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Numerical Simulation of the Seismic Behavior of Reinforced Concrete Masonry Structural Walls

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ABSTRACT: Reinforced concrete masonry structural walls are commonly used as lateral load resisting systems in seismic regions. In order to facilitate the adoption of reinforced masonry systems in the next generation performance based design codes, there is a need for experimentally validated numerical tools for reliable evaluation of their seismic response both in the elastic and inelastic range. The paper presents a validation study of the fiber-element modeling approach that is embedded in the software PERFORM-3D and its applicability to flexural dominated reinforced concrete masonry walls. Use of this modeling approach allows for a fairly detailed description of wall geometry, reinforcement and material behavior, and accounts for important response features such as migration of the neutral axis along the wall cross-section during loading and unloading as well as the influence of variation of axial load on wall flexural stiffness and strength. Literature experimental results were compiled from several case study reinforced concrete masonry walls that were tested under static-cyclic lateral loading. The case study tested walls varied in the amount and distribution of vertical reinforcement and the level of axial compressive stress. The validation is conducted by comparing the experimentally observed lateral force and deformation responses of the tested walls with that obtained from the numerical model. This paper presents the findings of the numerical studies and highlights the modelling parameters that require particular attention when modeling the walls.

1. Introduction

Reinforced Masonry (RM) structural walls are commonly used as a lateral load resisting system in seismic regions. In order to develop cost-effective and seismic resilient RM structural wall systems, it is necessary to develop reliable analytical and numerical tools for seismic performance evaluation in order to facilitate the adoption of RM seismic force resisting system (SFRS) in the next generation of performance-based seismic design codes.

The lateral seismic behavior of RM structural walls has been the subject of several experimental investigations. Priestley (1986) studied the seismic behavior of concrete masonry structural walls under reversed cyclic loading. Shing et al. (1990) tested 22 masonry structural walls to enhance the knowledge of their strength and ductility. Each wall was subjected to cyclic, in plane loading with a gradual increase of maximum displacement. Ibrahim and Suter (1999) tested and evaluated five concrete masonry structural walls to investigate the effects of the applied axial stress, the amount of vertical reinforcement, and the aspect ratio on the behavior of such walls. Eikanas (2003) studied the effects of varying wall aspect ratios and the flexural reinforcement ratios. Voon and Ingham (2006) tested and evaluated 10 masonry structural walls to investigate the effects of the amount and distribution of horizontal reinforcement, the applied axial stress, and the aspect ratio had on the shear strength of such walls. Shedid et al. (2008) tested six full-scale walls to failure under reversed cyclic lateral loading to investigate the effects of the amount and the distribution of vertical reinforcement and the level of axial load on inelastic behavior and ductility.

Complimentarily to experimental analysis, numerical modelling of RM walls can contribute to increasing the knowledge about their behavior and evaluate the system level seismic performance of prototype buildings. Zhuge (1995) developed a two-dimensional plane stress element model for the nonlinear analysis of URM shear walls. This model was developed using a homogeneous material model to predict the detailed load–deflection characteristics and critical limit states of unreinforced masonry walls under in-plane earthquake ground acceleration. Lourenco (1996) presented a macro model capable of accurately predicting the behaviour of the URM shear walls until the walls exhibited large lateral drift associated with wide crack. Ingham et al. (2001) examined the response of partially reinforced wall system subjected to in-plane shear loading.

The two main approaches for modeling of RM shear walls are micro modeling and macro modeling. Micro-modeling approach such as the finite element analysis is based on representing the behaviour of different materials that compose the element and the interaction between them. The member is discretized into small elements and principles of equilibrium are applied. This approach is complex and needs high numerical processing efforts, and hence it might not be practical for large structures and it is limited to model individual structural components such as a column, a beam or a wall.

