SIMULATION OF BRICK MASONRY WALL BEHAVIOR UNDER CYCLIC LOADING USING APPLIED ELEMENT METHOD

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ABSTRACT: Understanding masonry wall behavior under lateral cyclic loads is important as it helps both evaluating the seismic vulnerability of existing buildings and developing proper retrofitting measures. In this study, the simulation of brick masonry wall behavior was carried out using the Applied Element Method (AEM). By introducing the damage model proposed by Gambarotta and Lagomarshino (1997), AEM shows the capability to follow the cyclic behavior of the brick masonry walls fairly accurately. Moreover, the effect of wall aspect ratio on the governing failure pattern of the walls was successfully captured by the model. Simulation of the PP-band retrofitting was also done with simplified modeling of PP-band meshes. A reasonably good result was also found in comparison to the obtained experimental result. The comparison of the behavior of non-retrofitted and retrofitted cases for a shear wall under cyclic loading was performed and the increase in earthquake safety of masonry shear wall with PP-band retrofitting was numerically verified.

Key Words: Brick masonry, Cyclic loading, Discrete elements, Fractures, Computer analysis

INTRODUCTION

Damage to unreinforced masonry buildings has caused huge number of human casualties historically and during recent earthquakes in developing countries. It reveals that development of proper retrofitting technique for masonry buildings is the main challenge to increase seismic safety in those countries. Understanding masonry wall behavior under lateral loads, especially cyclic loads induced by earthquake ground motions, is therefore important as it helps both 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. So, it is important to capture the behavior of masonry after cracks.

Attempts have been made to implement micro-level modeling of masonry in Finite Element Method (FEM) and the Discrete Element Method (DEM). In the Finite Element analysis mesh sensitivity and failure to capture diagonal shear have been identified by Lofti et al (1991). The 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 quantitative results. To this end, the Applied

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Element Method (AEM) is a numerical tool capable to follow the complete structural response from initial stage of loading until total collapse with reasonable accuracy (Hatem and Meguro , 2001). So far, AEM has been used to simulate the behavior of RC structure by Hatem and Meguro (2001), steel structure by Elholy and Meguro (2004), masonry by Pandey and Meguro (2004) and Mayorca and Meguro (2004) for monotonic load case.

This paper focuses on numerical modeling to simulate cyclic response of masonry under the framework of the AEM. The accuracy of the developed numerical tool is evaluated with available experimental results. Behavior of shear walls with different wall aspect ratios is discussed. Finally, numerical simulation of PP-band retrofitting technique, an economically affordable and technically feasible method, is done. The details of PP-band retrofitting technique can be found in Mayorca (2003) and Meguro et al (2006). The numerical and experimental results are compared and the model is applied to a PP-band retrofitted shear wall to investigate the difference in the behavior of non-retrofitted and retrofitted shear walls for cyclic loading case.

MASONRY MODELING IN AEM AND MATERIAL MODEL

In the domain of micro-level modeling of masonry, the AEM is more suitable than other approaches because of mainly three reasons. Firstly, the AEM is capable to follow complete structural response from initial stage of loading until total collapse with reasonable accuracy so that inelastic responses after the cracks occur can be captured. Secondly, brick masonry, which is a composite of brick units and mortar and has discrete nature, can easily be modeled in the AEM by a set of square shaped elements connected at their contact edges either by 'Element springs' or 'Joint springs' according to their positions. Discretization of masonry in the AEM is illustrated in **Figure 1**. Thirdly, the progressive failure of masonry i.e. cracks initiation, propagation and their distribution is simulated better by the AEM.

