# SEISMIC PERFORMANCE EVALUATION OF R.C. SHEAR WALLS WITH IRREGULAR OPENING

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## ABSTRACT

Reinforced concrete shear walls have been usually used as the main lateral load-bearing components in concrete building because of their rigidity, bearing capacity and high ductility. Openings are generally present in walls according to the intention of the services, doors and windows, in other words for provision of architectural design. The presence of openings influences on the seismic response of the walls. Although the using of opening in shear walls is common among practitioners, however limited research on walls with openings has established to investigate their effects on seismic response. In this line it is required to comprehensively understand the influence of opening parameters such as size, location on the seismic performance of walls and consequently building behavior.

The main objective of this study is to investigate the effect of irregular openings in concrete shear wall seismic performance. In this paper, a nonlinear 3-D finite element analysis (FEA) model using ABAQUS was developed based on experimental data and calibrated with laboratory results. Based on calibrated models, a parametric study is carried out and the effect of aforementioned parameters on seismic behavior of shear walls with opening is investigated. The result of analysis show that the seismic performance of reinforced concrete shear walls is affected by size and location of openings.

## INTRODUCTION

Reinforced concrete shear walls are used widely as the main lateral resisting members in buildings. Architectural and mechanical requirements make that pierce shear walls regularly or irregularly. Since, staggered openings were not deeply inquired in the past and due to lack of detailed recommendations related to the seismic design and evaluation of these types of walls, use of them to be a serious concern. With regard to the application and importance of modeling shear walls with or without openings, several analytical and experimental studies have been proposed in literature. However, few experimental and analytical studies of the seismic behavior of shear walls with irregular openings are available. Among the limited experimental research conducted on shear walls with irregular openings, can be pointed to the research of Yanez et al. (1991). The results show that stiffness of walls was dependent on the size of the opening but not dependent on their arrangement. Other research studies for the same field were conducted by Ali and Wight (1991). In this paper the result of their work on a typical building with pierced shear walls in Chile, which remind intact after the earthquake in 1991was published. Li and Wu (2003) to compare with Yanez et al (1991) experimental study, flanges were added to their specimens. It can be concluded that the size and the arrangement of the openings did not have a significant effect on the wall with irregular openings and flanges. Wu and Li (2003a) with using a reliable nonlinear finite element program analyzed the Yanez et al. (1991) and Ali and Wight (1991) models. A parametric study was conducted on the walls with irregular openings to investigate the influence of critical parameters, such as flanges, axial load and the sizes and the positions of openings, on the behaviors of these walls subjected to earthquake loadings. The result indicate that the size and arrangement of openings may exert an influence on the walls with low aspect ratios when it was subjected to the combined actions of axial loading and reversed cyclic lateral loading (Wu and Li, 2003b). Mosoarca (2013a), under an experimental study, investigate for the failure modes concrete shear walls with openings. The result show that all the shear walls with staggered opening have developed a ductile failure mechanism but perforated specimen developed a brittle failure mechanism. Mosoarca (2013b) under an analytical study, investigate for the failure modes of concrete shear walls with openings. From all the experimental models, the largest degradation of the rigidity in the failure stage was recorded by the model with ordered vertical openings but models with staggered openings did not record sudden rigidity degradations in the failure stage. Mosoarca and Stoian (2012a) under experimental and analytical study, investigate for seismic performance and stiffness reduction of concrete shear walls. The results demonstrate that the horizontal displacements of walls with staggered openings are smaller than those recorded by the coupled wall and are higher than those recorded in the wall without openings. Moreover, moving door openings towards the wall extremities reduces wall stiffness, regardless of the direction of action of seismic loads. Mosoarca and Stoian (2012b) compared the results of the dissipated seismic energy in concrete shear wall, obtained by theoretical and experimental testing. Among the factors which influence the capacity of seismic energy dissipation of RC shear walls, an important role is played by the door and window openings by their dimensions and positioning. The highest energy is dissipated by solid wall followed by the models with staggered openings with lowest distance between the openings to the farthest and the wall with vertically ordered openings. Moreover, the experimental models with vertically ordered openings and staggered opening with highest distance between openings dissipate almost the same amount of energy. Stoian et al. (2004) under an experimental study on the structural elements investigate for reinforced concrete shear walls behavior. The amount of dissipated energy by the walls was not influenced by the direction of the horizontal force; it was influenced by the position of the openings. The biggest amount of energy is dissipated by the wall with no openings followed by the models with staggered opening with lowest distance between the opening to the farthest and by the coupled wall. Actually, by increasing the distance between the openings, a decrease of the amount of dissipated energy occur on each loading cycle.

