Investigating the Scaling of Masonry Structures in a Blast Environment

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Abstract

Full-scale experimental testing of masonry response to blast can be challenging with the requisite need for significant measurement area in conjunction with high construction and material costs. This paper investigates the use of dynamic similitude to produce reduced-scale masonry structures which model the damage state and debris distribution of a full-scale counterpart due to blast loading. An investigation into the fundamental physical components of masonry response to blast loading facilitated the development of a new scaling methodology which maintains the ratio of lateral and vertical force components as prescribed by dynamic similitude. It is shown that this can be accomplished by using a reciprocal scale factor for the reduced-scale structure's density. Computational models of full and reduced-scale masonry response to blast loading were produced with the Applied Element Method (AEM) to verify the underlying theory of the proposed scaling methodology. These utilised single-storey cuboid structures with non-responding roofs and half-thickness stretcher bond construction. Computational Fluid Dynamics (CFD) models of blast wave interaction with the masonry structures were defined at a range of peak overpressures, enabling a remap procedure into AEM. Importantly, AEM models utilised a constant 1:2 scale factor with masonry material parameters for commercially available units, demonstrating the practical applications of this scaling methodology for blast trials. Analysis of the AEM models demonstrated close qualitative agreement in damage state for full and reduced-scale structures at 55kPa and 110kPa peak free-field overpressure. These results also indicated agreement for a range of failure modes with the 110kPa model showing front-panel collapse versus the 55kPa model which indicated partial front-panel deflection. Chi-square analysis of the resultant debris distribution at 110kPa indicated quantitative agreement for the relative quantities of bricks found within the rubble pile as a function of their original panel wall location.

Keywords: Masonry, Structures, Blast, Scaling, Dynamic Similitude, Damage, Rubble

Notations

- $P(t)$: Pressure as a function of time, kPa
- A : Area of wall, m²
- S : Scale factor, N.D
- $\bar{F}_h$: Horizontal forcing vector, N
- $\bar{F}_v$: Vertical forcing vector, N
- m : Mass, kg
- g : Gravitational acceleration, m/s²
- w : Self-weight, N
- ρ : Material density, kg/m³
- V : Volume, m³
- $\bar{F}_d$: Drag force in lateral direction, N
- C_d : Drag coefficient, N.D
- W : Charge mass, kg
- R : Stand-off distance to explosive origin, m
- P_s : Free-field overpressure, kPa
- i_s : Specific free-field impulse, kPa.ms
- t^+ : Positive phase duration, ms
- Δ : Difference in mass, %
- O : Observed result, N.D
- E : Expected result, N.D

1. Introduction

The detonation of energetic materials such as high-explosive generates supersonic shocks which transfer momentum to ambient air particles. This process forms a discontinuous blast wave with significant static pressure in tandem with mass gas motion behind the blast front known as dynamic pressure. With the potential for substantial specific impulse, explosive events can result in severe damage for masonry structures. The complex dynamic response of masonry structures to blast loading can be classified by two phases, namely the lateral loading of an in-tact structure and the potential drag forcing of post-breakage projectiles. Specifically, the former characterises structural damage state while the latter relates to rubble distribution and associated hazard from airborne masonry fragments. The relative significance of these response modes is dependent upon explosive charge size and proximity, structural geometry and material properties.

In the simplest case, a non-load-bearing wall which is supported on multiple sides can be visualised as a panel wall. When subjected to the lateral loading of a blast wave, these tend to behave similarly to a two-way bending plate as shown in figure 1a. This results in two separate potential bending modes and thus enables two possible failure modes as shown in figure 1b. Closer examination of which reveals the potential for vertical bending with failure parallel to the mortar bed and horizontal bending with failure perpendicular to the mortar bed. Further inspection of figure 1b also reveals that blast loading can be visualised as a time-dependent lateral forcing to an in-tact structure, thereby representing a horizontal force component. Similarly, the self-weight of a structure can represent a vertical force component acting upon the structure. The post-breakage response of masonry projectiles is visually demonstrated in figures 2a-b. In these instances, masonry fragments will be propelled in the downstream direction with an initial horizontal velocity determined by the pre-break forcing and a potential horizontal motion component due to drag forcing. The vertical component of self-weight will determine flight time and hence overall throw distance.

Experimental blast testing of full-scale masonry structures can be challenging due to the requirement of a large and sufficiently robust testing area in addition to substantial costs for masonry materials and construction. Similar challenges have also been generally identified within the field of masonry structural dynamics, inspiring a number of investigations into potential scaling methodologies to circumvent these limitations. Principally, each of these studies have aimed to relate the response of a reduced-scale masonry structure (model) to its full-scale (prototype) equivalent.

When attempting to scale a dynamically loaded masonry structure there are typically two approaches available known as simple and complete modelling (Tomažević and

Velechovsky, 1992). A complete model aims to utilise proprietary materials which accurately scale the stress-strain relationship of the full-scaled material via a scale factor. This can be difficult to achieve as it requires the design, manufacture and verification of material properties for reduced-scale bricks which can only be utilised in a purely experimental scenario. Alternatively, simple models rely upon geometric scaling with reduced-scale structures being built from full-scale versions of the masonry materials as shown in figure 3.

Research by Dennis et. al (Dennis et. al, 2002) examined the response of $\frac{1}{4}$ scale walls with one-way spanning supports and single running mortar bonds via five blast trials. Masonry structures were constructed from standard concrete blocks with the global dimensions scaled to achieve geometric similarity. High-speed photography was used to monitor masonry response and wall deflection with each structure being found to have failed. FE models of wall failure were produced in DYNA3D and it was found that an inability to remove mortar elements from the FE model during deflection impeded agreement with the trials. Laefer et. al (Laefer et. al, 2011) investigated the manufacture and assembly of masonry walls at 1/10 scale to model the deflection and cracking of real-world structures due to nearby soil excavation. This study implemented a complete modelling approach with brick compressive strength, brick modulus of rupture, mortar tensile strength and masonry shear strength found to match a target reduction factor of 10. Post-trial analyses demonstrated an accurate representation of masonry crack patterns and vertical motion recorded for historic buildings at full-scale. The carefully controlled construction implemented within this study indicates that 1/10 scale is unlikely to be permissible in a typical blast test environment due to potential atmospheric variability in the form of moisture and wind.