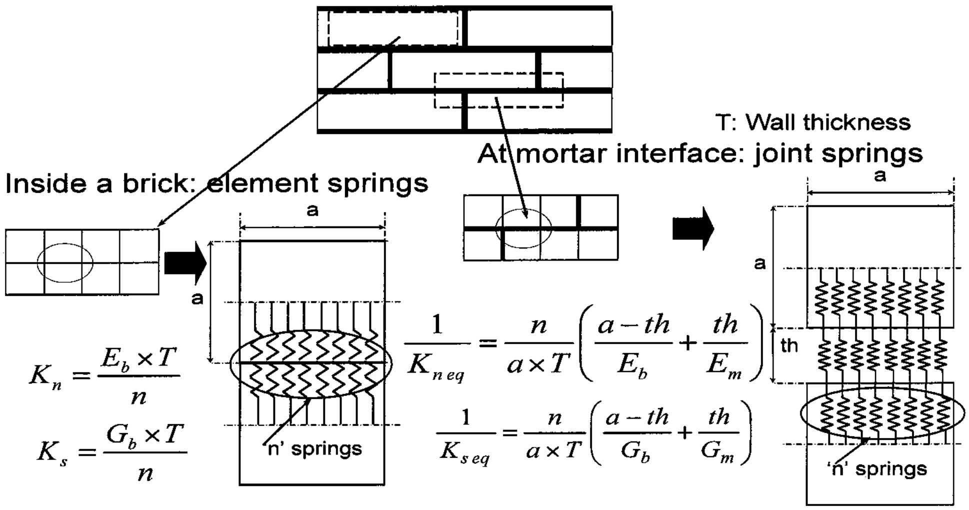


Figure 1. Discretization of brick masonry in AEM

The damage model proposed by Gambarotta and Lagomarshino (1997) is adopted in the AEM as the material model to capture the masonry cyclic response. This constitutive equation is based on damage mechanics and takes into account the mortar-damage and the brick-mortar de-cohesion which are considered to take place during crack opening and frictional sliding along the interface. Two internal variables, g* and a, represent the frictional sliding and the mortar joint damage, respectively. The evolution of sliding and damage variables evolution are both ruled by the frictional sliding and the mortar joint damage. The damage evolutions in tensile and compression zones as well as the frictional limit criteria are given in **Figure 2**.

