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EMPIRICAL TESTING OF INTERLOCKING COMPRESSED EARTH BRICK WALLS USING SCALED 3D-PRINTED MODELS

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ABSTRACT: This study investigates the feasibility of using 3D-printed scaled models to replicate the compressive behaviour of interlocking compressed earth brick (ICEB) units and walls. Full-scale testing of ICEB walls is costly and time-consuming, making scaled model testing an attractive alternative. Three-dimensional printing was used to fabricate scaled down ICEB units and wall specimens at scales of 1:5, 1:8 and 1:10. Compressive strength tests were conducted on both individual ICEB units and wall panels under restrained and unrestrained conditions, and the resulting load–deformation response, yield stress, and failure mode were compared with those of full-size specimens. The results showed that the load-carrying capacity of both the 3D-printed ICEB units and walls increased as the model scale decreased. For the individual units, the smallest model scale of 1:10 most closely reproduced the behaviour of the full-size ICEB unit. whilst the wall specimens showed the closest agreement with its full-size counterpart at the largest scale of 1:5. Restraints made little different to the wall yield stress except at the smallest scale of 1:10. The 3D-printed scaled ICEB unit and walls fail exhibiting ductile behaviour as opposed to the brittle splitting mode seen in full-size units. These findings demonstrate that 3D-printing can provide a practical method for scaled ICEB testing, although additional work would need to be carried out to correlate other scaling parameters such as material properties.

Keywords: Scaled model, Structural testing, 3D-printing, Interlocking compressed earth brick, Similitude theory

1. INTRODUCTION

Interlocking compressed earth bricks (ICEBs) are a form of stabilized earth masonry (Fig. 1) produced by compacting locally available clay, often with a small proportion of binder such as cement and fine aggregates such as sand into blocks [1] with interlocking features. Unlike conventional fired clay bricks, ICEBs are manufactured using high pressure hydraulic compaction, resulting in lower embodied energy, reduced carbon emissions, and lower construction cost [2]. The interlocking mechanism utilizes a " shear key" system—comprising raised ridges (projections) on top and matching recesses (depressions) below — to lock blocks together without mortar, enabling faster construction and reducing the need for skilled labour [3].

ICEBs have attracted increasing attention as a sustainable building material, particularly for low-cost housing in developing regions. In addition to their environmental benefits, ICEBs can provide good compressive strength, thermal performance, as well as impact resistance [4].

Despite these advantages, the structural behaviour of ICEB units and wall systems is still not fully understood, particularly for slender walls where the absence of mortar in joints may significantly influence the load transfer mechanism, stability, deformation behaviour, and failure characteristics. Empirical testing could be carried out on full-size walls, but these tests are often difficult and expensive. A full-scale wall may be several metres high and wide, and spacious laboratories with sufficient ceiling height are to accommodate the test setup alongside strong floors and large hydraulic actuators. Large quantities of bricks and mortar are also required, making material handling difficult for many laboratories. It is also equally difficult to reproduce the required loadings accurately and safety is another issue as masonry walls typically fail very suddenly and violently and can potentially eject large debris with considerable force. All these factors add up to make testing a full-scale wall a challenge. The usual alternative to full-scale testing is computer simulation; however, such models often involve numerous simplifications and assumptions (5).

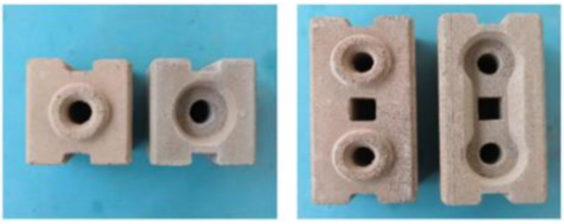

Fig. 1 Full size (ICEBs) - half (left) and full brick (right)

In civil engineering, similitude theory is widely applied where full-scale testing is impractical, expensive, or destructive. Scaled models are commonly used to investigate the structural response of buildings, bridges, high rise towers and many other structures that whose design are outside normal codified standards and too large for full-scale tests. When the required similitude relationships are satisfied, the response measured in the model can be extrapolated to estimate the behaviour of the full-size structure with acceptable accuracy [6].

For structural applications, one of the most important scaling parameters is usually the geometric scale factor, $\lambda = L_m/L_p$, where L_m and L_p are the characteristic lengths of the scaled model and full-size prototype respectively [6]. Geometric scaling is commonly employed to reduce the dimensions of a prototype specimen, thereby making laboratory testing more practical and manageable. Likewise, in masonry wall testing, similitude theory enables small-scale wall specimens to be used to study strength, deformation and failure mechanisms that would otherwise require costly full-scale experiments. However, complete similarity is often difficult to achieve because of differences in material properties, strain-rate effects, and construction details between the model and the prototype.