Fiber-element models are computationally efficient and well suited for flexure dominated walls with regular openings. They account for the axial load-moment interaction of a wall section, and can therefore closely simulate the flexure dominated behavior of a reinforced concrete and masonry shear wall (Koutromanos and Shing 2009). These models have also been extended by replacing the uniaxial stress strain relation of a fiber with a multi-axial constitutive law to capture the linear and nonlinear shear behavior of a reinforced concrete section (Petrangeli et al. 1999, Rose et al. 2002). While these models can capture axial-flexural-shear interaction, they idealize shear failure as developing at a section level, and do not represent a diagonal shear crack realistically. More often, shear behavior can be modeled simplistically by incorporating a non-linear empirical shear behavior (Marini and Spacone 2006).

However, in finite element method of analysis, the reinforced masonry member is discretized into a finite number of small elements (masonry and steel elements) interconnected at a finite number of nodal points. The number of the finite elements is chosen according to the level of accuracy required and the available analysis tool. This method of analysis is capable of tracking the member's global behaviour (e.g. member forces and displacements) in addition to its local behaviour (e.g. crack pattern, material stresses and strains). On the other hand, macro-modeling is based on representing the overall behaviour of the RM element, such as the wall deformations, strength, and energy dissipation capacity. The global behaviour of the RM elements using a macro-model should be calibrated using an experimental verification to adjust the parameters needed for the model. This approach is simple and does not require high numerical efforts, which makes it suitable to simulate the response of large structures.

In this paper, the fiber element modelling approach was chosen since it allows for a fairly detailed description of wall geometry, reinforcement and material behavior, and accounts for important response features such as migration of the neutral axis along the wall cross-section during loading and unloading as well as the influence of variation of axial load on wall flexural stiffness and strength. A validation study is presented on the applicability of using fiber-element modelling approach that is embedded in PERFORM-3D software for flexural dominated RM shear walls tested in the literature by Shedid et al. (2008). A numerical model is developed to emphasize the modelling parameters used to simulate the behavior of RM shear walls. Using Pushover analysis, the experimentally observed lateral load and deformation responses of the tested walls are compared with that obtained from the numerical model.

2. Validation Study

Five RM shear wall specimens, which are flexure dominated, are selected from Shedid et al. (2008) for numerical simulation. These walls varied in the amount and distribution of vertical reinforcement and the level of axial compressive stress. The numerical model applied to study the behaviour of RM shear walls is defined using the software PERFORM-3D. A pushover analysis is conducted by comparing the lateral force and deformation responses of the tested walls with the predicted response obtained from the numerical model. The following sections provide details of the wall specimens, modelling parameters used, pushover analysis results and discussion.

3. RM Shear Wall Specimen's Details

Specimen dimensions were selected to represent the aspect ratios of wall segments of potential concrete masonry structures whose behaviour is expected to be dominated by flexure. Specimens had an aspect ratio of 2, with a length l_w of 1.8 m and a height h_w of 3.6 m. A standard 2-cell hollow 20 cm concrete masonry block (190 x 190 x 390 mm) was used. Fig. 1 shows the RM specimen details used by Shedid et al. (2008).The loading beam simulated a rigid diaphragm for uniform transmission of horizontal earthquake load to the shear wall. The lateral load was supplied through a displacement based 1,400 kN hydraulic actuator with its centerline aligned with the top of the wall. The adopted cyclic loading scheme consisted of a series of displacement-controlled loading cycles. The walls were cycled twice at each displacement level. Displacements were increased incrementally until the specimen has achieved maximum lateral load resistance and then lost about 50% of its ultimate capacity.