Iqbal (Iqbal, 2013) sought to examine the blast response of a nuclear reactor containment chamber constructed from a coarse-grained schist at 1/8 scale via geometric similitude. Uniquely, this study calculated a hypothetical scaled distance parameter as a function of the geometrically scaled stand-off distance and charge mass. Five blast trials were conducted at a range of scaled distances for 5-100kg TNT equivalence. Post-trial visual analyses were utilised to determine the extent of containment unit cracking which enabled reasonable qualitative agreement to be demonstrated for FE models produced with SAP2000. Research by Herbert et. al (Herbert et. al, 2014) experimentally assessed the lateral capacity of six masonry structures subjected to wind loading at 1/6 scale by cutting full-scale bricks to the appropriate size to achieve geometric similitude. Loading was applied via a pressure bag rig within a swinging gondola centrifuge which enabled the effect of self-weight to be modelled. Deflection and cracking was measured in three dimensions via digital image correlation (DIC) and post-trial analyses indicated failure to be caused by vertical bending due to mortar cracking parallel to the bricks in each case. Failure loads were found to closely correlate with

Eurocode EC6 predictions in four trials whilst the other two trials differed with EC6 due to conservative predictions for the influence of a window aperture on failure loads.

To date, there have been no studies into the utilisation of dynamic similitude to produce reduced-scale models of masonry structure damage state and rubble distributions due to blast loading. This paper aims to redress this by developing a first principles methodology for the dynamic similitude of masonry structural response in a blast scenario. It will be shown that this can be accomplished by utilising a reciprocal scale factor for the reduced-scale structure's density. This methodology will be benchmarked via computational models of full and reduced-scale masonry response to blast with the Applied Element Method (AEM). Computational Fluid Dynamics (CFD) models will be implemented to simulate blast wave interaction with the masonry structures at a range of peak overpressures, enabling the configuration of forcing function for masonry loading. Importantly, these models will utilise a constant 1:2 scale factor in tandem with masonry material parameters for commercially available units, underscoring the novelty and practicality of this methodology. Initially, this study will focus on the damage state of the full (prototype) and reduced-scale (model) structures via panel deflection and cracking. Emphasis will then be placed on the resultant debris distribution for the full and reduced-scale structures due to the blast loading.

2. Scaling Methodology

The scaling methodology utilised within this research is built upon the principles of dynamic similitude which prescribes a ratio of lateral to vertical force components be maintained between full-scale and reduced-scale representations for the object of interest. In the case of masonry structures, this fundamental requirement is not satisfied when implementing simple geometric similarity as demonstrated in equations 1-4. The subscripts 'proto' and 'model' have been adopted to denote the full-scale and reduced-scale structural parameters respectively. The area utilised within equation 1 represents the frontal area of the masonry structure subjected to the blast wave. The subsequent multiplication of this area with the time varying blast pressure yields the horizontal force as shown in equation 1. Closer inspection of equation 2 indicates that a standard geometric scaling approach typically results in prototype and model structures being constructed from masonry units with equal density. The vertical force in equation 3 is shown to be the result of gravitational acceleration of the masonry structural mass and as such, the scale factor for this force is shown to be an inequality to that derived in equation 1 for the horizontal force. The by-product of which is visible in equations 3-4 where the ratio of lateral to vertical forces is not maintained.

$$A_{proto} \cdot S^2 = A_{model} \rightarrow P(t) \cdot A = \vec{F}_h \Rightarrow \vec{F}_{h_{model}} = \vec{F}_{h_{proto}} \cdot S^2 \quad (1)$$

$$\rho_{model} = \rho_{proto} = \frac{m_{proto} \cdot S^3}{V_{proto} \cdot S^3} \Rightarrow m_{model} = m_{proto} \cdot S^3 \quad (2)$$

$$\vec{F}_v = m \cdot g = w \Rightarrow \vec{F}_{v_{model}} = \vec{F}_{v_{proto}} \cdot S^3 \quad (3)$$

$$\left(\frac{\vec{F}_{h_{model}}}{\vec{F}_{v_{model}}} \right) \equiv \left(\frac{\vec{F}_{h_{proto}} \cdot S^2}{\vec{F}_{v_{proto}} \cdot S^3} \right) \equiv \left(\frac{\vec{F}_{h_{proto}}}{\vec{F}_{v_{proto}}} \right) \cdot S^{-1} \neq \left(\frac{\vec{F}_{h_{proto}}}{\vec{F}_{v_{proto}}} \right) \quad (4)$$

To circumvent the limitations associated with geometric scaling this study implemented a first principles methodology via fundamental mechanics, enabling a masonry structure to be represented as an inertial resistance to the momentum imparted by a blast wave. This study also aimed to develop a scaling methodology which can be readily adopted within blast tests.