Previous studies on scaled structural testing have adopted a wide range of geometric scales depending on the objectives of the investigation, laboratory limitations, and similitude requirements. In masonry engineering research, scales between 1:2 and 1:20 are commonly reported, with 1:5 and 1:10 [7] being among the most frequently adopted due to their balance between structural realism and experimental practicality.

One way in which a scaled model can be quickly prepared and tested is through 3D-printing. 3D-printing provides an efficient and accurate method for producing scaled structural models for experimental testing. In fact, this technology has already been previously used to model stiffener plates to increase rigidity of thin-walled bars [8] and also for modelling tunnel linings [9, 10]. By allowing complex geometries to be reproduced with high precision, 3D printing enables small-scale models of civil engineering components such as masonry units, walls, frames, and joints to be manufactured quickly and consistently [11]. The technique is particularly useful for scaled model testing because dimensions, internal features, and material distribution can be adjusted to satisfy similitude requirements while reducing the time and cost associated with conventional fabrication methods. As a result, 3D printing has increasingly been used to investigate the load-carrying behaviour, deformation characteristics, and failure mechanisms of structural systems at reduced scale [12].

The most common filament used in 3D-printing is PLA filament (Polylactic Acid). PLA is easy to print, inexpensive, and produces good surface quality. It is biodegradable and made from renewable resources such as corn starch. Because it prints at relatively low temperatures and does not warp much, PLA is often recommended for beginners and for decorative or prototype models. Another widely used filament is ABS filament (Acrylonitrile Butadiene Styrene). ABS is stronger and more heat-resistant than PLA, making it suitable for functional parts, automotive components, and items that may be exposed to higher temperatures. PETG filament (Polyethylene Terephthalate Glycol) combines some of the best features of PLA and ABS. It is stronger and more durable than PLA, while being easier to print than ABS. PETG is also resistant to moisture and chemicals, making it useful for bottles, containers, and mechanical parts [13].

For applications requiring higher strength and toughness, engineering filaments such as Nylon filament and Polycarbonate filament are often used. Nylon is strong, wear-resistant, and slightly flexible, making it suitable for gears and moving parts. Similarly, polycarbonate is strong and heat-resistant, but it requires high printing temperatures and a controlled environment.

Table 1. Typical mechanical properties of filaments

	PLA	ABS	PETG
Young's Modulus (MPa)	2300-3000	1800-2300	1000-1500
Bending Modulus (MPa)	1900-3300	1500-2400	1000-2000
Elongation at Break	~4–10%	~10–40%	~20–80%

Source: [13]

Although full-scale testing of ICEB units and walls provides the most reliable assessment of structural behaviour, such testing is expensive, time-consuming, and often impractical. Consequently, scaled model testing has been proposed in this research as an alternative, particularly using 3D printing to fabricate reduced-scale specimens. However, it remains unclear whether 3D-printed scaled ICEB models can accurately reproduce the load-carrying capacity, deformation response, and failure mechanisms of full-size ICEB units and walls. In particular, the influence of scaling factor and restraint conditions on the similarity between the model and prototype has not been sufficiently established. This uncertainty limits the reliability of using 3D-printed scaled models for predicting the behaviour of full-size ICEB structures.

1.1 Objectives

The objectives of the research that will be discussed in this paper are:

1. To determine the load carrying capacity and failure modes of scaled ICEB units at 1:5, 1:8 and 1:10 scales.
2. To determine the load carrying capacity and failure modes of scaled ICEB wall panels at 1:5, 1:8 and 1:10 scales.
3. To correlate results from scaled ICEB unit and wall testing with full-size reference ICEB unit and wall from past research.

1.2 Limitations

In this research, only geometric scaling is adopted. The largest scaling factor was limited to 1:5 due to limitations of the both the 3D-printer and the testing equipment, whilst the smallest scale was 1:10, limited by the size of ICEB unit that can be comfortably handled by human hands. For 3D-printing of the ICEB units, PLA (polylactic acid) type filament was used, using a density of 15 %.

For individual scaled ICEB unit testing, three (3) replicates were prepared and tested for each scale and for the scaled ICEB wall testing only one (1) replicate were prepared and tested due to time and material constraints.