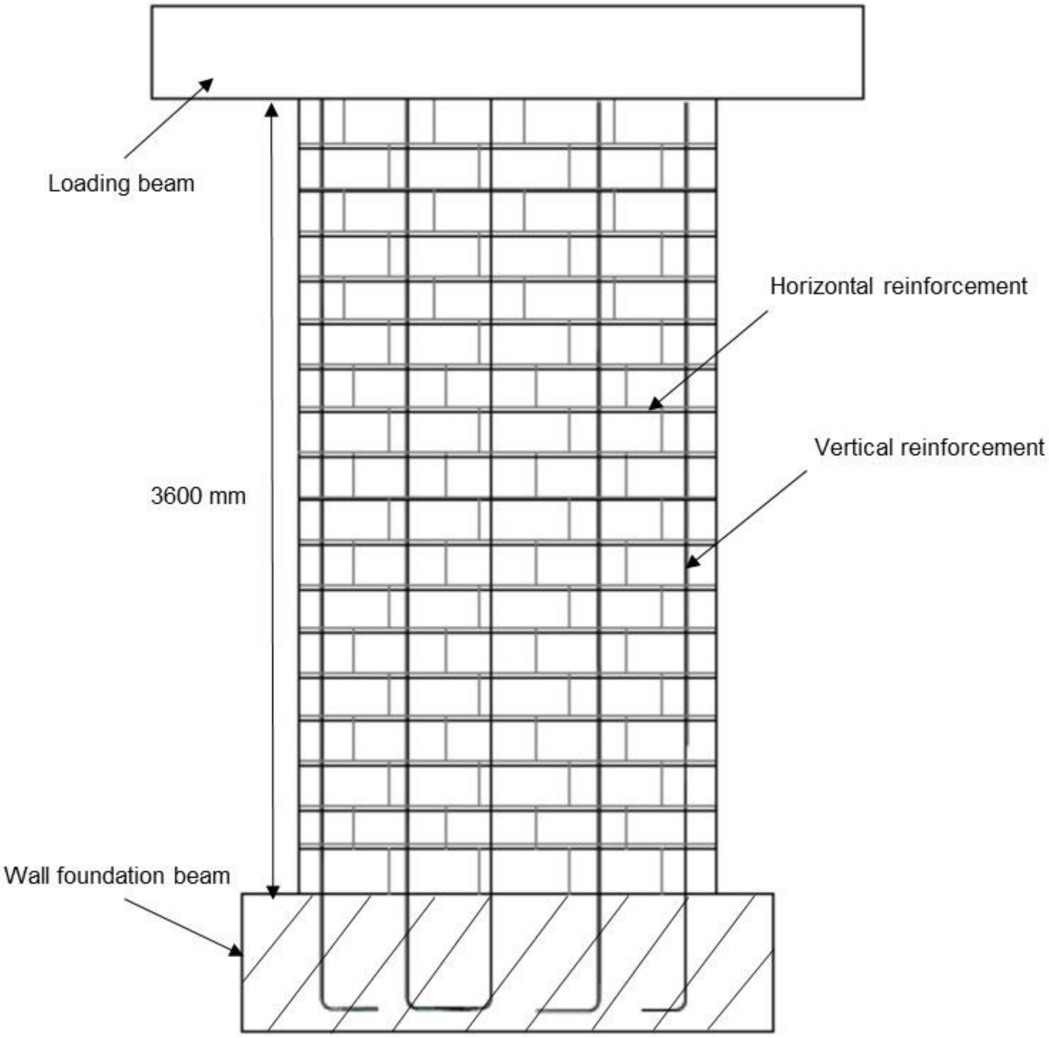


Fig.1- General test specimen details by Shedid et al. (2008)

A summary of the vertical and horizontal reinforcement arrangements and level of axial compressive stress for the test walls is given in Table 1.The vertical and horizontal reinforcement ratios ρ_v and ρ_h are defined as ratios of the areas of reinforcing bars to gross area of the horizontal or vertical masonry cross section, respectively. Walls 5 was subjected to axial compressive stresses of about 0.05 f'm (i.e. 0.75 MPa).

Table 1-Summary of wall details

Wall	Vertical reinforcement		Horizontal reinforcement		Axial compressive stress (MPa)
	No. and size	ρ_v (%)	No. and spacing	ρ_h (%)	
1	5 #15	0.29	#10@600 mm	0.08	0
2	9 #20	0.78	#10@400 mm	0.13	0
3	5 # 25	0.73	#10@400 mm	0.13	0
4	9 #25	1.31	# 10@200 mm	0.26	0
5	9 #25	1.31	#10@200 mm	0.26	0.75

4. Modeling Wall Specimens

4.1. Element

In PERFORM-3D software, there are two types of elements simulating RM shear walls, shear wall element and general wall element based on PERFORM-3D Manual (2006). The shear wall element consists of vertical fibers and shear layer as shown in Fig.2 while the general wall element consists additionally of horizontal fibers, and diagonal compression layers. The fiber layers are used to model the bending and axial behavior, the concrete shear layer takes the contribution of concrete to the shear strength into account, and the diagonal compression layers can transmit shear force and consider the contribution of reinforcing steel to the shear strength through interaction with the fiber layers. Usually, the shear wall element is used to model the flexure-dominant slender walls while the general wall element is for analyzing complex walls with irregular openings. In this study, RM wall segments are idealized using the shear wall element.