After an initial examination of the parameters in equations 1-4 it was evident that the effect of gravity could not be scaled via a centrifuge or similar methodologies due to the inherent challenges of fielding these within an experimental blast environment, namely charge size and geometry. The remaining parameters available for numerical manipulation were therefore the lateral forcing vector due to blast pressure or the material density. Of the two variables, it was elected to focus on material density as this is likely to be more reliably controllable versus a complex blast environment. The derivation shown in equations 5-8 details the methodology implemented within this study to achieve dynamic similitude in the pre-break phase via modified material density for the model structure. The resultant effect is visible in equation 9 where the ratio of lateral to vertical forces has been maintained as prescribed by dynamic similitude. It can also be seen that geometric similarity has been maintained in equation 7 to ensure accurate structural proportions. By implementing an increase in structural density for the model structure, it can be said that the scaling methodology utilises a pseudo-increase in the model structure's inertia to offset the inability to scale gravitational acceleration directly in a blast environment.

$$\text{for dynamic similitude} \rightarrow \vec{F}_{v_{model}} \equiv \vec{F}_{v_{proto}} \cdot S^2 \quad (5)$$

$$\text{if } \vec{F}_{v_{model}} = m_{model} \cdot g \Rightarrow m_{model} = m_{proto} \cdot S^2 \quad (6)$$

$$\text{for geometric similitude} \rightarrow V_{model} = V_{proto} \cdot S^3 \quad (7)$$

$$\rho_{model} = \frac{m_{proto} \cdot S^2}{V_{proto} \cdot S^3} = \rho_{proto} \cdot S^{-1} \quad (8)$$

$$\text{where } \rho_{model} = \rho_{proto} \cdot S^{-1} \Rightarrow \left(\frac{\vec{F}_{h_{model}}}{\vec{F}_{v_{model}}} \right) = \left(\frac{\vec{F}_{h_{proto}} \cdot S^2}{\vec{F}_{v_{proto}} \cdot S^2} \right) \equiv \left(\frac{\vec{F}_{h_{proto}}}{\vec{F}_{v_{proto}}} \right) \quad (9)$$

Altering the model structure density will also affect the post-break response of masonry fragments. The transition to this phase can be characterised by the onset of fragmentation after the exceedance of a deflection limit which is a linear function of structural height. The

initial horizontal velocity of a fragment will in turn be determined by the pre-break lateral forcing due to blast pressure. The application of geometric similarity can be shown to equally reduce the model structure's height and resultant deflection limit for breakage by the applied scale factor. The result of which will be a decrease in break time and initial fragment velocity. The application of this study's scaling methodology within the post-break phase is shown in equations 10-12 below.

$$A_{model} = A_{proto} \cdot S^2 \rightarrow \vec{F}_d = q_s(t) \cdot C_d \cdot A \Rightarrow \vec{F}_{d_{model}} = \vec{F}_{d_{proto}} \cdot S^2 \quad (10)$$

$$\text{for dynamic similitude} \rightarrow \rho_{model} = \rho_{proto} \cdot S^{-1} \Leftrightarrow \vec{F}_{v_{model}} = \vec{F}_{v_{proto}} \cdot S^2 \quad (11)$$

$$\left(\frac{\vec{F}_{d_{model}}}{\vec{F}_{v_{model}}} \right) = \left(\frac{\vec{F}_{d_{proto}} \cdot S^2}{\vec{F}_{v_{proto}} \cdot S^2} \right) \equiv \left(\frac{\vec{F}_{d_{proto}}}{\vec{F}_{v_{proto}}} \right) \quad (12)$$

While equation 12 indicates that dynamic similitude may be maintained within the projectile fragmentation phase, there are a number of additional considerations to note. The magnitude of the lateral forcing component can be shown to be a function of the geometry and mass of a fragment, demonstrating the need for correlation in the relative shape and size of model fragments versus the prototype when dynamic pressure effects are non-negligible. The maintenance of geometric similarity will produce a decrease in structural height that in turn will decrease flight-time and throw distance for model fragments when compared to equivalent masonry courses in a prototype structure. The process of structural collapse is also likely to produce inelastic brick collisions before ground contact occurs. The combination of which with 'bounce and roll' during ground contact introduces a random process that is likely to influence the final rubble distribution. Finally, the initial horizontal velocity of a model fragment may also be lower than a prototype counterpart as discussed above.

The magnitude and influence of dynamic pressure within the post-break phase of masonry response is likely to be minor unless the blast scenario represents a very large event indicative of a hydrocarbon or large-scale TNT explosion. A recent example of which is the chemical explosions at the Port of Tianjin, China (2015). This study will not be focussing on such events but the preceding discussion is provided for instances where the blast wind from dynamic pressure results in sizable fragment throw distances and widely dispersed rubble distributions. This research will be focussing on smaller charge sizes which can be related to improvised explosive devices (IED) and similar explosive events that are associated with small scale terrorist attacks that have become increasingly prevalent in the 21st century. The post-break phase of a masonry structure can therefore be simplified to represent the continued deflection and potential collapse of panel walls, resulting in a rubble distribution that is confined to the immediate area within and surrounding the structure. As demonstrated above, the implementation of a modified material density in a model scenario yields a range of masonry

response and blast flow parameters which may or may not be influenced by the applied scale factor. Table 1 details each of the relevant parameters for the prototype and model structures in primary dimension format (Mass, Length, Time) with the addition of a scale factor where necessary for the model.

3. Masonry structure design

The practical application of this study's scaling methodology is fundamental to the principal aim. By researching a range of industry standard bricks and blocks it was possible to identify two commercially available units which adhere to the reciprocal scale factor relationship for density at a 1:2 level as shown in figure 4. This demonstrates that prototype structures can be constructed from solid concrete blocks at $\sim 950\text{kg/m}^3$ density and model structures from solid concrete commons bricks at $\sim 1900\text{kg/m}^3$ density. It is also shown in figure 4 that the concrete brick volume is effectively scaled by a factor of 0.47, which closely matches the desired factor of 0.5 at 1:2. This study will therefore maintain a constant 1:2 scaling level with all structures designed and constructed from the aforementioned units. As a means of providing an initial scientific benchmark for the scaling method, this research focussed upon simplified residential construction in the form of single-storey, enclosed structures with half thickness stretcher bonds and cuboid dimensions as shown in table 2 and figure 5. The roof enclosures implemented within these models simulate a non-responding surface to enable the study to focus on individual panel wall response. Future models will integrate load-bearing roof structures. The masonry dimensions at full-scale were selected to represent a single UK storey as shown by the prototype's 3.14m dimension in the vertical axis.

