Sensitivity Analysis of the Parameters used in the Simulation of Brick Masonry Wallettes under Diagonal Shear using Applied Element Method

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1. Introduction

Human casualties due to earthquakes in the 20th century are mostly due to structural damage and most of which is assigned to unreinforced masonry buildings. Understanding of masonry wall behavior under lateral load is important in evaluating the seismic vulnerability of existing buildings and developing proper retrofitting measures.

Masonry sustains damage in form of cracks at early stage of loading as the mortar breaks at a low level of load compared to brick units. Start of cracking along the mortar joints is indication of masonry inelastic response rather than failure [Langenbach, 1]. So, it is important to capture the behavior of masonry after cracks have developed.

Attempts have been made to implement micro-level modelling of masonry in Finite Element Method (FEM) and Discrete Element Method (DEM). In Finite Element analysis mesh sensitivity and failure to capture diagonal shear have been identified [Lofti et al, 2]. DEM can deal easily with large displacements and total separation of the bodies. However, poor constitutive laws for brick and mortar interface have been used leading to poor quantative results. To this end, Applied Element Method (AEM) is a numerical tool capable to follow the complete structural response from initial stage of loading until total degradation in large displacement ranges with reasonable accuracy [Meguro et al, 3].

So far, AEM has been used to simulate the behavior of masonry by [Pandey et al, 4] and [Mayorca et al, 5]. Constitutive models for anisotropic materials, such as masonry, contain several parameters that have to be quantified experimentally. However, it is quite difficult to get such parameters from simple material tests. So, the parametric study of such parameters using appropriate numerical simulation tools and data from simple experiments can help to choose proper values for the analysis of larger structures. This work makes a sensitivity analysis of some of the parameters required to simulate the behavior of masonry. Diagonal shear tests [ASTM, 6] are commonly used to determine masonry strength and were therefore used for the sensitivity analysis in this study.

2. Applied Element Formulation and Material Modeling

In AEM, the structure is assumed to be virtually divided into small square elements each of which is connected by several pairs of normal and shear springs set at contact locations between adjacent elements. These springs bear the constitutive properties of the domain material in the respective area of representation. The structure global stiffness is built summing up all element stiffness which are contributed by the springs around them. The 2D problem global matrix equation is solved at the three degrees of freedom of each element. Stress and strain are defined based on displacements of spring end points on element edges. Details of Applied Element scheme can be found elsewhere [Meguro et al., 3].

For the parametric study presented in this paper, the AEM program for masonry developed by Mayorca et al [5] was used with some minor changes. The constitutive relations, formulated in the framework of plasticity theory, use two yield surfaces known as tension cut-off criterion and Mohr-Coulomb criterion given in equations (1) and (2) respectively.

$$f_1(\sigma,\kappa_1) = \sigma - \bar{\sigma}_1 \text{........}(1) \qquad \bar{\sigma}_1 = \begin{cases} f_t\left(1 - \dfrac{f_t}{G_f^I}\kappa_1\right) & \kappa_1 \le \dfrac{2G_f^I}{f_t} \\ 0 & \kappa_1 > \dfrac{2G_f^I}{f_t} \end{cases}$$

$$f_2(\sigma,\tau,\kappa_2) = |\tau| - \sigma\tan\phi - \bar{\sigma}_2 \text{......}(2) \qquad \bar{\sigma}_2 = \begin{cases} c\left(1 - \dfrac{c}{G_f^{II}}\kappa_2\right) & \kappa_2 \le \dfrac{2G_f^{II}}{c} \\ 0 & \kappa_2 > \dfrac{2G_f^{II}}{c} \end{cases}$$

Where, f_t: tensile strength of masonry, c: masonry cohesion, G_f^I and G_f^{II} : fracture energy for pure tension and shear respectively, and ϕ: friction angle between mortar and brick unit, K_1 and K_2: hardening parameters, σ and τ: normal and shear stress respectively.

3. Experimental Model and AEM Result

At first, the model accuracy was verified using the tests carried out by [Sathiparan, 7]. Masonry wallettes of dimensions 292.5×290×50 mm^3 consisting of 7 rows of 3 and half brick each with mortar thickness of 5 mm were tested for diagonal shear. A masonry wallette of same dimensions was modeled with AEM and similar boundary conditions were used. The parameters used for the numerical simulation are given in **Table 1**.

Table1: Parameters used for numerical simulation

E_b	E_m	f_t	c	G_f^I	G_f^{II}	tanϕ
(kN/mm^2)				(kN-mm/mm^2)		
15.0	0.03	5.9e-5	8.6e-5	4.8e-6	4.8e-5	0.75

Among these parameters, Eb, Em (Young's modulus of brick and mortar), f_t and c were obtained from experiments, while the parameters G_f^I, G_f^{II} and tanϕ were obtained from parametric study.

Figure 1 shows the boundary conditions and crack patterns from experiment while **Figure 2** shows the same from the numerical simulation. The crack patterns are similar in both cases. Force-Displacement relation from the experiment and the numerical simulation were compared and a good agreement was found. Experimental results from three

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tests of masonry wallettes and the result obtained from numerical analysis are plotted in **Figure 3**.