The main objective of this paper is to study the effect of irregular openings in concrete shear wall seismic performance. In this paper, a nonlinear 3-D finite element analysis (FEA) model using ABAQUS was developed based on experimental data and calibrated with laboratory results of Yanez et al. (1991). After verification of the FE model, parametrical studies were also performed for investigating of opening size and location in reinforced concrete shear walls seismic performance.

## NUMERICAL MODDELING

### EXPERIMENTAL MODELS SYNOPSIS

In order to prove the accuracy of the proposed numerical models which are used in this study, experimental results of the reinforced concrete shear walls specimens tested by Yanez et al.(1991) is used. The wall was 2 m wide, 2.3 m high and 120 mm thick and connected to an upper beam (2.6 m long, 400mm deep and 400 mm thick) as load beam and a lower beam (3.576 m long, 500 mm deep and 400 mm thick) as foundation beam. The lower beam of specimens was bolted to the floor to avoid any movement of the base. Specimens S2, S3 have 600x600 mm openings. The wall specimens are shown in Fig. 1.

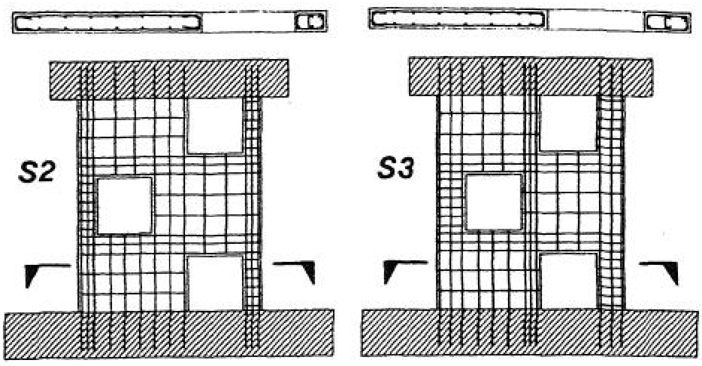



Figure 1. Wall specimens S2 and S3 (Yanez et al., 1991)

## ELEMENT PROPERTIES

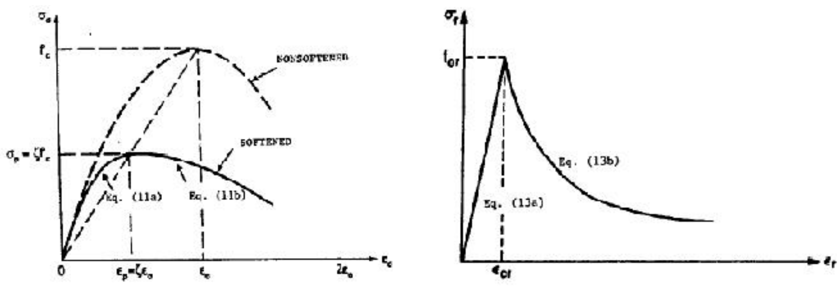
In this study, nonlinear analysis was utilized using the finite element analysis software ABAQUS. The concrete part of shear wall was modelled using 10-node quadratic tetrahedron elements (C3D10). In the ABAQUS software, there are two possible ways to model reinforcement bars in concrete elements. The first way is an embedded rebar layer and the second way is truss elements. In this paper the second way was used and reinforcement was modelled in form of three dimensional truss elements (T3D3) which are embedded in C3D10 solid elements.