Prototype and model structures will utilise a constant type (iii) mortar with a predicted crushing strength of 4MPa. This mortar specification utilises a constant 10mm bed thickness to meet the durability criteria specified by BS5628 (The British Standards Institution, 2005) for external walls. The utilisation of a constant mortar material and thickness was chosen to mitigate potential issues with workability, curing and crushing strength due to modifying the mortar density in an applied scenario. Similarly, the specification of 10mm bed thickness moderates the issue of application uniformity when specifying a challenging thickness such as 5mm. The decision not to scale the material density or the bed thickness of the mortar may seem counter-intuitive, but it is evident in equations 15-18 that this practical approach yields the same mass scaling factor of S^2 for the model mortar when compared with the idealised scenario in equations 13-14.

$$Ideal \rightarrow \rho_{mortar_{model}} = \rho_{mortar_{proto}} \cdot S^{-1} \quad (13)$$

$$Ideal \rightarrow V_{mortar_{model}} = V_{mortar_{proto}} \cdot S^3 \quad \text{and} \quad m_{mortar_{model}} = m_{mortar_{proto}} \cdot S^2 \quad (14)$$

$$Practical \rightarrow V_{mortar_{model}} = (Width_{proto} \cdot S) \cdot (Breadth_{proto} \cdot S) \cdot Thickness_{proto} \quad (15)$$

$$Practical \rightarrow V_{mortar_{model}} = V_{mortar_{proto}} \cdot S^2 \quad (16)$$

$$Practical \rightarrow \rho_{mortar_{model}} = \rho_{mortar_{proto}} \Rightarrow m_{mortar_{model}} \equiv \rho_{mortar_{proto}} \cdot V_{mortar_{proto}} \cdot S^2 \quad (17)$$

$$Practical \rightarrow m_{mortar_{model}} \equiv m_{mortar_{proto}} \cdot S^2 \quad (18)$$

This study's scaling method relies upon first principles and the representation of a masonry structure as an inertial resistance to blast loading. It is important therefore to ensure that a composite model structure possesses an appropriate global density scaling factor when compared with the ideal reciprocal of the 0.5 scaling level. Tables 3 to 5 compare composite volume, mass and density respectively for a model structure built with commercially available units with the idealised model and the similarly constructed prototype. The culmination of which is visible in table 5 where it can be seen that an effective scaling factor of 0.54 closely matches the ideal case of 0.5, resulting in a 1:1.84 scaling level versus the idealised 1:2 level.

4. Computational Methodology

4.1 Blast scenario

This study investigates the response of full and reduced-scale masonry structures to the blast loading generated by a 100kg TNT equivalent spherically shaped charge positioned 1m above the ground surface. This charge size was selected to represent a small to medium explosive event indicative of the growing trend of global terrorist attacks seen throughout the 21st century due to the detonation of improvised explosive devices (IED). This was poignantly demonstrated by the Easter Sunday Bombings in Sri Lanka (April 2019) which led to 253 fatalities and a further 500+ sustaining injuries. In particular, the St. Sebastien's Church bombing in Negombo was found to produce a significant distribution of internal masonry debris. The 100kg TNT configuration examined within this research can be defined as a hemispherical ground burst due to the aptly named blast wave shape in three-dimensional space and the proceeding ground surface reflection. Critically, this reflection can be shown to significantly increase blast pressure values by an amplification factor of ~1.8 when compared with spherical air bursts. Design free-field overpressures of 55kPa and 110kPa were selected to represent a range of potential damage states and each structure was positioned with a face-on loading orientation. The notional blast wave thickness examined within this study results in the application of a pressure gradient to a structure as a function of its length. The result of which is differing pressure gradients for the model and prototype structures due to their absolute differences in length. To counter this phenomenon, an average pressure gradient was applied to the model and prototype structures as shown in table 6. This was accomplished

by positioning the centroid of each structure at equal stand-off distances, the result of which was differing stand-off distances for the front and rear faces of the model and prototype as shown in figure 6. The predicted blast parameters shown in table 6 were determined via the Kingery and Bulmash (Kingery and Bulmash, 1984) predictive polynomials for a hemispherical blast scenario.

4.2 CFD models

The use of CFD provides the capability to generate blast flow data and the subsequent blast forces present at structural faces during an event. As a result, this data can be re-mapped to configure forcing functions for masonry loading within an AEM model. Each CFD simulation was initiated using a dedicated quad-core Intel i7-3840QM 2.8GHz system with 16GB RAM. CFD analyses were conducted using the Air3D hydrocode (Rose, 2001) to simulate the reflected and free-field blast environments blast environment expected for a 100kg TNT charge with 1m height of burst. Each of the CFD models utilised an optimised 1D simulation from 0m in the X direction up to 1m to represent the height of burst. These 1D simulations were re-mapped into 2D with the domain extents and cell size detailed in tables 7-8. The visual interpretation of these domain extents can be seen in figure 7a for the X-Y plane in 2D. The 2D simulations were subsequently re-mapped into 3D with the domain extents and cell size detailed in tables 7-8. Figure 7b illustrates the resultant domain visualisation for the X-Y plane in 3D whilst figure 7c details the X-Z plane in 3D. Closer examination of figure 7b indicates that each of the boundaries were set to flow out in the X-Y plane whilst the ground surface was set to reflect in the X-Z plane as shown in figure 7c.