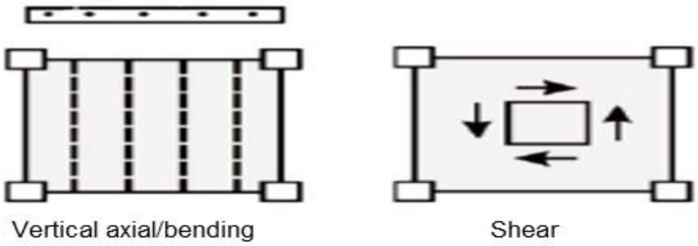


Fig.1- Fiber components of shear wall elements (taken from PERFORM-3D technical manual, 2006).

A schematic diagram of the wall is shown in Fig. 3(a).The specimen is modeled by using 900 x 600 mm element mesh based on recommendations of Powell (2007). A plastic hinge length of 900 mm which is half of l_w was assumed,leading to 4 elements in the long direction and 3 elements in the short direction. A schematic diagram representing the element mesh used to capture the response of the walls is shown in Fig.3(b).The supports at the base of the wall are all fixed to reflect the boundary conditions observed in the experimental test.

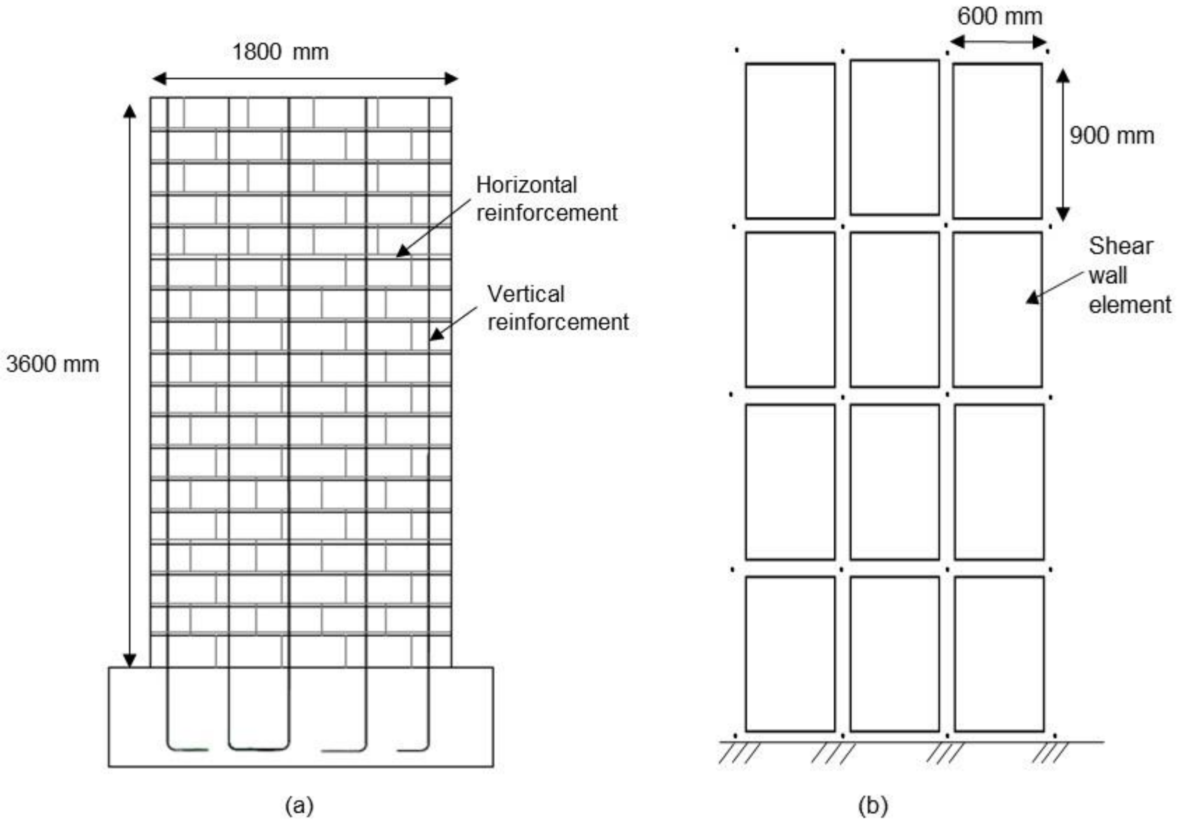


Fig.3- (a) Schematic diagram of wall; (b) Sketch of element meshing

4.2. Fiber Sections

Fig.4(a) shows the cross-section details of the wall.In the modelling process, inelastic fiber sections are used to explicitly model the non-linear properties of the wall cross-section. According to (PERFORM-3D Manual 2006), Shear