2. RESEARCH SIGNIFICANCE

This research contributes to the understanding of how scaled 3D-printed models can be reliably used to simulate the structural behaviour of ICEB units and walls. By systematically examining the parametric effects such as scaling factor, infill density and restraint conditions, the study provides insight into the limitations and applicability of similitude theory in masonry systems fabricated using alternative materials The findings highlight the extent to which scaled models can replicate load-carrying capacity, deformation characteristics, and failure modes of full-size structures, offering a practical pathway for reducing the cost and complexity of experimental testing. Existing literature on this topic remains limited, particularly in the application of either use of 3D-printing or scaled models for ICEB behaviour.

3. METHODOLOGY

3.1 ICEB Unit Testing

The scaled ICEB units were produced using similitude relationships and were scaled down geometrically using equations derived from past research [6] in Equation 1 below.

$$\lambda_s = L_a / L_r \quad (1)$$

where:
L_a= full scale model length
L_r= reduced scale model length

To ensure geometric similarity whereby the entire shape of the is retained after scaling, all relevant dimensions such as height, width, thickness of the full size ICEB unit were scaled down following the same geometric scale in equal ratios. Three scaling factors, λ_s, were investigated for the ICEB units (Table 2); namely 1:5, 1:8 and 1:10. These scales were chosen based past studies [5, 7] involving masonry as well which were able to produce results that replicated those of full-sized models. These scales were also limited by maximum governing size that the universal testing machine could accommodate as well as minimum size where the individual ICEB units could be comfortably handled by human hands.

Table 2. Dimensions of ICEB units at test scaling factors

ICEB	Scale	Dimensions (l x w x h) mm
Reference ICEB	1.0x	250 × 125 × 100
1:5 scale ICEB	0.2x	50.0 × 25.0 × 20.0
1:8 scale ICEB	0.125x	31.3 × 15.6 × 12.5
1:10 scale ICEB	0.1x	25.0 × 12.5 × 10.0

All scaled ICEB units were printed with the same slicer settings. A layer height of 0.1 mm to achieve fine resolution of small features, especially on the smallest scale ICEB brick to ensure the interlocking features such as the raised keys and the recesses on the brick could be physically printed. Although the 3D printer was capable of layer thicknesses down to 0.08mm, this was deemed unnecessary and would significantly increase the printing time. In terms of shell thickness, three perimeters were adopted for the two larger scales whilst two perimeters used for the smallest 1:10 scale ICEB units.

For infill density, two variations were investigated as it was determined that like mortar or concrete, infill density of the ICEB unit should present quite a significant effect its compressive strength. Hence for this research a low 15% infill density and high 75% infill density (Fig. 2) were both tested. The infill pattern adopted for both is a 45° (diagonal) grid of extruded filament.

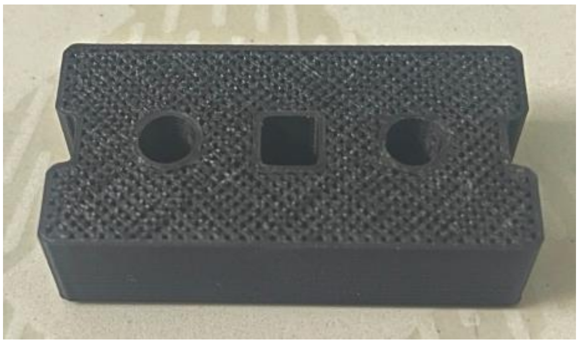

Fig. 2 Cross-section through a 3D-printed ICEB unit showing 75 % infill

The ICEB units were printed lying flat, i.e., with the bottom surface on the print bed (keys facing up). This means layer lines ran mostly horizontally along the length. This orientation ensured the load during compression (applied top down) was perpendicular to the layer deposition direction for most part. This orientation was chosen to avoid shear failure between layers and to maximize compressive strength of the print. It does, however, create a subtle anisotropy: the interlocking keys were built from the bottom up in layers, which could be a weak point if loaded laterally, but under direct compression it was acceptable.

The ICEB units were fabricated using Fabbxible PLA Pro filament, which had a nominal diameter of 1.75 ± 0.03 mm and a recommended nozzle temperature of 200–230 °C with a bed temperature of 30–50 °C. The choice was made to go with a PLA type filament as it had one of the highest Young's Modulus whilst at the same time demonstrated brittleness and low elasticity, which are very similar properties to masonry and ICEB units. Furthermore, PLA filaments are the most commonly used filament type on the consumer market.