Each CFD model implemented a non-responding cuboid object to simulate the presence of a masonry structure. This methodology is well-suited to a short-duration blast scenario as the structural response time will far exceed the duration of the blast event, indicating that the structure is likely to retain much of its original shape during the application of blast loading. Figures 7b-c show the positioning of the non-responding cuboid structure with the centroid located at the desired stand-off. This visually represents the stand-off details shown in table 6 which aims to average the pressure gradient applied to the model and prototype structures. This is further demonstrated in figure 7d where the front, mid and rear stand-off locations have been identified.

Pressure gauges were defined throughout the domain of each CFD model to measure free-field and reflected parameters. Free-field pressure was monitored at the front, mid and rear stand-off distances for both the model and prototype structures with gauges located ~2m away from the lower and upper X boundaries at a 1.5m height to prevent reflections or interference from the blast wave's interaction with the structure. The measurement of free-field

blast parameters in particular provides an important accuracy check for simulation of the blast wave throughout the domain and by extension, its interaction with the structural objects.

Reflected pressure gauges were located at multiple positions on the front, side and rear face of the cuboid structures as shown in figures 8a-c. In particular, the front face was instrumented with two reflected pressure gauges down the centre line of the structure as shown in figure 8a. Initially, three gauges were located at equidistant intervals within regions which represented $\frac{1}{3}$ of the frontal area, however analysis of pressure time history results from these gauges demonstrated approximately equal results over the bottom $\frac{2}{3}$ of the area. The utilisation of fewer monitoring regions can be potentially useful for reducing simulation complexity within the AEM models of masonry response.

Figure 8b demonstrates that the side face was instrumented with three vertical regions, each representing $\frac{1}{3}$ of the area with one gauge located at the centre of each region. Due to the symmetrical nature of the structures with face-on loading, the pressure data from these gauges can be seen to represent both sides of the structure. Figure 8c demonstrates that the rear face was divided into three equal regions with each accounting for $\frac{1}{3}$ of the area. Reflected gauges were subsequently located at the centre of each area, allowing the pressure to be monitored due to clearing and rarefaction at the rear face.

4.3 Applied element method models

The Applied Element Method (AEM) was selected to fulfil the structural dynamics component of this study and in particular the explicit Lagrangian solver, Extreme Loading for Structures (ELS). Each ELS solution is modelled within a Lagrangian reference frame with an underlying force-displacement methodology, which provides a natural parallel with the first principles approach that underpins the scaling methodology of this research. The masonry loading aspect of these AEM simulations has been configured by re-mapping the reflected pressure data produced by the CFD models detailed in section 4.2. Each AEM simulation was conducted using a dedicated quad-core Intel i7-3840QM 2.8GHz system with 16GB RAM. ELS (Applied science international, 2010) is an explicit dynamics solver which utilises an AEM solver to simulate structural response to blast. Importantly, ELS provides the capability to model elastic and discrete inelastic phases of masonry response to blast loading. This is accomplished by the virtual discretization of the material continuum which enables continuum de-coupling via element separation into discrete bodies after the exceedance of a separation strain threshold. This methodology permits the simulation of rubble distributions after masonry failure. Consequently, AEM implements a continuous and discrete structural method within a single solver, representing a synergy of the Finite Element Method (FEM) and the discretized rigid bodies utilised by the Discrete Element Method (Lupoae and Bucur, 2009). Unlike the FEM which utilises nodes located at element vertices and boundaries, AEM alters element

connectivity by using a combination of face connecting normal springs and shear springs in the x-z and y-z planes.

The modification of element connectivity versus the nodal approach of FEM was borne out of the need to enable automatic element separation whilst generating an accurate model of global structural failure for a range of extreme loading scenarios including blast. In particular, the developers of AEM aimed to overcome the constraints associated with the FEM's Discrete Crack Method for modelling concrete cracking and element separation. Specifically, the need to pre-define failure location was found to constrain the Discrete Crack Method to the determination of fail/no-fail without the ability to represent global failure mode (Meguro and Tagel-Din, 2000). Recent attempts to combat these limitations with the FEM include a study which implemented an element deletion methodology (Pelfrene, 2016). This aimed to achieve automatic element removal after failure but encountered issues with model instability and the onset of large instantaneous cracks which compromised global structural behaviour.

In order to demonstrate the suitability of ELS for modelling extreme loading scenarios, the developers conducted nine blind test cases (Tagel-Din, 2009) of walls subject to blast loading for the US Defence Threat Reduction Agency (DTRA). The results of which demonstrated that ELS was able to closely match FEA analyses produced with LS-Dyna in terms of load-displacement and failure patterns, demonstrating the viability of AEM as an alternative method for producing sufficiently accurate results for DTRA. More recently, Keys and Clubley (Keys and Clubley, 2017) found that ELS simulations were able to closely match experimental data for the cracking mode and debris distribution of free-standing masonry panels when subject to blast loading from a 41kg TNT charge.

A series of AEM models were produced to analyse prototype and model masonry response to blast utilising the configuration details described in section 3 as shown in figures 9a-b. These models do not include a roof enclosure due to its non-responding design. Each model utilised the material parameters detailed in table 9 within which the separation strain and friction coefficient represent the default ELS settings for concrete. Table 10 details the element quantities and solution parameters for each of these models.

The forcing functions utilised to represent blast loading within the AEM simulations were configured by re-mapping reflected pressure data produced within the CFD models. This was fundamentally accomplished by dividing the masonry structures into loading regions matching the areas demonstrated in figures 8a-c. Figure 10 illustrates a magnified view of the stretcher bond construction and mortar application that was utilised to define model and prototype structures within ELS.