wall elements in PERFORM-3D can have a maximum of 16 fibers.In order to accommodate additional fibers, the walls were modelled using two shear wall elements acting in parallel.The vertical distributed steel was modelled in one fiber element while the masonry was modelled in a separate element. The two elements were then applied in parallel by using the same four nodes to define their locations in 3-dimensional space. As shown in Fig.4(b),the model has fiber cross-sections consisting of steel and masonry fibers. The inelastic steel fiber section is described by the wall thickness and reinforcement ratio, as well as material properties. Since the reinforcement is uniform across the full cross section width, the program’s option to locate fibers automatically was used to better replicate the uniform reinforcement distribution.However, masonry fibers were defined manually by specifying the corresponding location and area of each fiber.

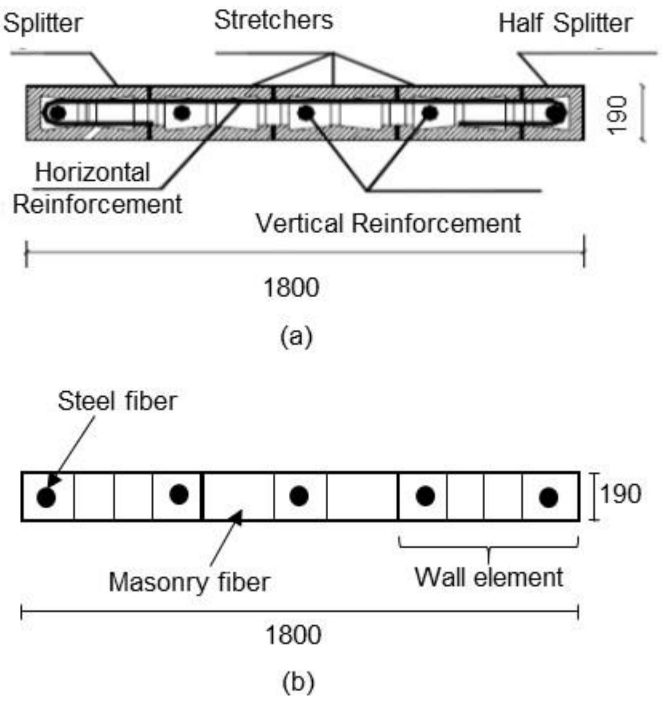
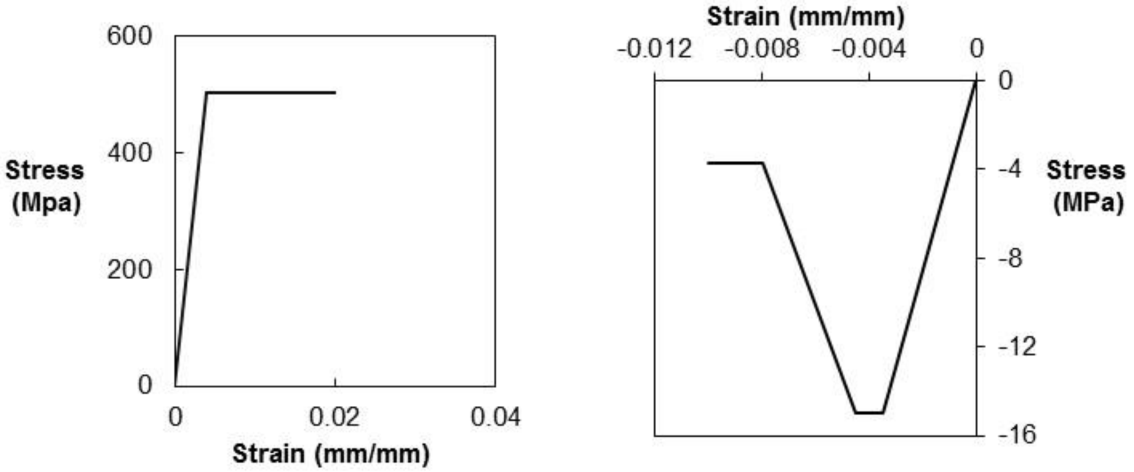