To start off the fabrication of scaled ICEB units, a digital model of the ICEB unit was first reproduced in Sketchup Pro based on dimensions taken off a full size ICEB unit. This digital model was then imported into the 3D-printer native software where the geometric scaling was carried out prior to slicing and printing (Fig. 3). A desktop 3D printer employing fused deposition modelling (FDM) technique was used for 3D-printing of each individual ICEB unit using a 0.4 mm nozzle. Fig. 4 shows the printed ICEB unit at the three different scaling factors.

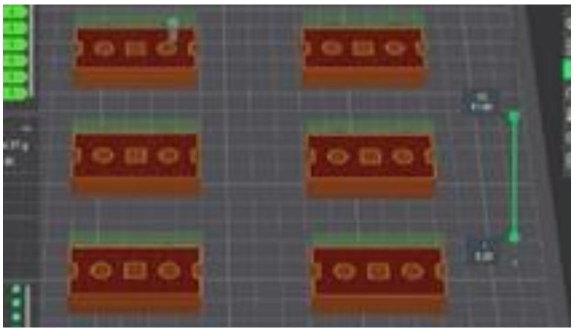

Fig. 3 Modelling the ICEB units digitally

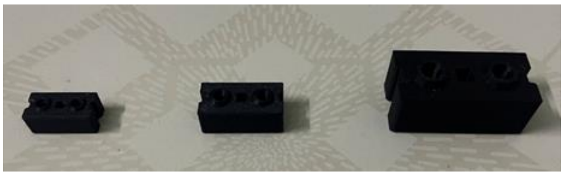

Fig. 4 3D-printed ICEB units at 1:10, 1:8 and 1:5 scales

The tests for the ICEB units mainly consist of compressive strength which would produce a load-deformation graph as well as the modulus of elasticity (slope of the curve). This compressive strength test allows comparison between the behaviour of ICEB units under different scaling factors to be studied as well as the effect of infill density. A summary of the test samples along with its respective tests is presented in Table 3.

Table 3. ICEB unit test specimens at differing scales

Samples	Infill %	Tests
Reference ICEB	-	Compressive strength
1:5 scale ICEB	15	Compressive strength
1:5 scale ICEB	75	Compressive strength
1:8 scale ICEB	15	Compressive strength
1:8 scale ICEB	75	Compressive strength

1:10 scale ICEB	15	Compressive strength
1:10 scale ICEB	75	Compressive strength

3.2 ICEB Wall Panel Testing

The scaled ICEB wall panel tests were carried out based on a full-size Reference Wall (Fig. 6) tested by previous research [14]. The Reference Wall measured 1000mm tall x 1000mm wide constructed using a mix of standard full ICEBs bricks and half bricks. With a wall thickness of 125mm, this gave the wall an aspect ratio of 1 and slenderness ratio of 8. The Reference Wall was retrained at the bottom and top using horizontal roller- supports (Fig. 5) to prevent out-of-plane deflection but nothing in between. Vertical compressive load was applied at the top of the wall with a plate with no eccentricity.

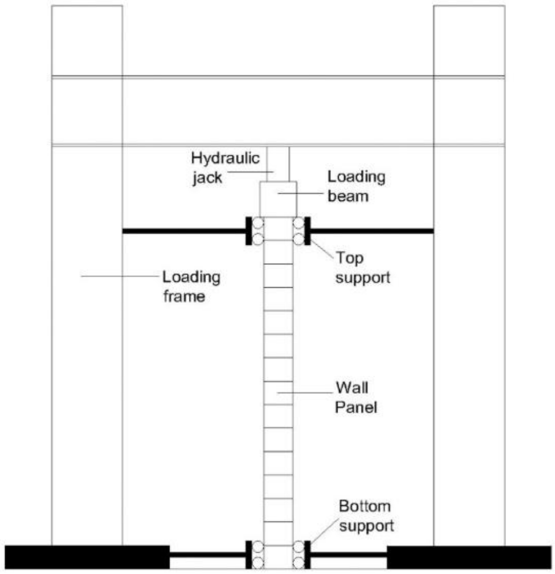

Fig. 5 Experimental Setup for Reference Wall

The scaled ICEB test wall panels were constructed using individually 3D-printed ICEB units comprising full and half bricks and scaled down based on the scaling rule established earlier for the ICEB units. Only ICEB units with 15 % infill were used in the wall test. The scaling factors investigated were 1:5, 1:8 and 1:10 (Fig. 6) and the final wall sizes are tabulated in Table 4. The boundary conditions of the Reference Wall were also replicated in the scaled wall panel by using makeshift steel frames to act as the top and bottom restraints/supports of the wall. Just like the reference wall as well, no mortar was used in the scaled wall panels.