5. Results and Discussion

5.1 CFD models

Tables 11-12 compare CFD solutions for the free-field environment over the range of relative stand-off distances for the prototype and model structures against predicted values from section 4.2. Closer inspection of table 11 for the prototype shows the CFD values for free-field overpressure to be within $\pm 5\%$ of the predicted parameters at the front, mid and rear stand-offs for both the 55kPa and 110kPa scenarios. Similarly, results for specific impulse can be seen to be within $\pm 6\%$ of the predicted values for the prototype structure across the stand-off range. Examination of the positive phase duration results reveals CFD values ranging from -11% to -21% below the predicted values across the stand-off distances, indicating an accuracy level of $\pm 21\%$. These results infer that CFD solutions tend towards underestimating the positive phase duration, further demonstrated by a mean underestimation of -17% for the prototype results. Examination of table 12 for the model structure shows the CFD results for free-field overpressure to be within $\pm 5\%$ of the predicted parameters at the front, mid and rear stand-offs for both the 55kPa and 110kPa scenarios. Results for specific impulse can be seen to be within $\pm 6\%$ of the predicted values for the model structure across the stand-off range. Analysis of the positive phase duration results reveals values ranging from -11% to -19% below predicted values across the stand-off distances, indicating an accuracy level of $\pm 19\%$ and a mean underestimation of -16.3% . These results can therefore be seen to correlate with the prototype structure.

As described in the scaling methodology section, the approach adopted within this study considers a masonry structure to represent an inertial resistance to blast loading, inferring an importance on the accurate delivery of blast energy. For the purposes of this study, an acceptability criterion of $\pm 10\%$ was applied, indicating that an agreement level of $\pm 6\%$ for impulse in both the prototype and model solutions across the stand-off range represents an acceptable level of accuracy for modelling the effect of the blast force when compared with predicted values. Figures 11a-d illustrate the free-field overpressure and specific impulse time histories produced by the CFD solutions for the prototype and model scenarios in both the 55kPa and 110kPa scenarios. Closer examination of these figures demonstrates a close approximation to an idealised Friedlander curve for each stand-off distance, indicating that the blast wave was properly represented throughout the 3D domain.

Based on acceptable levels of accuracy for CFD solutions in the free-field environment, it was possible to utilise reflected pressure data to configure blast load forcing functions within AEM models of masonry response. Figures 12a-d illustrate the reflected pressure and impulse results for each gauge location detailed in figures 8a-c. Figures 13a-d illustrate time-history

progressions of blast wave interaction with the masonry structures. Examination of these demonstrates that a relatively small blast wave width does give rise to a pressure gradient as it progresses over and beyond the structures as discussed in section 4.1.

5.2 AEM models

Figures 14a-b show a time-history progression of masonry response for the 55kPa loading scenario. Closer inspection of these images shows the blast wave inflicts front face deflection and cracking within the model and prototype structures, resulting in a borderline collapse state for both structures. Figures 15a-b show a time-history progression of masonry response for the 110kPa scenario. These images demonstrate the blast wave inflicts significant front face deflection and cracking within the model and prototype masonry structures, leading to the collapse of the front panel wall. The rubble distribution within these models is confined to the inner area of the structures.

Table 13 details AEM rubble distribution results for the prototype and model structures by specifying relative percentages of total mass within the rubble pile as a function of original panel wall position. It can be noted that the model structure closely matches the prototype with minimal differences of +2%, +1% and +1% for the rubble distribution from the front, left and right panels respectively. The culmination of which was a minor difference of +4% of total structural mass within the rubble pile for the model structure versus the prototype. Table 14 details the results of a Chi-square goodness of fit test (Stattrek, 2018) for the discrete distributions shown in table 13. In this case, a significance level of 5% has been selected with the null hypothesis defined as “the model distribution matches the prototype distribution” whilst the alternative hypothesis has been defined as “the model distribution does not match the prototype distribution”. Examination of table 14 reveals a P-value of 20.6%, which indicates that there is insufficient evidence to reject the null hypothesis. Thereby adding weight to the argument that the model distribution of rubble matches the prototype.

6. Conclusions

This paper has numerically and computationally investigated the utilisation of a new scaling methodology for masonry response to blast loading by implementing dynamic similitude. It was shown that this can be accomplished by applying a reciprocal scale factor for the reduced-scale structure’s density. The practical application of this methodology was fundamental to the principal research aim and as such, this study emphasised commercially masonry available units which can be readily acquired trials whilst also adhering to the scaling requirements at 1:2. As a means of providing an initial scientific benchmark, simplified residential construction was investigated in the form of single-storey, enclosed structures with

half thickness stretcher bonds and cuboid dimensions with a constant type (iii) mortar as specified by BS5628. CFD solutions were defined using a hydrocode to simulate the free-field and reflected blast environments prescribed by the blast scenario design outlined in section 4.1. Examination of the free-field blast parameters versus predictions revealed impulse error levels of +/- 6%, indicating that models met the acceptability criteria of +/- 10%. This further enabled the reflected pressure records to be re-mapped for the purposes of configuring blast load forcing functions within the AEM models of masonry response.

Numerical models of masonry response were defined with AEM to investigate damage state and rubble distribution results for model and prototype structures. Examination of the numerical models for the 55kPa load-case revealed front panel wall deflection and cracking for the model and prototype structures, resulting in a borderline collapse states and close levels of qualitative agreement. Numerical solutions for the 110kPa load-case revealed significant front panel deflection within both the model and prototype structures, resulting in the collapse of the front panel wall and close levels of qualitative agreement. The aforementioned collapse at 110kPa also resulted in a masonry rubble distribution which was confined to the inner area of the structures. The utilisation of a Chi-square goodness of fit test indicated that the model structure's discrete distribution correlated with the prototype. This was confirmed by a minor difference of +4% of total structural mass within the model's rubble pile versus the prototype.