Fig.4-(a) Cross-section of specimens; (b) Fiber sections

4.3. Material Parameters

Tested material properties were used for the parameters in the material models. Input material modelling parameters include steel, masonry and shear materials.

1) **Steel**: The material model for reinforcing steel was defined based on an elastic perfectly plastic (E-P-P) stress-strain relationship. An elastic modulus of 200,000 MPa was used, and tensile yield and ultimate strength were based on the results of material tests from Shedid et al. (2008). Buckling of reinforcing bars was not included in the model. The backbone stress-strain curve used to define reinforcing steel fibers is shown in Fig.5 (a).
2) **Masonry**: The material model for masonry fibers was defined using the tri-linear stress-strain relationship shown in Fig.5(b). In Shedid et al. (2008), only the masonry compression strength was reported with no information about the complete stress-strain curve for masonry prisms, therefore, the idealized masonry stress-strain model was assumed based on the recommendations of Ahmadi (2012) from test results on concrete masonry prisms.
3) **Shear**: For the analyses, the walls were assumed to remain elastic in shear. An elastic shear material for the wall was assigned to the shear wall elements. The elastic shear modulus, G_m of $0.4*E_m$ where E_m is the elastic modulus of masonry was used based on recommendations in ASCE 41-06 (2012).



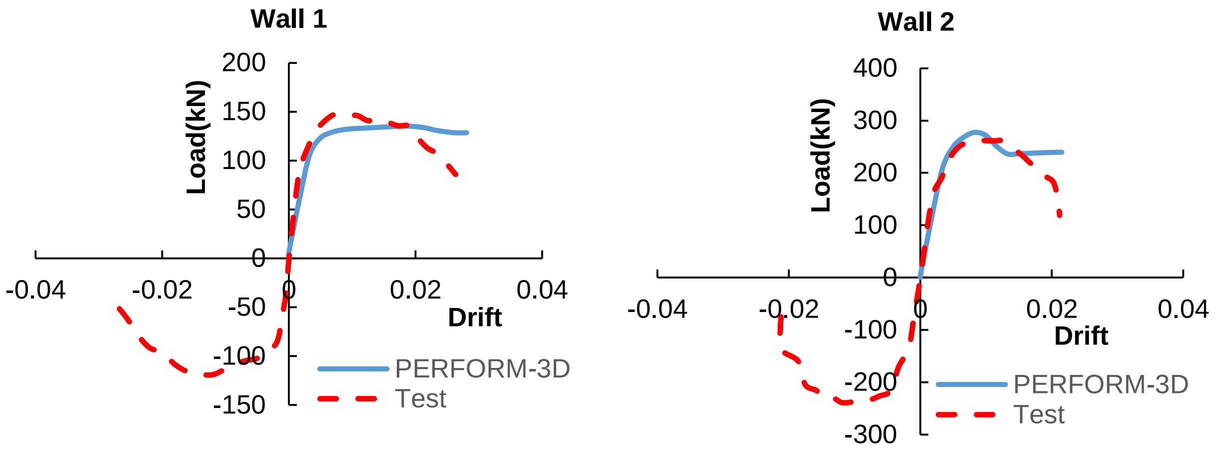
(a) (b)