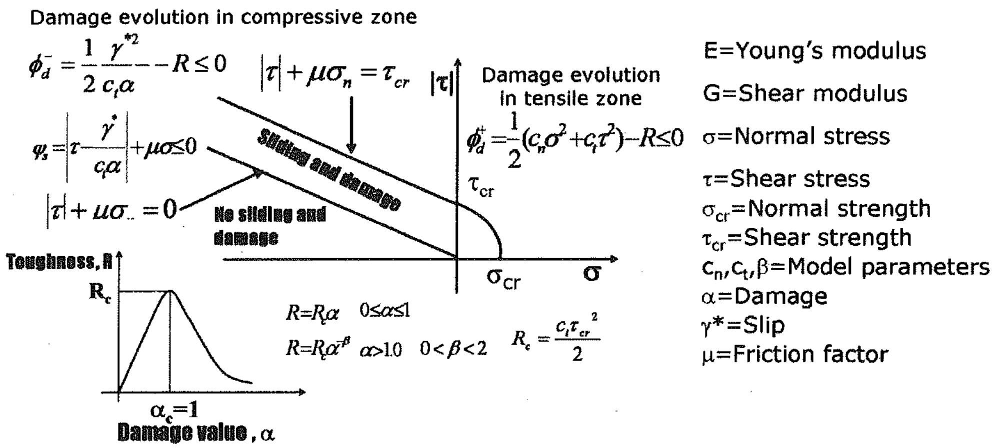


Figure 2. Masonry constitutive equation for cyclic response

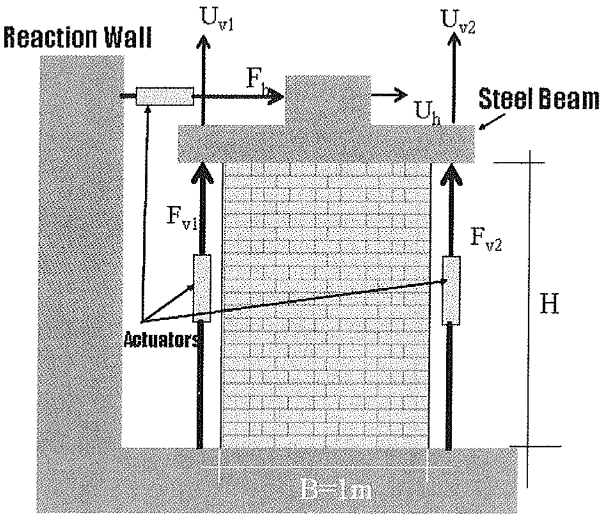


Figure 3. Schematic diagram of the experimental setup (Anthoine et al, 1995)

SIMULATION OF EXPERIMENTAL RESULTS

Experiments carried out by Anthoine et al. (1995) are used for the verification of the developed model for cyclic load case. Two two-wythes walls made of 250x120x55 mm3 brick units and hydraulic lime mortar arranged in English bond pattern as shown in **Figure 3** were tested. Width (1000mm), thickness

(250mm), and joint thickness (10mm) were same while two heights were considered. The higher wall had a height/width ratio of 2.0 whereas the lower wall had a ratio of 1.35. Tables 1 and 2 give the material properties for brick and mortar and assumed model parameters respectively.

Table 1. Material properties of the experiment (Anthoine, 1995)

	Young's modulus E (kN/mm^2)	Shear modulus G (kN/mm^2)	Tensile strength σ_{cr} (kN/mm^2)	Shear strength τ_{cr} (kN/mm^2)	Friction coefficient μ
Mortar	E_m	G_m	σ_{crm}	τ_{crm}	μ_m
	0.53	0.1	0.1x10^{-3}	0.4x10^{-3}	0.6
Brick	E_b	G_b	σ_{crb}	τ_{crb}	μ_b
	2.5	1.0	0.4x10^{-3}	1.2x10^{-3}	0.6

Table 2. Assumed model parameters

	Model Parameter $1/c_t$ (Low wall) (kN/m^2)	Model parameter $1/c_t$ (High wall) (kN/m^2)	Model Parameter β
Mortar	$1/c_{tm}$	$1/c_{tm}$	β_m
	20	2	0.8
Brick	$1/c_{tb}$	$1/c_{tb}$	β_b
	12.5	1.67	0.8

Both walls were initially subjected to a uniform vertical load of 150 kN, resulting in an average normal stress of 0.6 N/mm2. In the **Figure 3**, the sum of the forces Fv1 and Fv2 was constant i.e. Fv1+Fv2=150kN. The vertical displacements of the steel beam ends was equal i.e. Uv1=Uv2, so that the beam had no rotation. The horizontal displacement Uh was imposed and the horizontal force Fh was measured. **Figure 3** shows the loading protocol