The evidence presented within this study indicates that a scaling methodology derived via dynamic similitude offers the opportunity to conduct accurate blast trials within smaller testing arenas with reduced cost and build times without compromising on data quality for masonry damage state and rubble distributions for a range of blast scenarios. Future work will seek to experimentally verify this conclusion by implementing the scaling method within a range of blast trials. The masonry construction within these trials will be accomplished by using the commercially available units described within this study with a similar, simplified residential construction approach for a range of design overpressures.

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Figure 1: Masonry wall visualisation: (a) Panel wall assumption; (b) Subdivision of panel wall failure modes.

Figure 2: Masonry fragment visualisation: (a) Velocity components of in-flight fragments; (b) Bounce and roll of masonry fragments.

Figure 3: Geometric similitude of a masonry structure.

Figure 4: Masonry unit specifications: (a) Concrete block; (b) Concrete brick.

Figure 5: Front elevation schematic of single-storey stretcher bond courses with brick requirement in lateral and vertical directions.

Figure 6: Plan schematic of stand-off range for prototype and model structures: (a) 110kPa; (b) 55kPa.

Figure 7: CFD domain schematic in 2D-3D: (a) X-Y plane 2D; (b) X-Y plane 3D; (c) X-Z plane 3D; (d) Masonry cuboid proportions and location.

Figure 8: CFD pressure gauge schematics: (a) Front face; (b) Side face; (c) Rear face.

Figure 9: ELS masonry structure visualisation in isometric view (a) Prototype structure; (b) Model structure.

Figure 10: ELS masonry structure stretcher bond visualisation with magnified view.

Figure 11: CFD free-field overpressure and impulse: (a) Prototype at 55kPa; (b) Model at 55kPa; (c) Prototype at 110kPa; (d) Model at 110kPa.

Figure 12: CFD reflected overpressure and impulse: (a) Prototype at 55kPa; (b) Model at 55kPa; (c) Prototype at 110kPa; (d) Model at 110kPa.

Figure 13: Time-lapse of CFD blast wave progression: (a) Prototype at 55kPa; (b) Model at 55kPa; (c) Prototype at 110kPa; (d) Model at 110kPa.

Figure 14: AEM masonry response at 55kPa: (a) Model & Prototype 0-200ms; (b) Model & Prototype 300-500ms.

Figure 15: AEM masonry response at 110kPa: (a) Model & Prototype 0-100ms; (b) Model & Prototype 250-750ms; (c) Model & Prototype 1000-3000ms.

(a)

Failure plane perpendicular
to mortar bed

Failure plane parallel
to mortar bed

(b)

(a)

(b)

Density = $950 \text{ kg/m}^3 \pm 10\%$

Volume = 0.016 m^3

(a)

Density = $1900 \text{ kg/m}^3 \pm 10\%$

Volume = $0.0014 \text{ m}^3 = 0.016 \times 0.47^3$

Effective Scale Factor = 0.47

(b)

(i) Stretcher course

(ii) Stretchers with header ends

(a)

(b)

(c)

(d)

(a)

(b)

(c)

(a)

(b)

Magnified

(a)

(b)

(c)

(d)

(a)

(b)

(c)

(d)

Overpressure
(kPa)

(a)

Overpressure
(kPa)

(c)

Overpressure
(kPa)

(b)

Overpressure
(kPa)

(d)

Table 1: Dimensional analysis of masonry and blast parameters.

Parameter	Prototype (MLT)	Model (MLTS)
Length, L	L	L·S
Area, A	L ²	L ² ·S ²
Volume, V	L ³	L ³ ·S ³
Material Density, ρ	M·L ⁻³	(M·S ²)·(L ⁻³ ·S ⁻³) = M·L ⁻³ ·S ⁻¹
Free-field Pressure, P _s	M·L·T ⁻² /L ²	M·L·T ⁻² /L ²
Horizontal Force, F _h = P _s ·A	M·L·T ⁻² /L ² ·L ² = M·L·T ⁻²	M·L·T ⁻² /L ² ·(L ² ·S ²) = M·L·T ⁻² ·S ²
Vertical Force, F _v = m·g	M·L·T ⁻²	(M·S ²)·L·T ⁻² = M·L·T ⁻² ·S ²
Drag Force, F _d = q _s (t)·A·C _d	ML ⁻³ ·L ² T ⁻² ·L ² = M·L·T ⁻²	ML ⁻³ ·L ² T ⁻² ·(L ² ·S ²) = M·L·T ⁻² ·S ²

Table 2: Masonry structural design parameters.

Structure Type	Dimensions in x, y, z (m)	Bond Type
Prototype	3.14 x 3.14 x 3.14	Stretcher
Model	1.57 x 1.57 x 1.57	Stretcher
Prototype	3.14 x 3.14 x 3.14	Stretcher
Model	1.57 x 1.57 x 1.57	Stretcher

Table 3: Effective scale factor of model structure volume.

Structure type	Structure volume (m ³)	Effective Scale Factors	
Prototype	7.56	$S^3 = (\text{Volume}_{\text{model}} / \text{Volume}_{\text{prototype}})$	$S_{\text{volume}} = (S^3)^{1/3}$
Ideal Model	0.94	0.125	0.5
Model	0.90	0.119	0.49

Table 4: Effective scale factor of model structure mass.

Structure type	Structure mass (kg)	Effective Scale Factors	
Prototype	7956	$S^2 = (\text{Mass}_{\text{model}} / \text{Mass}_{\text{prototype}})$	$S_{\text{mass}} = (S^2)^{1/2}$
Ideal Model	1989	0.25	0.5
Model	1741	0.22	0.47

Table 5: Effective scale factor of model structure density.