## MATERIAL PROPERTIES AND CONSTITUTIVE MODELS

However, constitutive models are available in the ABAQUS predefined material library; their detailed input material properties which have been used in this study are briefly discussed. The property of the reinforcing bars was input in terms of stresses as a tabular function of plastic strains by using perfect plastic model. Results of tensile strength tests of the reinforcing bars and Belarbi et al. (1994) were used to determine the rebar behavior. After peak strengths were achieved, the stress within the reinforcing bars was assumed to decline linearly to $0.15 f_u$ at the fracture strains. Other material properties of steel, such as Elasticity modulus, Poisson's ratio and Specific weight are taken as E= 200 GPa, ν=0.3, γ=7850 kg/m$^3$, respectively The constitutive model used to analyze and simulate the behavior of concrete under monotonic loading was a concrete damaged plasticity model. The CDP model defines the behavior of concrete under multi-axial loading conditions based on input uni-axial properties and other material properties such as elasticity modulus (E), Specific weight (¥), Poisson's ratio (³), dilation angle (·), flow potential eccentricity (£), ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress ($f_{b_0}/f_{c_0}$), ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (k), viscosity parameter. Aforementioned parameters taken as $5000\sqrt{f_c'(MPa)}$, 2400 kg/m$^3$,0.15, 15 (Buch et al., 2007), 0.1, 1.16, 0.667 and a value of approaching zero, respectively. Concrete strength is taken as σ=23 MPa for S2 and σ=26 MPa for S3 specimen, too.

Degraded response of concrete in concrete damage plasticity model was defined for concrete both in compression and tension. According to ABAQUS user's manual (2012), usually to prevent numerical instability, damage parameters are not chosen more than 0.99. Accordingly, for evaluation of compression damage, Britel and Mark (2006) formulation and for evaluation of tension damage, Pavlović et al. (2013) formulation is used.

The stress-strain relationship of concrete under uni-axial compression and uni-axial tension were described by Belarbi et al. (1996). The behavior of concrete in tension and compression is expressed graphically as follow in Fig. 2. In this study by using embedded element constraint, impose a perfect bond between reinforcement and concrete.




(a) (b)

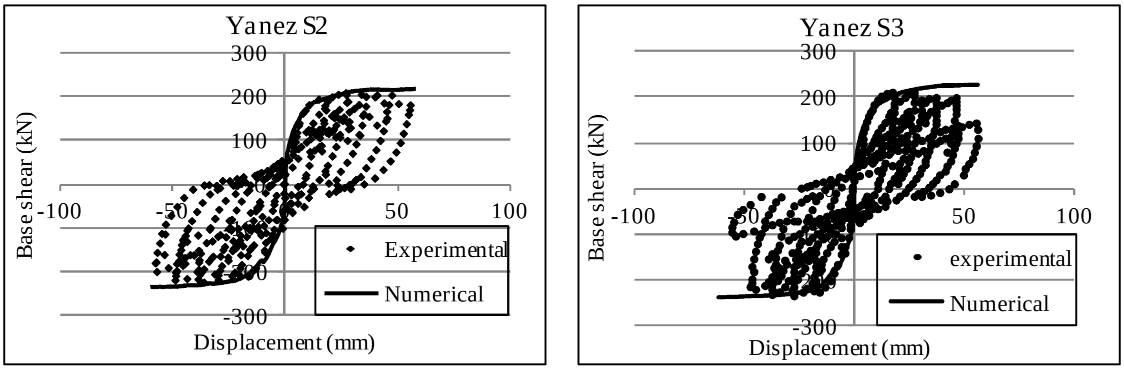
Figure 2. a) Compression stress-strain curve of concrete b) Tensile stress-strain curve of concrete (Belarbi et al., 1996

## LOAD APPLICATION AND BOUNDRY CONDITION

In this study, displacement-controlled loading was applied at the top of the wall on the load beam as distributed load. For defining boundary condition, foundation beam is fixed and in order to prevent out of plane moving, the out of plane moving of wall is closed.

