Experimental and numerical investigation on penetration of clay masonry by small high-speed projectile

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Masonry is one of the most common building materials, which is used due to low cost, good sound and heat insulation properties, easy availability and locally available material [1]. Masonry walls are consisted of bricks and mortar which interconnect regularly, the bricks are jointed together by the mortar through various conventional patterns. Since its extensive application it would certainly be subjected to a variety of strikes from human activities such as wars and military conflicts apart from erosion of natural forces wind, rain and so on. The knowledge of masonry will be useful if on urban battlefield because of the inability of conventional forces to manoeuvre troops and vehicles with ease. Many reviewer hold that urban warfare is on the increase, with recent events in Iraq, Libya and Syria indicating that the battleground is shifting inexorably to large and small conurbations. Thus it is necessary to work out how to operate in the future urban environment and maximise our capabilities at a time of diminishing military strength [2]. As pointed out by C. S. Meyer, the U.S. Army’s concern in urban operations has brought about efforts at the U.S. Army Research Laboratory to develop an initial set of material model parameters to enable physics-based penetration simulations of high-fidelity brick and mortar masonry wall models. A search of publicly released literature turned up not much concerning modeling and simulation of weapon effects against brick and mortar targets. The characteristic of concrete under dynamics load has been studied in detail however the investigation of dynamic material properties of brick and mortar is in early stages [3].

What has been historically employed to investigate the dynamic characteristic of concrete includes theoretical method, experimental method and the numerical simulation. It has been shown that numerical stimulation is a cost-effective method and can provide more information of process history for sophisticated analysis than experimental method. Nevertheless, the data from experiments were crucial because on the one hand any modern analysis and stimulation computation should necessarily be validated by those come from real range tests, on the other hand the material parameters which are of vital importance to obtain a reasonable and compelling result must be furnished by or refer to experimental data [4]. The experimental exploration indicates that brick and mortar joint act similarly as concrete. Many material models are proposed to describe the behaviour of concrete, which are able to apply to solution of simulating behaviour of masonry reasonably. Li et al. [5] investigated the response mode of masonry subjected to vented gas explosion through experiment and simulation, in which the anisotropic material model *MAT_96 (MAT_BRITTLE_DAMAGE) has been adopted. The material model has been developed by Govindjee et al.[6]. Meyer explored profoundly the potential of the HJC model to apply in simulation of penetrations, which was initialled by Holmquist and Johnson in 1993 [3].
The effect of strain rate has been called concern in case of high velocity impact. Under dynamic loading the material behaves differently from quasi-static, most materials show an increase of strengths and stiffness with an increase of the strain rate. To better represent the behavior of structure under dynamic loadings these dynamic phenomena must be taken into account in the material modes [7]. Hao and Tarasov studied clay brick and mortar at different strain rate in detail and defined DIF (Dynamic Increase Factor) to characterize the relationship between magnitude of material parameter (including ultimate strength, yield strength, strain at ultimate strength, yield strain, Young’s modulus) at high strain rate and low strain rate, based on uniaxial compressive test strain rate ranging from \(2 \times 10^6 \text{s}^{-1}\) to \(200 \text{s}^{-1}\) [8]. The experimental results of brick and mortar obtained from Pereira and Lourenço revealed similarity of the relationship between dynamic and static property of clay brick and mortar. And the masonry built using four cut clay bricks (original solid bricks were cut to match the dimensions of test setup) and three mortar joints (10-mm joint) in a stacked pattern was also investigated as well [9]. They also included the DIF of facture energy of material and masonry. And the numerical simulation has been adopted to explore the effect of strain rate in [10]. It should be noted that [8], [9], [10] studied the dynamic characteristic of material under compressive impact. The tensile dynamic increase factor (DIF) of masonry joints was investigated in [11] and the DIF 3.1 relative to its quasi-static reference for a strain rate of \(1 \text{s}^{-1}\) was concluded. And both the tensile and compressive experiments of several varieties of clay bricks have been conducted by Gebbeken et al., which revealed that different kind of brick display different DIF, about 1 for ceramic brick for example, though an overall enhancement has been validated of other kinds of brick [7].

The strategies to numerically model masonry wall fall into three categories [7]. First method is macro-model in which the inhomogeneous composite material masonry, consisted of brick and mortar, is homogenised to one single material, either with isotropic or anisotropic physical characteristic, as applied to simulate unreinforced masonry with a plane stress macro-model in [12]. The second approach is simplified micro-model which simplifies the mortar joints as a surface of no thickness described by interface element and the size of the masonry units have to stretch correspondingly to adapt to the whole wall, as Michaloudis et al. in [13], Su in [14], Wei and Hao in [10] and Medeiros et al. in [12] simulating reinforced masonry. The last one is micro-model which constructs masonry with an assembly of bricks connected by mortar joints retaining the most detail. The bricks and mortar joints have the same size as in reality. And the interaction between bricks and mortar joints can be described by interface element or by defining contact in simulation software, as Li et al. in [5]. Then the model is able to examine the failure of brick, mortar joint and the bond between the brick and mortar, as Li et al. in [5] using detailed micro model to simulate the response of confined brick masonry walls subjected to vented gas explosion.