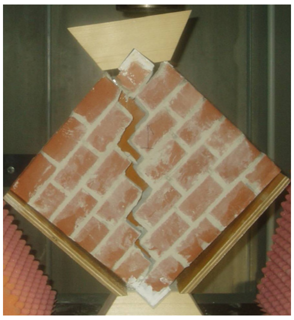

Figure 1: Crack patterns of masonry wallette from experiment [Sathiparan,6]

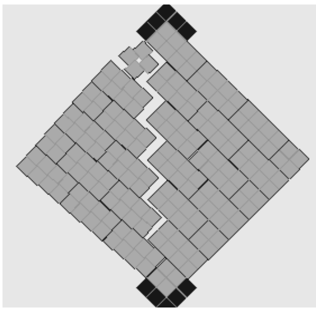

Figure 2: Crack patterns obtained from numerical simulation

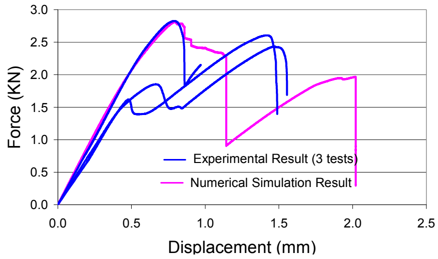

Figure 3: Results from experiment and numerical simulation (Experimental results from [Sathiparan, 7])

4. Sensitivity to Friction Angle

Seven analysis cases varying the friction coefficient from 0.3 to 0.9 were done keeping other parameters same as given in **Table 1**. From the study it was found that there is a significant role of friction angle in the behavior of masonry. More than 50% of the peak load was increased with the increase of the friction coefficient from 0.3 to 0.9. As the friction between the mortar and brick unit depends not only on the material strength but also on the roughness of the masonry units, a good behavior of masonry can be obtained by using rough surfaced units like hollow bricks or blocks. Further, it was found that increase /decrease in friction alter the prevalent failure mode. In case of low friction, the prevalent failure mode was slip along the joint plane while as in case of high friction the prevalent failure mode was splitting tension.

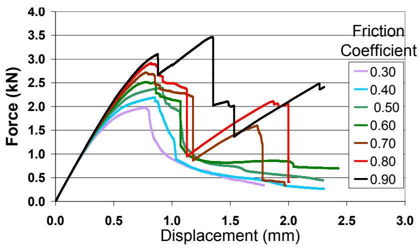

Figure 4: Wallette behavior for different friction angle

5. Effect of Fracture Energy

Fracture energy, which is associated with unit-mortar interface, is one of the most important parameters because it controls the nonlinear response of masonry joints. The fracture energy is defined as the amount of energy required to create a unit area of crack along the joint. Lourenco [8] suggested values for G_f^I from 5.0e-6 to 2.0e-5 kN-mm/mm^2 for tensile bond strength between 3.0e-4 to 9.0e-4 kN/mm2, and G_f^{II} from 1.0e-5 to 2.5e-4 kN-mm/mm^2 for initial cohesion range from 1.0e-4 to 1.8e-3 kN/mm^2.

Five cases in which G_f^I varied from 4.8e-6 to 2.0e-5 kN-mm/mm^2 and other four cases in which G_f^{II} changed from 1.0e-5 to 7.0e-5 kN-mm/mm^2 were analyzed. **Figure 5** and **6** show the effect of G_f^I and G_f^{II} on behavior of masonry wallette respectively. The change in maximum force was less than 10% when increasing G_f^I by four times and the failure patterns were almost similar. However, change in maximum force was about 30% when increasing G_f^{II} by four times and the failure patterns (crack patterns, force displacement curves) also changed. So, the effect of G_f^{II} is larger than the effect of G_f^I on the overall behavior.

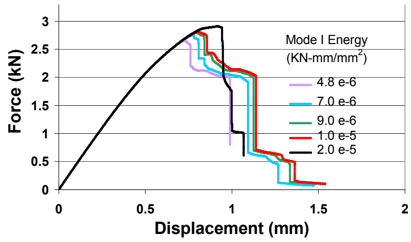

Figure 5: Wallette behavior with different G_f^I

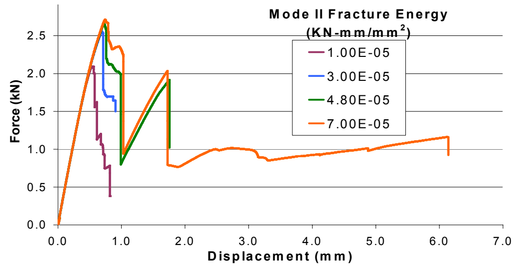

Figure 6: Wallette behavior with different G_f^{II}

6. Conclusion

Masonry wallette behavior from the diagonal shear tests was simulated in AEM. Good agreement between experimental and numerical results was found. A parametric study of friction angle and two fracture energies was made. Effect of the friction angle and mode II fracture energy was found to be larger than the effect of mode I fracture energy. These results can be used to suggest ways to improve masonry strength e.g. increase the roughness of the masonry unit surface.

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