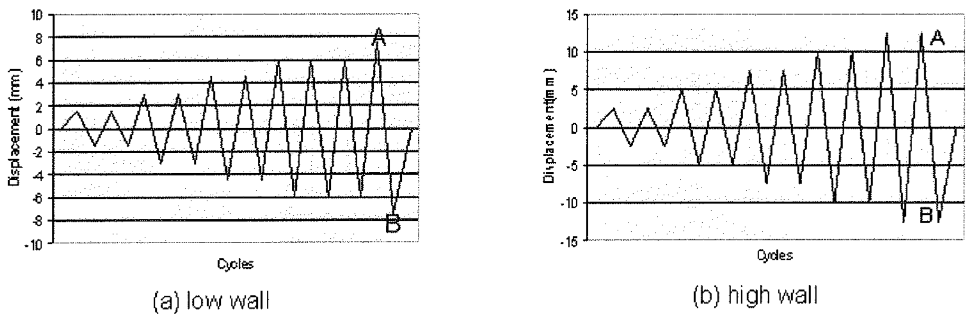
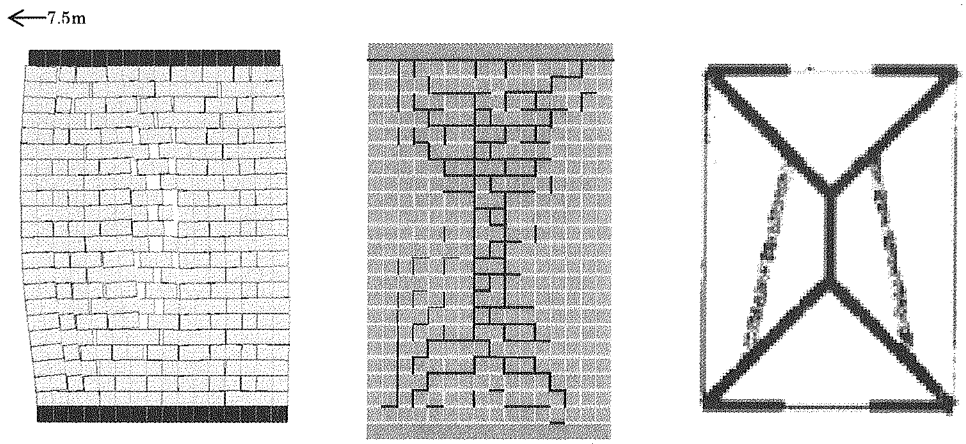


Figure 4. Imposed horizontal displacements in experiments

LOCATION OF ELEMENT NODES AND SPRINGS

In the original square AEM, the element node is placed at the center of the element and the springs are distributed around the center of element side. Due to its square shape, the line connected between two nodes passes through the centroid of distributed spring therefore no eccentric forces occur when loading is applied. In contrary, VAEM does not possess this property. If we put the element node at the center of gravity and distribute the spring around the center of element's side according to the previous version, the sum of the distributed spring force on an element side will not pass through the element node and create an unbalanced moment which affects the rotation at the material point, which is not considered realistic in case of continuum material. The alternative is to put the element node at the Voronoi nuclei and put the center of distributed spring at the middle point between these nodes which is the element boundary according to Voronoi diagram property, thus all of the eccentric forces are eliminated.

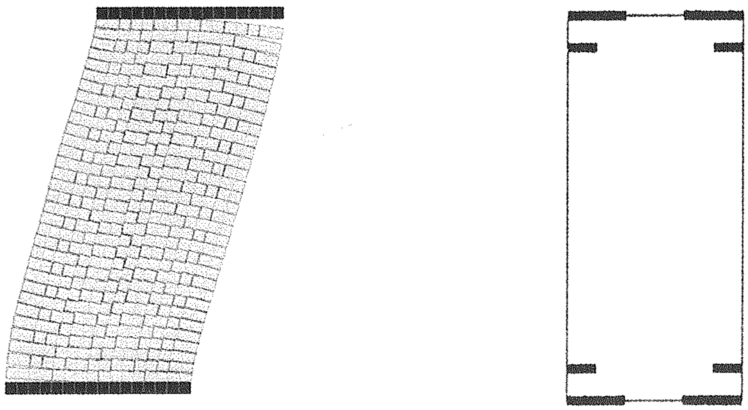


(a) Deformed shape from simulation (Deformations are multiplied by 10)