## VERIFICATION OF FINITE ELEMENT MODEL

Comparison between the experimental and numerical results indicated the ability of the finite element method to predict the behavior of concrete shear walls reasonably. (Fig. 3 and Fig. 4)




(a) (b)

Figure 3. Comparison of load- displacement curve of experimental models of Yanez et al. (1991) and numerical results

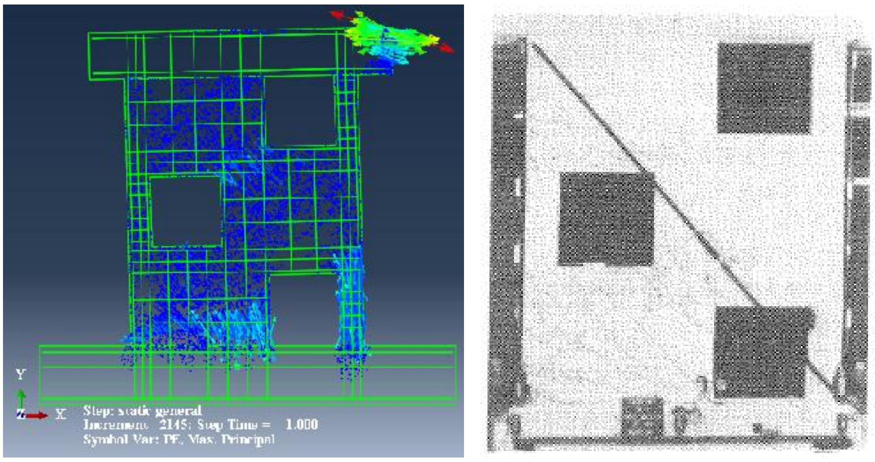



Figure 4. Cracking pattern of S2 specimen numerical model (left) and experimental wall of Yanez et al. (1991) (right)

## PARAMETRIC STUDY

Several parameters such as opening size and locations have influence on the seismic performance of reinforced concrete shear walls. Due to the high cost of experimental investigation, the difficulties in making samples, it is preferred to conduct numerical modeling for comprehensive parametric study. After verification of the finite element method, in order to study the effects of openings size and location, several opening with different size and location were created in 12-story concrete shear wall. The aforesaid wall detail is presented in Kim and Foutch (2007) study. The 12-story wall modeling approach in ABAQUS is same to experimental walls but loading procedure and boundary condition. The applied load pattern for nonlinear static analysis is based on the first mode ordinates so that at each floor modal ordinates is normalized to the last floor and it has been applied to the wall. In order to define boundary conditions in the 12-story concrete shear wall, the edges of the wall have been fixed while the displacement and rotation in z direction in the center of the wall is not fixated. It is noteworthy that in 12-story wall models for cost analysis only four first stories was dedicated nonlinear behavior.

The models were divided into some main groups based on the opening size and location. The size of openings to be determined in such a way that some have been limited by and some have exceeded the limition of Chinese and Japanese codes recommendations (Taleb et al., 2012; Wang et al., 2010). In the finite element model, the steel reinforcement intercepted by the opening was cut. Table 2 illustrates the details of openings.

Table 1. Details of openings

| Model | Opening Height | Opening Width | Opening area to wall area (percent) | α | Japanese code limitation | Chinese code limitation |
|---|---|---|---|---|---|---|
| 12S-13a | 2.5 | 2 | 13 | 90 | Ok | Ok |
| 12S-13b | 2.5 | 2 | 13 | 36 | Ok | Ok |
| 12S-19 | 2.5 | 3 | 19 | 90 | Not ok | Not ok |

For example, 12S-13b model is a 12-story wall with staggered openings (12S) attached to the boundary with the aspect ratio 13 percent (13b). 13a in 12S-13a model means opening is close to the boundary with the aspect ratio 13 percent. Finally in order to do better comparison, a solid wall samples were prepared by the 12-solid name. The 12S-13a and 12S-13b wall scheme is shown schematically in Fig. 5.