Fig. 5-Stress-strain curve (a) Steel; (b) Masonry

5. Pushover Analysis

5.1. Load-Drift Relationship Results

After initially applying the gravity loads, the standard load sequence was used to perform the static pushover analysis. Envelopes of the lateral force and deformation responses of the numerical models by PERFORM-3D were compared to experimental results from the walls tested under quasi static-cyclic lateral loading by Shedid et al. (2008).The load-drift relationships for the five walls are presented in Fig. 6. As shown in the load-displacement curves, the five models for the different wall specimens provide an accurate prediction of the yield strength and elastic stiffness of the wall specimens. However, the drift at 20% strength degradation, $\Delta_{20\%}$ was not predicted well. The PERFORM-3D models had sudden reductions in lateral load mainly due to sequential crushing of masonry.



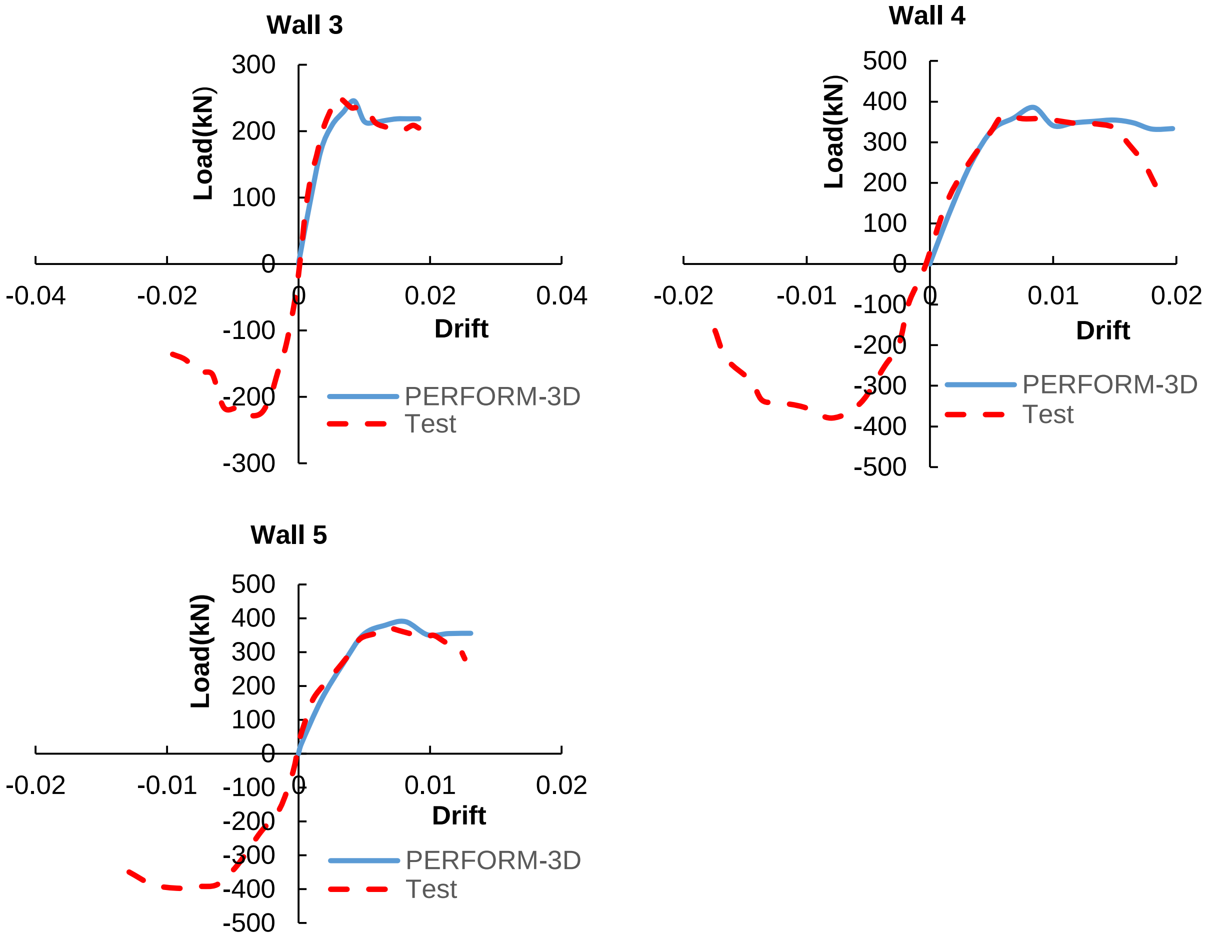


Fig. 6-Load-drift relationships for all walls

5.2. Discussion

Table 2 shows a summary of the test results and predicted yield strength, Q_y, ultimate flexural strength, Q_u, and drift at 20% strength degradation, $\Delta_{20\%}$ of all walls .The percentage difference (% difference) was also calculated from the lateral loads and drift values obtained from the experimental testing by Shedid et al.(2008) and numerical modelling by PERFORM-3D. Results show that the % difference for Q_y and Q_u is below 10% for all wall specimens which is a good indication for the accuracy of the developed numerical model. However, the % difference for drift at 20% strength degradation was higher than 15% which indicates a low accuracy in prediction of drift. Overall, the numerical responses agree well with the experimental test results by Shedid et al. (2008). In general, the predicted model responses developed by PERFORM-3D are quite close to the envelopes of the experimental measured responses. However, there are some differences in the responses mainly due to the fact that the reversed cyclic loading test method causes strength and stiffness degradation with every cycle; whereas the pushover analysis method is based on monotonic loading. There were also sudden reductions in the lateral capacity of the analytically predicted responses probably due to sequential crushing of masonry.

Table 2- Summary of lateral loads and drift.

Wall	Test results by Shedid et al. (2008)						Predicted by PERFORM-3D		