(b) Crack patterns from simulation

(c) Schematic crack patterns from experiment

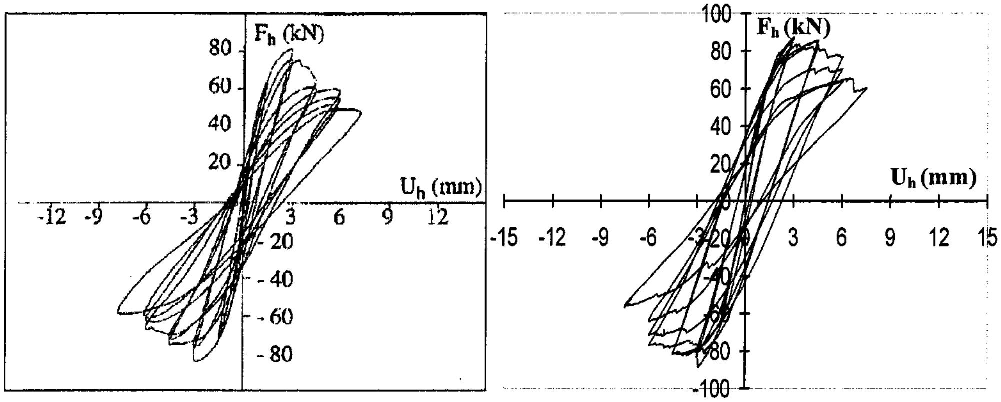
Figure 5. Comparison of crack patterns (Low wall)



(a) Deformed shape and crack patterns from numerical simulation (Deformations are multiplied by 30)

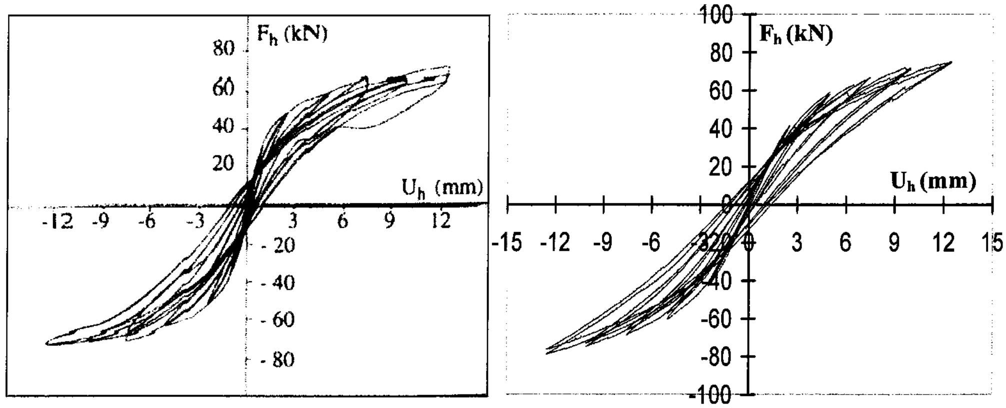
(b) Schematic crack patterns from experiment

Figure 6. Comparison of crack patterns (High wall)