Analytical modeling of masonry demands the properties and interrelationships of brick and mortar; it is not easily available because of limitation of experimental tests and variation in properties and proportion of material [15]. However, simply exploring the researches on masonry just demonstrated that the study of experiment and simulation towards the distinct, composite, old structure have gown gradually. Still, the knowledge and code drafting on structural masonry is far less consensual than reinforced concrete or steel [14]. Mentioned researches previously have investigated quasi-static and dynamic behavior of brick, mortar, and masonry from a wide scale. Some of them focused on the constitutive formula and failure criteria of brick, mortar and cohesion between them, some of them detailed ways of constructing model of simulation, some investigated the mode of failure when masonry was subjected to quasi-static pressure or explosive blast loads, which all take us further on the road of understanding masonry as a composite and its anisotropic constituents, namely brick and mortar, and interaction between them. The exploration of penetration towards masonry was not found though.

In this article, an experimental system was designed to capture velocity of the bullet and ensure safety at the same time. As shown in figure 1, using it, the penetration experiment of small high-speed projectile, namely type 54 12.7mm diameter bullet, towards masonry at different velocities was performed. A detailed micro-model was developed to investigate the effect of velocity of projectile
and behavior of the masonry in the process of penetration. The method of discretization and the contact algorithms employed was elaborated. The material tests was conducted to study the property of brick and mortar under static and dynamic loadings (i.e. different strain rate), which contributed to determine material parameters of numerical stimulation. The DIFs of compressive strength were obtained by fitting the experimental data using least square method presented in equation (1) and (2) for brick and mortar, respectively.

\[
\text{DIF} = 0.126 \ln(\dot{\varepsilon}) + 0.1208 (0.0074 / s \leq \dot{\varepsilon} \leq 993 / s) \quad (1)
\]

\[
\text{DIF} = 0.084 \ln(\dot{\varepsilon}) + 1.089 (0.0042 / s \leq \dot{\varepsilon} \leq 829.83 / s) \quad (2)
\]

The result of simulation has been validated by test data. The response of masonry has been reflected by state of stress of an element selected from adjacent area of perforation, which was presented in figure 2. The two dot-lines represented the velocity-time curves of bullet penetrating 37 wall and 24 wall both setting left axis to y axis and the line denoted the pressure-time curve of element setting right axis to y axis. It was demonstrated that the trend of velocities of the bullet before 500 microseconds were similar either in 37 wall or 24 wall then the absolute value of deceleration of bullet penetrating 24 wall decreased more rapidly than 37 wall, which attributed to the thinner thickness and the simpler bonding pattern. And when the bullet departed from the masonry, constant velocity as a sign, the pressure of element indicated that the masonry didn’t cease to response, which illustrated that though the process of penetration is transient ranging 0 ~ 1100 microseconds but the response of masonry is continuing after the bullet has separated from the masonry, of which ranged 1100 ~ 1250 microseconds. And the trace of stress indicated the energy was dissipated as form of stress wave.

![Figure 1. Experimental delineation.](image-url)
Figure 2. The velocity of bullet of 24/37 wall and pressure of the element

By altering the position where bullet impacted the different efficiency of penetrating was investigated. This paper is an extended abstract – the full version of this extend abstract will appear in Defence Technology in 2020.

Reference
[1] Kumavat H R 2016 Journal of The Institution of Engineers (India): Series A vol. 97 3 199–204
[2] Fremont-Barnes G 2020 A History of Modern Urban Operations Ed G. Fremont-Barnes (Switzerland :Springer Nature ) p 58
[3] Meyer C S 2011 Development of Brick and Mortar Material Parameters for Numerical Simulations Dynamic Behavior of Materials Volume 1 New York NY 351–59
[4] Lin S L 2016 Experimental and Simulation of Projectile Penetrating Concrete Target Beijing University of Technology.
[5] Li Z, Chen L, Fang Q, Hao H, Zhang Y D, Xiang H B, Chen W S, Yang S G and Bao Q Jun. 2017 Experimental and numerical study of unreinforced clay brick masonry walls subjected to vented gas explosions,” Int. J. Impact Eng. 104 107–26
[6] Govindjee S, Kay G J and Simo J C 1996 International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 33(4)
[7] Gebbeken N, Linse T and Araujo T 2012 Masonry under Dynamic Actions - Experimental Investigations, Material Modeling and Numerical Investigations
[8] Hao H and Tarasov B 2008 Experimental Study of Dynamic Material Properties of Clay Brick and Mortar at Different Strain Rates Australian Journal of Structural Engineering 8 117–32
[9] Pereira Joao M and Lourenco Paulo B 2017 Experimental Characterization of Masonry and Masonry Components at High Strain Rates Journal of Materials in Civil Engineering 29 2 04016223
[10] Wei X and Hao H 2009 International Journal of Impact Engineering 36(3) 522–36
[11] Burnett S, Gilbert M, Molyneaux T, Tyas A, Hobbs B and Beattie G Jun. 2007 The response of masonry joints to dynamic tensile loading Materials and Structures 40 (5) 517–27
[12] Medeiros P, Vasconcelos G, Lourenco P B and Gouveia J Apr. 2013 Numerical modelling of non-confined and confined masonry walls Construction and Building Materials 41 968–76
[13] Michaloudis G and Gebbeken N Jan. 2019 Modeling Masonry Walls under Far-field and
Contact Detonations *International Journal of Impact Engineering* **123** 84–97

[14] Su Y, Wu C, and Griffith M C Jan. 2011 Modelling of the bond-slip behavior in FRP reinforced masonry *Construction and Building Materials* **25** no. 1 328–34

[15] H. R. Kumavat, 2016 An Experimental Investigation of Mechanical Properties in Clay Brick Masonry by Partial Replacement of Fine Aggregate with Clay Brick Waste *Journal of The Institution of Engineers (India): Series A* **97** no. 3 199–204