Table 4. ICEB wall specimens at test scaling scales

Wall	Scale	Dimensions (l x w x h) mm
Reference wall	1.0x	1000 x 1000 x 125
1:5 scale wall	0.2x	200 × 200 × 25
1:8 scale wall	0.125x	125 × 125 × 15.6
1:10 scale wall	0.1x	100 × 100 × 12.5

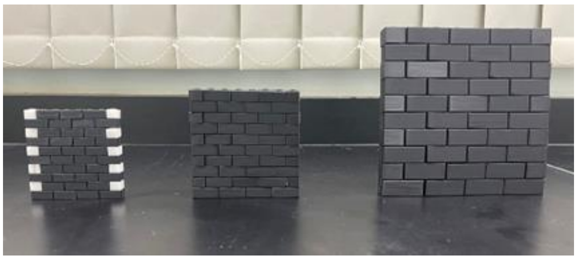

Fig. 6 Wall units assembled using 3D-printed bricks at 1:10, 1:8 and 1:5 scaling factors (left to right)

The scaled ICEB wall panels were subjected compressive strength tests using a universal testing machine (UTM) which would produce a load-deformation graph as well as the modulus of elasticity (slope of the curve). At the same time, the deformation of the wall as the load is being applied is observed using high-speed camera to determine the mode of failure.

Table 5. ICEB wall test specimens at differing scales

Samples	Restraint Condition	Tests
Reference wall	Unrestrained	Compressive strength
1:5 scale wall	Unrestrained	Compressive strength
1:5 scale wall	Restrained	Compressive strength
1:8 scale wall	Unrestrained	Compressive strength
1:8 scale wall	Restrained	Compressive strength
1:10 scale wall	Unrestrained	Compressive strength
1:10 scale wall	Restrained	Compressive strength

4. RESULTS AND DISCUSSIONS

4.1 Individual ICEB Units

The load-deformation diagrams of the scaled 3D-printed ICEB units are shown in Fig. 7.

For the largest ICEB scale of 1:5, the load increases steadily to a peak of approximately 4,400 to 4,500 N at around 1.1 to 1.2 mm deformation.

After the peak, all specimens show a gradual reduction in load, indicating post-peak softening. Overall, the three replicates display similar ultimate capacity but slightly different post-peak behaviour which is within acceptable standard deviation.

The 1:8 scale ICEB unit follow a very similar trend to the 1:5 samples, with load increasing rapidly and reaching a maximum of approximately 2,600 to 2,700 N at about 0.9 to 1.0 mm deformation. After the peak, the load remains relatively stable with only a slight decrease. The curves are closely grouped, indicating good repeatability between specimens. Differences in peak load and residual strength are small.

The smallest scale ICEB of 1:10 exhibit a two-stage response. Initially, the load rises to about 2,600 to 2,700 N at approximately 0.8 to 1.0 mm deformation and then remains nearly constant, forming a plateau up to around 1.4 to 1.5 mm deformation. After this, a second increase in load occurs, reaching a higher peak of approximately 6,000 to 6,500 N at around 1.9 to 2.0 mm deformation. Following the peak, the load decreases slightly.

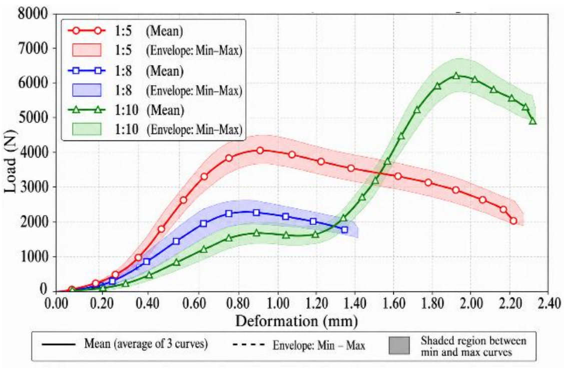

Fig. 7 Load-deformation diagram for 3D-printed ICEB units

In summary, the largest ICEB unit at 1:5 scale shows moderate load capacity with noticeable post-peak softening whilst the 1:8 scale specimen had the least post-peak reduction. Both the 1:5 and 1:8 scale ICEB units demonstrated response similar to that of a clay brick's sharp linear rise in elastic load-deformation zone but only the 1:5 scale post-peak behaviour replicated that of the clay brick's [15].