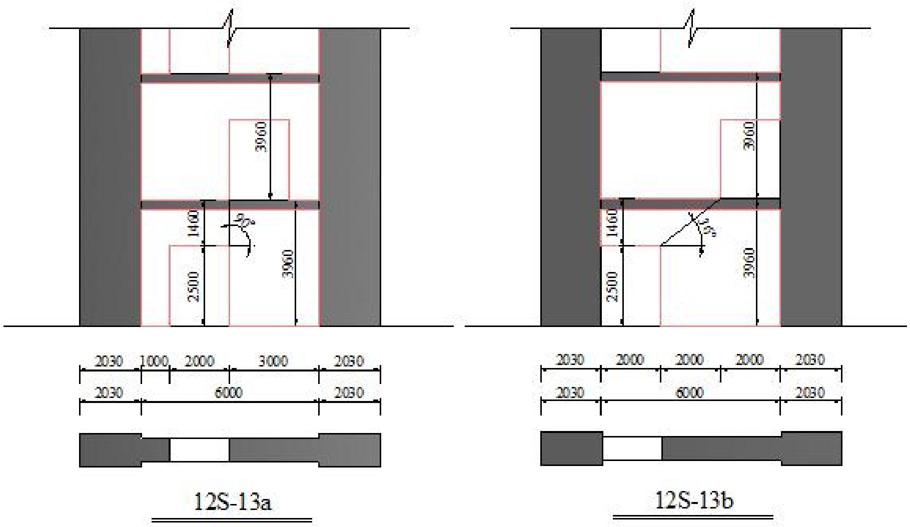



Figure 5. 12S-13a and 12S-13b wall scheme (Notations of dimensions in mm)

## RESULT AND EVALUATION

Figure. 5 shows the load-drift curves of finite element results.

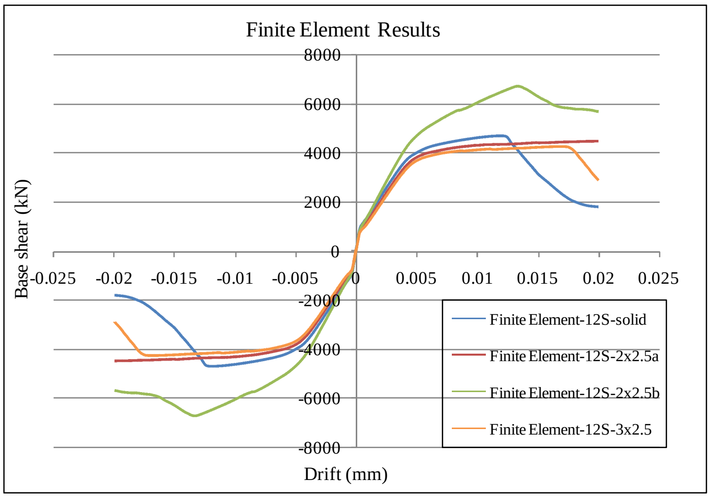
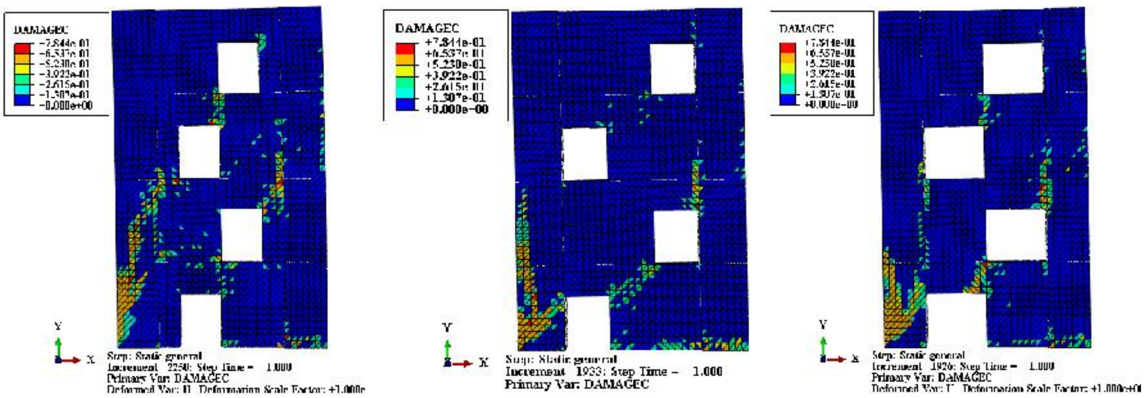