Experimental Numerical

(a) Low wall



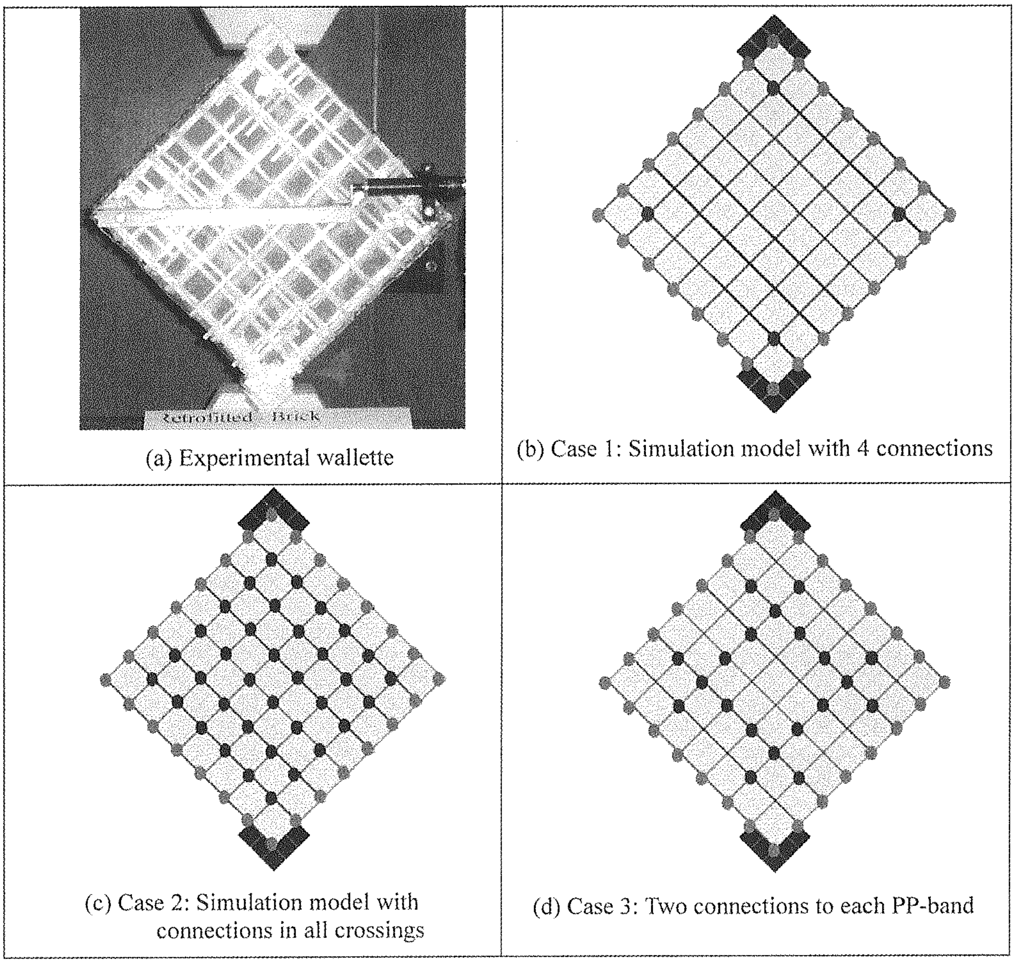
Experimental Numerical

(b) High wall

Figure 7. Comparison of force-displacement relation

Figure 5 compares the crack patterns from the numerical simulation with the schematic crack patterns from the experiment. The detail crack patterns from the experiment at the different stages of loading could not be found in the related articles. In the simulation, the low wall exhibited a brittle failure by diagonal cracking (shear behavior) and the high wall got flexure cracks at top and bottom corners (flexural behavior) as shown in **Figure 6**. The behavior was similar in the experiment.

The force displacement relations obtained from the numerical simulations are overlapped on the experimental results in **Figure** 7. A good agreement in terms of strength, energy dissipation and failure patterns is obtained. Different failure behavior with respect to wall aspect ratio was observed. In case of low wall, the governing failure pattern was dissipating shear and it is characterized by wider loops in the force displacement relation. In case of high wall, the dominant failure pattern was flexure and it is characterized by narrow loops with low energy dissipation. The numerical model captured both behaviors fairly accurately.



(a) Experimental wallette

(b) Case 1: Simulation model with 4 connections

(c) Case 2: Simulation model with connections in all crossings

(d) Case 3: Two connections to each PP-band

Figure 8. Experimental and numerical simulation models for retrofitted wallette

SIMULATION OF PP-BAND RETROFITTED MASONRY STRUCTURES

The experimental results conducted for the PP-band retrofitting technique showed very good results in terms of strength, ductility and energy dissipation (Mayorca, 2003 and Meguro et al, 2006). In this retrofitting technique, individual PP-bands are connected to each other to form a mesh, which is fixed to the masonry with wires. One PP-band can transfer stresses to others through band to band connections and also some slip can take place at the wire connection locations. In the current model, the simulation of PP-bands is simplified considering some assumptions. In the present form, the model does not consider either band to band connections or the possible band slip at the wire connector locations.