Structure type	Structure density (kg/m ³)	Effective Scale Factors	
Prototype	1052	$S^{-1} = (S_{\text{mass}}/S_{\text{volume}})$	$S = (S^{-1})^{-1}$
Ideal Model	2105	2	0.5
Model	1934	1.84	0.54

Table 6: Design blast parameters.

Structure Type	Charge, W (kg)	Structure Position	Stand-off, R (m)	Design Blast Parameters		
				Overpressure, P _s (kPa)	Impulse, i _s (kPa.m s)	Positive Phase, t ⁺ (ms)
Prototype	100	Front	18.5	65	336	15.9
		Mid	20	55	314	16.5
		Rear	21.5	50	294	17
Model	100	Front	19.25	61	324	16.2
		Mid	20	55	314	16.5
		Rear	20.75	53	304	16.8
Prototype	100	Front	12.75	140	466	12
		Mid	14.25	110	422	13.4
		Rear	15.75	90	386	14.4
Model	100	Front	13.5	124	442	12.8
		Mid	14.25	110	422	13.4
		Rear	15	99	403	13.9

Table 7: CFD domain parameters for 100kg TNT at 14.25m stand-off.

	X Direction (m)	Y Direction (m)	Z Direction (m)	Cell Size (mm)	Cell Count in X	Total Cells	Run Time (min)
1D	0-1	-	-	4.6	-	218	32
2D	0-12	0-10	-	25	480	192 x 10 ³	
3D	4-24	0-15	0-10	100	200	3 x 10 ⁶	

Table 8: CFD domain parameters for 100kg TNT at 20m stand-off.

	X Directi on (m)	Y Directi on (m)	Z Directi on (m)	Cell Size (mm)	Cell Count in X	Total Cells	Run Time (min)
1D	0-1	-	-	4.6	-	218	15
2D	0-18	0-10	-	25	720	288×10^3	
3D	10-30	0-15	0-10	100	200	3×10^6	

Table 9: ELS material parameters for masonry simulations.

	Densi ty (kg/m³)	Young' s Modul us (GPa)	Shear Modul us (GPa)	Compres sive Strength (MPa)	Tensil e Streng th (MPa)	Separat ion Strain	Friction Coeffici ent
Concr ete Blocks	950	26.2	10.5	7.3	0.73	0.1	0.8
Concr ete Bricks	1900	26.2	10.5	20	2	0.1	0.8
Type (iii) Morta r	2100	26.2	10.5	4	0.4	0.1	0.8

Table 10: ELS solution parameters for masonry simulations.

Design Overpressure	Structu re Type	Whole Brick Elemen ts	Half Brick Elemen ts	Mortar Elemen ts	Proble m Time (s)	Solutio n Step (μs)
55kPa	Prototy pe	400	240	2080	4	100
	Model	400	240	2080	4	100
110kPa	Prototy pe	400	240	2080	4	100
	Model	400	240	2080	4	100

Table 11: CFD free-field blast results for prototype structure.

		w = 100kg, r = 20m			w = 100kg, r = 14.25m		
		P_s (kPa)	i_s (kPa.ms)	t⁺ (ms)	P_s (kPa)	i_s (kPa.ms)	t⁺ (ms)
Front (R - 1.5m)	CFD	66.7	351	14.2	146.1	437	9.6
	Predicti on	65.4	336	15.9	139.6	466	12
	+/- %	2%	4%	-11%	5%	-6%	-20%
Mid (R)	CFD	57.5	317	13.9	116.1	403	10.8
	Predicti on	56.4	314	16.5	110.2	422	13.4
	+/- %	2%	1%	-16%	5%	-5%	-19%
Rear (R + 1.5m)	CFD	50.4	296	13.4	93.5	395	12.3
	Predicti on	49.5	294	17	89.7	386	14.4
	+/- %	2%	1%	-21%	4%	2%	-15%

Table 12: CFD free-field blast results for model structure.

		w = 100kg, r = 20m			w = 100kg, r = 14.25m		
		P_s (kPa)	i_s (kPa.ms)	t⁺ (ms)	P_s (kPa)	i_s (kPa.ms)	t⁺ (ms)
Front (R - 0.75m)	CFD	61.9	324	14.4	129.4	416	10.4
	Predicti on	60.6	324	16.2	123.5	442	12.8
	+/- %	2%	0%	-11%	5%	-6%	-19%
Mid (R)	CFD	57.5	317	13.9	116.1	403	10.8
	Predicti on	56.4	314	16.5	110.2	422	13.4
	+/- %	2%	1%	-16%	5%	-5%	-19%
Rear (R + 0.75m)	CFD	53.9	306	13.6	103.9	397	12
	Predicti on	52.7	304	16.8	99.1	403	13.9
	+/- %	2%	1%	-19%	5%	-1%	-14%

Table 13: AEM rubble distribution, model & prototype, 110kPa overpressure.

Structure	Wall Panel	Number of Blocks	Equivalent Mass	% Total Mass
Model	Front	110	369	21%
Prototype		101	1548	19%
			Δ %	+2%
Model	Left	37	124	7%
Prototype		31	475	6%
			Δ %	+1%
Model	Right	36	121	7%
Prototype		30	460	6%
			Δ %	+1%
Model	Sum	183	613	35%
Prototype		162	2483	31%
			Δ %	+4%

Table 14: Chi-square goodness of fit, AEM rubble, model & prototype, 110kPa overpressure.

Chi-Square Goodness of Fit Test			
Panel	Model = Observed (O)	Prototype = Expected (E)	(O-E)²/E
	Number of Bricks	Number of Blocks	
Front	110	101	0.80
Left	37	31	1.16
Right	36	30	1.20
Sum = χ^2			3.16
P-value			20.6%

Conflict of Interest Statement:

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Based on the declaration of these associations, the authors state that no conflicts of interest exist within this research.