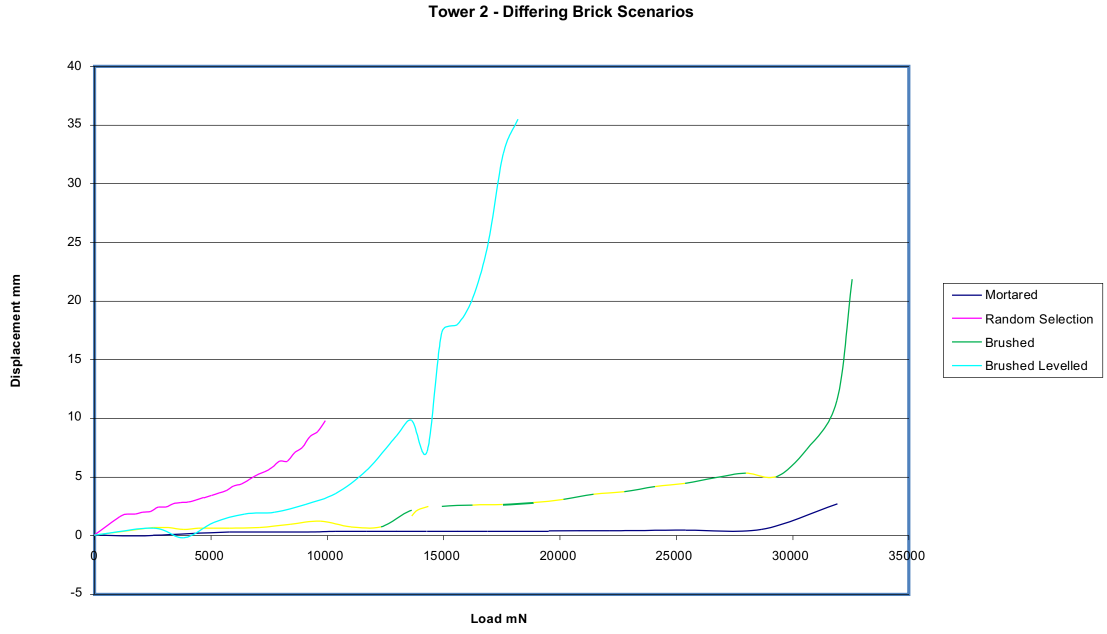

Figure 10 – Load-Displacement graphs for the different laying strategies used to construct Tower 2

The graph in Figure 12 shows clearly the increase in stiffness of the towers when the bricks were brushed. It also indicates the relatively small difference in force required for failure for the brushed and mortared towers. On careful observation, small plateaus are visible of the towers sudden increase in displacement with a small increase of load, before a long flat period where the increase in load has little effect on the position of the tower.