	Qy (kN)		Qu (kN)		$\Delta_{20\%}$		Qy kN)	Qu ((kN)	$\Delta_{20\%}$
	(+) ve	(-) ve	(+) ve	(-) ve	(+) ve	(-) ve			
1	95	84	143	122	2.15	2.21	100.00 (5.26%)	135.24 (5.43 %)	2.48 (15.3%)
2	185	182	265	246	1.80	1.79	191.02 (3.25%)	277.46 (4.70 %)	1.3 (27.78%)
3	174	190	242	230	1.30	1.22	163.00 (6.32%)	245.67 (1.52 %)	1.00 (23.07%)
4	296	292	360	380	1.71	1.51	289.50 (2.19%)	385.69 (7.14 %)	2.1 (22.8%)
5	311	316	377	407	1.26	1.31	305.00 (1.93%)	389.98 (3.44 %)	1.03 (18.26%)

6. Conclusion

In this paper, the application of the PERFORM-3D software in simulating the behavior of RM shear walls was introduced. Fiber element modelling approach in the software was used for numerical modelling of five flexural dominated RM shear walls from Shedid et al. (2008). In order to simulate the behavior of RM shear walls, a numerical model was developed to highlight the modelling parameters used. The selection of element mesh, fiber details and the determination of the constituent material parameters were specified in detail. The envelopes of the lateral load and deformation responses of the tested walls from Shedid et al. (2008) are compared with those obtained from the pushover analysis of the numerical model. In this study, it was concluded that:

1. The shear wall element used in PERFORM-3D, captured the behavior of flexure-dominant RM shear wall well.
2. The element size that was selected was based on recommendations of Dr. Powell (2007).However, more research is needed to investigate the effect of element size on the response results.

Therefore, a sensitivity analysis that includes parametric variations of materials, fiber sections and element size will be studied.

3. Overall, the pushover results agree well with the experimental test results by Shedid et al. (2008). The predicted model responses developed by PERFORM-3D are quite close to the envelopes of the experimental measured responses. There are some differences in the responses mainly due to the fact that the reversed cyclic loading test method causes strength and stiffness degradation with every cycle; whereas the pushover analysis method is based on monotonic loading. There were also sudden reductions in the lateral capacity of the analytically predicted responses probably due to sequential crushing of masonry.
4. The yield strength and elastic stiffness were accurately predicted. However, the ultimate drift at 20% strength degradation was not predicted well.

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