The smallest ICEB specimen at 1:10 has the highest load capacity and a distinctive two-stage response in the elastic zone, suggesting progressive engagement of additional resistance mechanisms before peak load was reached.

It needs to be noted here that the load-deformation diagram should not be used to assess the strength of the ICEB units as it doesn't take into account the changes in contact surface area as scale changes.

For a more representative strength assessment, the yield stress should be derived based on the peak load for all three scales as summarized in Fig. 8. It shows the variation in yield stress of the 3D-printed scaled specimens at different scaling factors. The results indicate a significant increase in yield stress as the scale of the specimens decreased. The 1:5 specimens recorded the lowest yield stress at approximately 3.6 N/mm², followed by the 1:8 specimens at approximately 5.3 N/mm². In contrast, the 1:10 specimens exhibited a substantially higher yield stress of approximately 20.7 N/mm².

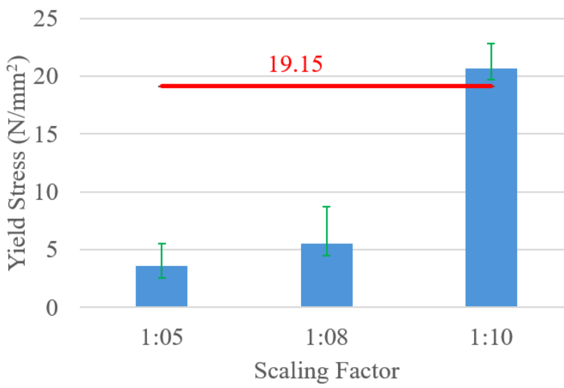

Fig. 8 Summary of the yield stress for scaled ICEB compared against the reference ICEB (in red)

The observed trend suggests that the smaller-scaled specimens demonstrated considerably greater resistance to yielding under compressive loading. The observed trend suggests that the smaller-scaled specimens demonstrated considerably greater resistance to yielding under compressive loading. Similar behaviour has been reported in previous studies on quasi-brittle materials such as concrete, where smaller specimens were found to exhibit higher apparent compressive strength due to size effect phenomena. Previous researchers have reported that compressive strength decreases with increasing specimen size and that specimen dimensions can significantly influence measured compressive strength values [16, 17]. These observations have commonly been attributed to factors such as reduced internal defects, shorter crack propagation paths, and more uniform stress distributions in smaller specimens.

In the present study, the increase in yield stress with decreasing scale may also be associated with characteristics of the 3D printing process. Smaller specimens may possess reduced geometric imperfections and improved interlayer continuity relative to their dimensions, resulting in greater apparent stiffness and strength. Furthermore, the smaller printed geometries may have promoted more uniform load transfer throughout the specimen, thereby delaying the onset of yielding under compressive loading.

Among the investigated scales, the 1:10 specimens produced yield stress values closest to the strength of the full-size reference ICEB unit, whereas the 1: 5 and 1:8 specimens remained substantially lower. This suggests that the 1:10 scaling factor provided the closest approximation to the target or prototype yield behaviour.

The error bars indicate some variability in the measured results for each scaling factor with the maximum standard deviation recorded at 3.2 % only. These findings demonstrate that scaling factor significantly influences the mechanical response of 3D-printed ICEB specimens and highlight the importance of considering scale effects in reduced-scale physical modelling investigations.

Full-size reference ICEB units exhibit a predominantly brittle failure mode (Fig. 9). Cracks initiate at the corners and along the web between the hollow cores, then propagate vertically and horizontally through the block. Materials at the face of brick ultimately spalls off into separate pieces with little visible deformation before failure [18], indicating the material has relatively low strain capacity and fails suddenly once its strength is exceeded.

Fig. 9 Failure of individual full-size ICEB is characterized by brittle splitting and breaking

In contrast, the scaled 3D-printed ICEB (Fig. 10) shows a more ductile failure mode. Instead of splitting apart, the block undergoes progressive crushing, flattening and squishing around the loaded region. The walls deform outward and the top surface compresses, while the brick remains largely intact. Failure occurs gradually through yielding and local crushing of the printed layers rather than through sudden cracking.

The different behaviour is likely due to the 3D-printed brick having a layered polymer material with lower stiffness but greater deformability, whereas the full-size ICEB is a cementitious material that is stiffer and more brittle. Thus, although the scaled brick may reproduce the general load path and geometry, it does not replicate the brittle splitting mechanism of the real brick exactly.