Simulation of PP-band Retrofitted Masonry Wallette

In order to investigate effectiveness of PP-band retrofitting technique for in-plane action, PP-band mesh retrofitted brick wallette of size 280x280x50mm3 were tested by Sathiparan (2005). A total of 4 connectors were used to fix the PP-band meshes from both sides of the wallette. The retrofitted masonry wallette tested for in-plane loading is shown in Figure 8(a).

For the numerical simulation, a masonry wallette of the same size is modeled. Eight PP-bands in each direction are included for retrofitting. Different number of connectors is considered. In the first case, only 4 connectors are used. In the second case, connections are provided at each crossing of PP-bands and in the third case, each PP-band is provided with two connections. **Figures 8 (b), (c)** and **(d)** show the numerical model simulated with different number of connectors.

The force-deformation relation obtained from numerical simulations is compared with the experimental result in **Figure 9**. The numerical result varies with different numbers of connectors. The case with 4 connectors in total gave the lower bound and the case with connections at all crossings gave the upper bound. The third case is in between. However, even with the simplified model used in the simulation of PP-band, reasonably accurate results were obtained.

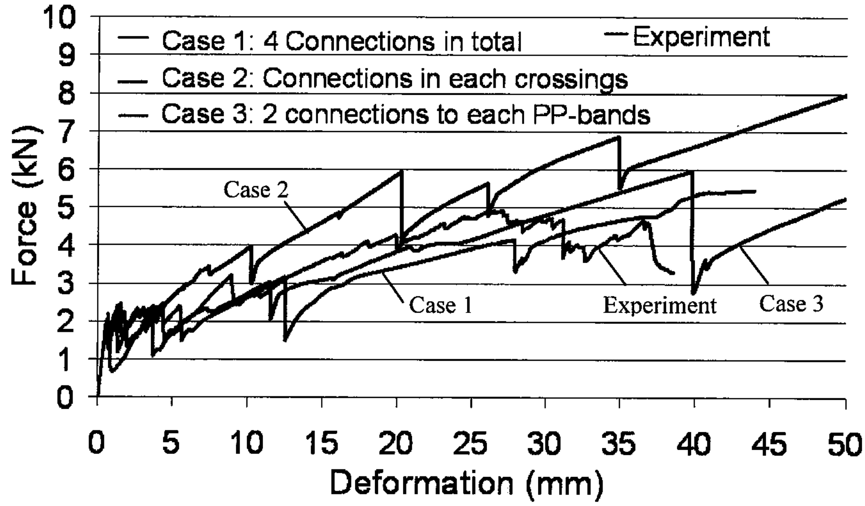


Figure 9. Comparison of force-deformation relations for retrofitted wallette with different connections

Application of the model to PP-band retrofitted shear wall

After simulating the experimental case with masonry wallette, the model is applied to a PP-band retrofitted shear wall subjected to cyclic loading. The retrofitted shear wall geometry, material properties, boundary conditions and loading patterns are exactly same as the low wall model analyzed in previous section. A PP-band mesh with 125 mm pitch and strength per band equal to 1.35kN is considered for simulation. The connections are considered in each PP-band crossing. **Figure 10** shows the PP-band mesh retrofitted shear wall with connectors. **Figure 11** depicts the comparison of force deformation relations for non-retrofitted and retrofitted cases and the comparison of energy dissipation is shown in **Figure 12**. If we considered only the strength increment due to the PP-band retrofitting, it is quite nominal. However, if we considered the total energy dissipation, the retrofitted case shows nearly twice the energy dissipation capacity than the non-retrofitted case. As the structure with higher energy dissipation capacity of the structures is safer for earthquake, the effectiveness of PP-band retrofitting for the enhancement of earthquake safety is therefore verified with the numerical model.