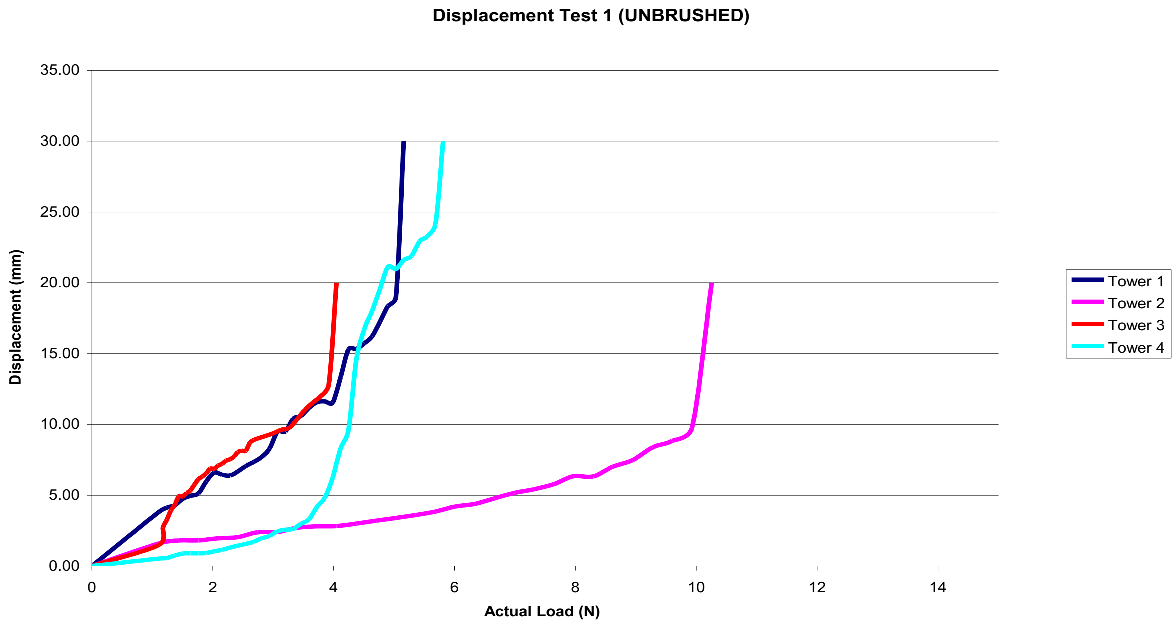

Figure 11 – Load-Displacement Graphs for the 4 towers tested

Figure 13 shows the large variation in displacement patterns for the 4 towers tested in Set 1. Tower 2 held a considerably larger load before collapse than tower 3. It also indicates the displacement spread before collapse with towers 1 and 4 moving 10 mm further before collapse than towers 2 and 3. Finally Figure 13 also shows the sudden displacements followed by long periods of no movement of the towers.

Analysis and Discussion

After comparing results for the 4 towers under the various different conditions, several conclusions could be drawn.

Perhaps the most important result was the drastic improvement in stiffness to the tower, once the brick was brushed (Set 2). This generated a 600% increase in the force that the tower could withstand before collapse, and was approximately the same to the mortared tower as shown in Figure 13. This would indicate that a change in the brick mould would be beneficial to incorporate the new shape after brushing into the design.

Results also show that the mortar-less bricks have a greater displacement before collapse compared to the mortared tower. This could be viewed in two ways; either this indicates a greater factor of safety as it would be visible that the wall was becoming unsafe, however structurally this is a negative and would have to be studied for further work.

As a greater load was applied, the displacement went up at different rates, sometimes increasing under an increase in load, whereas at other times appearing to not move at all. This was because the force being applied had to be used to overcome friction, and when the friction limit was reached, a sudden jump would occur. This was to be expected as similar results occurred during Simion Kintingu's work[3].

Finally it can be concluded that the extra effort required for Set 3 was an inefficient method as the extra time spent in levelling each brick had little effect on the final failure load; if anything it reduced the load which was somewhat surprising.

Overall there can be quite a high degree of confidence in the results and the conclusions reached as it agrees with work already undertaken in the area. However, the high variation in the results indicate that 4 towers was not a large enough sample size and therefore the results are not statistically significant.

Conclusions

Using unbrushed bricks and laying them randomly, creates towers with a high level of variability in both straightness and stiffness. This is likely to be due to the high level of variability in dimensional accuracy as discussed in Section 3.1.1. The straightness and stiffness performance was found to be both poor and unpredictable, confirming the need to improve the technology before it can be used safely in building construction.

Brushing the bricks improved stiffness by 600%, bringing it level with the performance of the mortared tower. Brushing also caused a small improvement in straightness, reducing the variability by approximately 10%. This shows that the new brick geometry achieved by the brushing process greatly improves the structural performance. However the brushing process was an inefficient use of labour and time and is therefore not a viable strategy to adopt in full scale construction. Hence this new brick shape should be incorporated into the mould geometry so that this greatly improved performance can be achieved without the need for additional post-mould processing.

Levelling generated significant improvements in tower straightness; reducing the variability by approximately 90% and removing bias. By adopting this method, a tower straightness accuracy of ±10 mm was achieved. The single brick tower demonstrates the worst case scenario, and if the levelling process were adopted in the construction of more stable structures such as walls then straightness accuracy is likely to be even better and therefore well within the equivalent acceptable limit set by British Standards of ±10 mm for a 3 m high mortared wall. However, the lengthy levelling process did not appear to improve the stiffness of the towers, in fact a small decrease in failure load was observed. This observation could be due to experimental or statistical error and so further investigation would be required to confirm whether or not a reduction in stiffness was caused by this levelling process. The brushed and levelled towers still offered greatly improved stiffness compared to the unbrushed towers, and was still comparable to the mortared tower performance. This suggests that the huge improvements in straightness outweigh any potential negative impact on stiffness and therefore should be incorporated into the construction process.

A final observation is that the mortarless bricks have a greater displacement before collapse compared to the mortared tower. This suggests that the mortarless towers behave more elastically, however as the sample size of mortared towers was just one, more investigation would be required to confirm this.

The conclusions reached from this testing offer a big step in the progress of mortarless brick technology. Two potential improvements have been indentified:

1. Changing the brick mould geometry to provide a smaller contact area between bricks and improve dimensional accuracy
2. Adopting an efficient process of levelling

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1. Straightness of ISSB columns (March 2016 experiments at NHBRA)

2. Column lateral stiffness and strength, for variants of ISSB assembly

3. Crushing strength of mortarless masonry (NHBRA 2016)

4. Comparing the lateral stiffness of different ISSB wall plans

5. Cost comparison - ISSB versus mortared walling