Fig. 10 Failure of individual scaled 3D-printed ICEB is characterized by more ductile form of crushing and squishing

4.2 ICEB Wall Panels

The load-deformation response for unrestrained ICEB is shown on Fig. 11. The load–deformation curve for 1:5 scale wall panel shows a continuous increase in load throughout the test. The response is initially gradual, then becomes steeper after approximately 2.5 to 3.0 mm deformation. The load reaches about 19,000 N at roughly 5.5 to 5.8 mm deformation, with no post-peak drop observed.

The 1:8 scale wall demonstrated a non-linear load increase followed by a distinct peak and subsequent reduction in load. The load rises slowly at first, then rapidly after about 3 mm deformation, at peak with around 6.8 to 7.0 mm deformation.

The load–deformation response for the smallest scale is similar in shape to 1:8 scale wall. The load remains low initially, then increases rapidly after about 3.5 to 4.0 mm deformation. A peak load of approximately 13,500 N is reached at around 7.0 to 7.5 mm deformation, followed by a drop to about 10,500 N. This indicates post-peak softening and failure, with lower strength than test walls 1:5 or 1:8. When these loads were converted to stress, the largest wall at 1:5 scale had the lowest sustained yield strength. The second largest wall at 1:8 reached a similar maximum load but showed clear post-peak failure. The smallest scaled wall, 1:10, had the lowest load capacity and the greatest reduction after peak load, indicating the weakest behaviour among the three specimens. All three responses were very similar to stress-strain curves from past research on compressive strength behaviour of clay fired bricks [19].

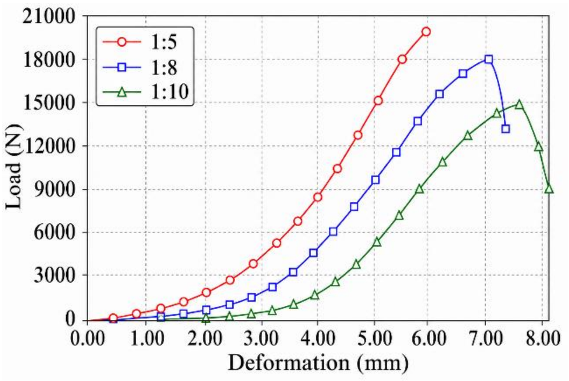

Fig. 11 Load-deformation diagram for 3D-printed ICEB walls (unrestrained)

Similar tests were also carried out for scaled 3D-printed ICEB walls but with 3D-printed grout tubes inserted through the hollow vertical cores of the ICEB unit to act as restraints. Fig. 12 shows the relationship between the scaling factor and yield strength for both unrestrained and restrained walls. The curve for the unrestrained walls shows a positive albeit non-linear relationship where the yield stress increases as the scale gets smaller. The largest reference wall at 1:1 scale had a strength of 2.54 N/mm² [14]. This gradually increased to 3.82 N/mm² for 1:5 whilst the 1:8 scale wall recorded a strength of 9.56 N/mm². The smallest wall at 1:10 recorded the highest strength at 10.91 N/mm². The increase is not as significant at larger scales where the 1:5 scale wall is about 1.6 times stronger than the reference wall. The most significant increase was observed at the 1:8 scale wall where the strength is about 3.7 times stronger than the reference wall. Finally, the 1:10 scale wall is about 4.3 times higher than the reference wall.

This indicates that all unrestrained wall specimens developed substantially greater yield stress than the reference value, with the difference becoming more pronounced at higher scaling factors. This result is also in agreement with past research that found individual ICEB units almost always have higher yield strength compared to its wall counterparts [20].

The effect of restraints appears to have little influence at low and medium scaling factors and only becomes much more significant at the highest scaling factor. At a scaling factor of 10, the restrained wall shows approximately 15.3 N/mm² greater yield stress, corresponding to about 35–40% higher strength than the unrestrained wall.

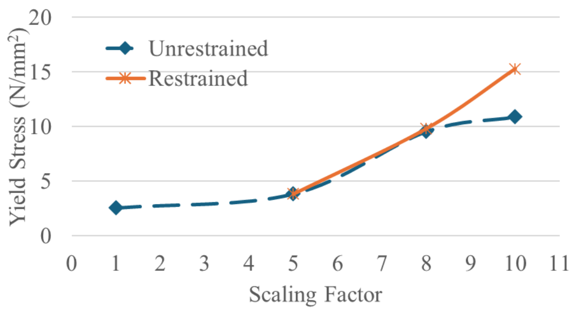

Fig. 12 Summary of the scaling factor effect on yield stress for walls

The unrestrained wall curve begins to level off after a scaling factor of about 8, indicating diminishing improvement in yield stress. In contrast, the restrained wall continues to increase sharply, suggesting that restraint becomes increasingly effective in enhancing wall strength as the scale factor increases.