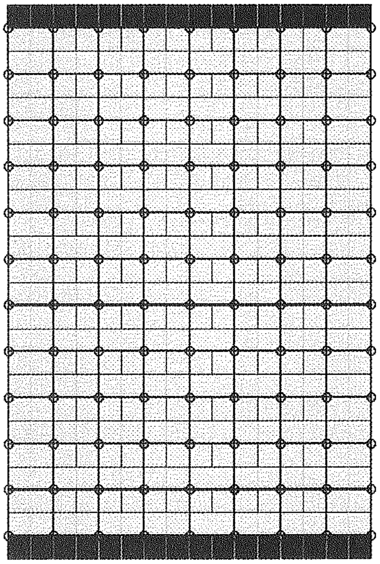


Figure 10. Retrofitted shear wall

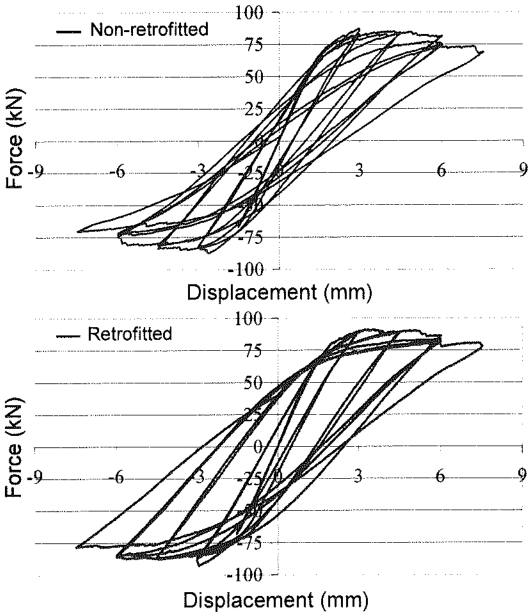


Figure 11. Comparison of force deformation relation

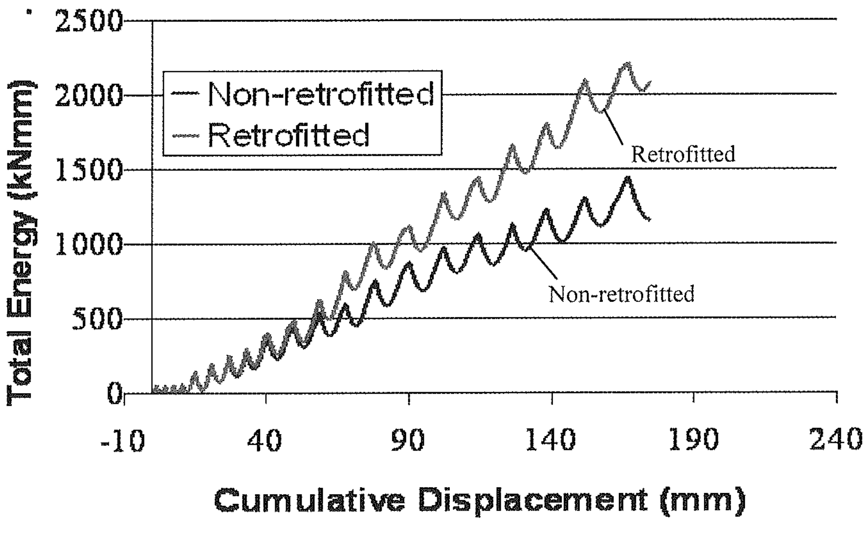


Figure 12. Comparison of energy dissipation

CONCLUSIONS

Numerical model to simulate the cyclic response of masonry was developed by adopting a damage model in the AEM. Comparison was made between experimentally observed behavior and numerical prediction of crack patterns, their evolution and hysteretic behavior and good agreement was found. The effect of wall aspect ratio on the governing failure pattern of the walls was successfully captured by the model. Simulation of the PP-band retrofitting was also done with simplified modeling of PP-band meshes. A reasonably good result was also found in comparison to the obtained experimental result. The comparison of the behavior of non-retrofitted and retrofitted cases for a shear wall under cyclic loading was performed and the increase in earthquake safety of masonry shear wall with PP-band retrofitting was numerically verified.

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