Figure 5. Load-drift curves of finite element results

The results clearly indicate that wall with small sized openings can perform better than walls with larger openings; due to reduced wall section by creating larger openings, wall stiffness and strength decrease. The analysis also pointed out that stiffness of walls was dependent on the size of the opening but not dependent on their arrangement. Moreover, to close the openings in the extremity of the wall so that the wall will not affect the behavior of the boundary element can improve the behavior of the wall. As specified in

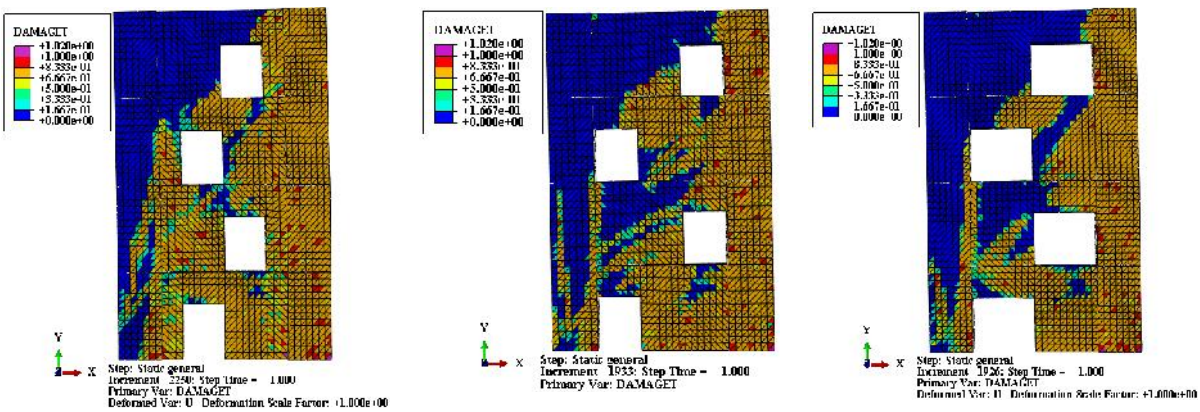
Fig. 5, the walls with α angle greater than 36 degrees are a ductile behavior to solid wall. In addition, when opening is not attached to the boundary element, concrete shear wall is more ductile behavior. Furthermore, concrete shear wall with small sized irregular openings show more ductile behavior.

Fig. 6 and Fig. 7 show compression damage (crushing) and tension damage (cracking) in 12-story concrete shear walls with irregular opening, respectively, where damage value 0 indicates concrete elastic behavior and value 1 indicates full concrete failure.



a) 12S-13a b) 12S-13b c) 12S-19

Figure 6. Contour plot of compression damage



a) 12S-13a b) 12S-13b c) 12S-19

Figure 7. Contour plot of tension damage

As it can be seen in Fig. 7 in model with highest distance between the openings, damage in the middle part of the wall is less. In other words, by increasing distance between two consecutive openings, the impact of middle part of wall on the overall behavior of the wall is less and margin parts of the wall determines the behavior of shear walls with staggered openings.

## CONCLUSIONS

In this study, three-dimensional finite element models have been developed to investigate the effect of size and location of openings on seismic performance of concrete shear walls. The numerical results indicate good agreement with the experimental data. Parametrical study results show that the seismic performance of reinforced concrete shear walls is affected by piercing shear walls irregularly. It was found that using openings with limited size by codes recommendation show better behavior. Furthermore, openings location should be selected so that the effect of middle part of wall behavior on overall behavior of wall is limited to wall strength and stiffness get better (openings close to boundary element) and also does not affect the wall ductility (The distance between two consecutive openings are not large).

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