All the scaled ICEB walls failed via lateral bulging or buckling at around mid-height, with the horizontal joints separating and opening up (Fig. 13) similar to that of a flexural failure due to out-of-plane loading [21]. This was observed for all three scaling factors tested; namely 1:5, 1:8 and 1:10. This observation is contrary to the direct compressive crushing expected. From past studies [22], masonry walls under vertical compression commonly exhibits vertical splitting cracks, crushing or spalling near the loaded ends as well as local crushing of mortar joints. Sometimes a combination of vertical cracking and slight outward bulging could also be observed.

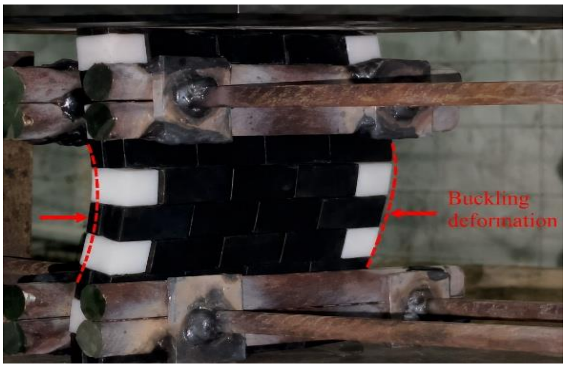

Fig. 13 Failure of scaled 3D-printed wall panel is characterized by lateral buckling instability

The scaled ICEB wall failure mode indicates instability due to excessive slenderness. This pronounced outward deformation at mid-height resembles compressive buckling of a slender column or panel and could still occur in full-size walls, especially if the wall is slender (high height-to-thickness ratio), the load has been applied eccentrically. This result could potentially mean that the slenderness at which a full-size ICEB wall buckles is different to that if a scaled ICEB wall.

5. CONCLUSION

Based on the uniaxial compressive strength tests and analysis of the results, the following conclusions are drawn:

1. Geometric scaling factor plays an influential role in determining the compressive strength of scaled ICEB units and walls.
2. The 3D-printed ICEB units show increasing load capacity with decreasing scales, with the 1:10 specimens exhibiting the highest peak load and a distinctive two-stage response. Meanwhile the 1:5 specimens show the lowest strength and greatest post-peak softening, with load-deformation curve very similar to that of a full-size clay brick.
3. The load-deformation curve can be used to study the elastic behaviour of ICEB units, it cannot be used to assess its strength because load is presented as a force in N or KN and does not take into account the reduced surface area of ICEB units as scales reduce. A better gauge of strength would be stress study.
4. In terms of stress, the smaller the ICEB unit scale got, the higher its yield strength was. The scaled ICEB unit that achieved yield strength closest to a full-size ICEB unit was the smallest scale ICEB at 1:10 scale. This finding agrees with past research involving scaled models of concrete members.
5. The full-size ICEB failed in a brittle manner through splitting and fracture, whereas the scaled 3D-printed ICEB exhibited a more ductile failure characterized by crushing and squashing.
6. The load-carrying capacity of the 3D-printed ICEB wall specimens increased as the model scale decreased, following a trend like those observed for the scaled ICEB units. Nevertheless, unlike the individual ICEB units, the wall specimens showed the closest agreement with the full-size ICEB wall behaviour at the largest scale of 1:5.
7. The inclusion of 3D-printed tubes to simulate grouted vertical restraints appear to contribute very little to the load carrying capacity of the walls at all scales but the smallest.
8. All the scaled walls failed through buckling at mid-height which is more commonly seen in wall subjected to lateral loads or walls that are very slender.

5.1 Future Work

1. Similar experimental work can be replicated using other filament types such ABS or PETG filaments, but these are unlikely to yield more accurate results as these materials are no stiffer than the PLA filaments tested here. A more promising research route would be to vary the printing parameters such as infill density, wall and layer thicknesses to better replicate ICEB behaviour.
2. As ICEBs are formed mainly from clay/earth, future investigations can include studies to identify which types of filament material most closely resemble the behaviour of clay/earth.
3. Further investigation should be undertaken to determine the critical slenderness ratio which triggers buckling failure in the different scaling factors of an ICEB wall. The ICEB material should also be investigated to determine if it plays a role in affecting this critical slenderness ratio too.

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