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# Seismic Performance of RC Structural Walls with Slits: Analytical Study

[1]Athulya Das A S, [2] Sajith A S
[1] Student, M Tech Structural Engineering, National Institute of Technology, Calicut,
[2] Assistant Professor, Dept. of Civil Engineering, National Institute of Technology, Calicut
[1]athulya181990@gmail.com, [2] sajithas@nitc.ac.in

**Abstract: — Structural walls, mostly referred as shear walls, are efficient lateral load resisting system in a building structural configuration owing to their high strength and stiffness. But while considering ductility and energy dissipation capacity, which are the key elements in earthquake resistant design of structures, structural walls cannot be considered that efficient since the plastic hinge formation is concentrated at the base of the wall and the major portion of ductility of the wall remains unused. Structural walls with slits have an advantage over solid structural walls in this regard, because in structural wall with slits the plastic hinge formation (and hence the damage induced to the whole building) during an earthquake is distributed at the base of the wall as well as above the base, near the slits. Thus the capacity of the structure is enhanced. In this study, the seismic performance of the structural walls with slits is carried out analytically. A 10 storey slitted structural wall is analyzed using a commercial software package, the structure being subjected to four standard earthquake time histories namely: El Centro, Athens, Parkfield and Northridge earthquakes and compared with a solid structural wall. Non-linear time history analysis is carried out and seismic performance is studied by noting the natural period, top storey displacement, acceleration response of top storey, base shear force and base moment. The results reveal that structural walls with slits exhibit improved performance than solid structural walls.**

***Index Terms*—Ductility, plastic hinge, seismic performance, time history analysis**

## I. INTRODUCTION

Earthquakes are not supposed to kill human beings, but the structures that are designed and constructed inadequately for resisting the earthquakes do so. The structural damages during the recent earthquakes are repeatedly proving the inadequacy of the structures to resist earthquakes. The statistics of Taiwan earthquake that hit on February 6, 2016 having intensity VII caused as many structural damages along with fatalities. The alarming fact is that all the casualties reported are due to structural failures. Even though structural walls suffer nil and less damages during weak and moderate earthquakes, their performance is not satisfactory during strong and severe shakes. Based on experiences from past earthquake, several seismic design methods and alternate seismic retrofitting and strengthening solutions have been developed by researchers to improve the dynamic performance of structures. In this context, we intended to study the performance of slitted structural walls.

The proposed structural walls with slits are similar to solid structural walls and are having slits of width 20 cm. The slits can be filled with energy dissipating materials like paper, rubber, asbestos etc. This type of structural wall can be considered as extreme case of coupled shear walls with very short coupling beams. By suitable design of these coupling beams (by reducing strength of beams than the wall), plastic hinge formation at the ends of such beams can be ensured, which can effectively increase ductility and energy dissipation capacity of coupled shear walls. Unlike active seismic control devices, the structural walls with slits are cost effective as well. The natural time period of the building can be increased without increasing the number of storeys, which is also beneficial.

The concept of slit shear walls was introduced as earlier as 1960's by K Muto [1]. The author successfully demonstrated the dynamic behavior of steel slit shear wall in a building at Tokyo. Kwan et al. [2] conducted monotonic and cyclic shear tests on short connecting beams in slit shear walls and the results were found useful in predicting the dynamic behavior. Kwan et al. [3] plotted the non-linear load deflection curves of the connecting beams, using softened truss model theory. Kwan et al.[4] modelled slit shear walls based on wide column frame analogy and conducted non-linear seismic tests employing the elasto-plastic behavior of connecting beam and observed that the model is having sufficient accuracy. Toko Hitaka [8] conducted experiments on steel slit shear wall and established that the steel plate segments between the slits behave as a series of flexural links and they provide sufficient ductility to the structure without heavy stiffening of the wall.

## II. NEED FOR PRESENT WORK

Shear walls are integral part of multi-storey buildings in earthquake prone areas. The main limitation of shear wall is the concentration of plastic hinges and the failure at bottom storeys alone. In order to achieve a good seismic control over solid shear walls, slit shear wall is found to be a good choice. Steel slit shear walls have successfully found application in tall buildings in Japan. A handful of literature on RC shear walls is available and the seismic energy dissipation by replacing solid shear wall by a slit shear wall is acceptable. Unlike various seismic control measures, these are economical also. So it is intended to study the performance of RC structural walls with slits using commercial software. The advantage of the chosen software is that the walls can be modelled as such. A non-linear time history analysis will be best to study the seismic performance. The structural walls with slits were analyzed making use of various other concepts: like wide column frame analogy; still a straight forward analytical study is not conducted yet. In this lacuna, this work is intended to carry out.

## III. MODEL MANIFESTATION

### A. *Model Geometry and Reinforcement*

A 10 storey structural wall is used as model for analysis. Height between storeys is 3m, length of wall is 13 m and thickness 200 mm. Thus the aspect ratio (h/d) is 2.3. Since the aspect ratio is 2<h/d <4, theoretically the total deflection include 16% of shear deformation along with flexural deformation. For enhancing flexural strength of wall, concentrated vertical reinforcement is provided at both ends of wall. Floor thickness of the shear wall building is assumed to be 15 cm. The structure is assumed to be in seismic zone IV. M30 grade concrete and Fe 415 grade steel are used for model concrete and model reinforcement.

Reinforcement in the wall is designed as per IS 13920:1993 [9]. As per the code, a minimum reinforcement equal to 0.25% gross area of the wall shall be provided in longitudinal and transverse direction at spacing not exceeding $l_w/5$, $3t_w$ and 450 mm, where $l_w$ and $t_w$ denotes length and thickness of the wall. Accordingly wall is reinforced with 0.25% steel throughout. At both ends of wall, for a length of $0.1l_w$, concentrated vertical reinforcement is provided to increase flexural strength. The code suggests that, each concentration shall consist of a minimum of 4 bars of 12 mm diameter arranged in at least 2 layers. For the model, 36 numbers 20 mm diameter bars in two layers are provided at each ends of the wall. Thus the percentage vertical reinforcement at the ends is 2.17%, which satisfied the code provision $0.8<P_t<6\%$. Percentage reduction in reinforcement at slits is supplemented around the slits as specified in Cl.9.6 of IS 13920:1993.

***Fig. 1and 2 show the overall geometry of the structure and sectional plan.***

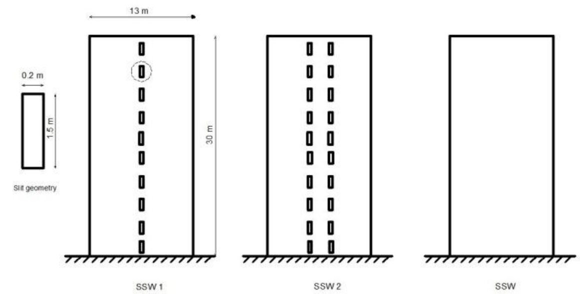



***Fig 1: Model geometry***

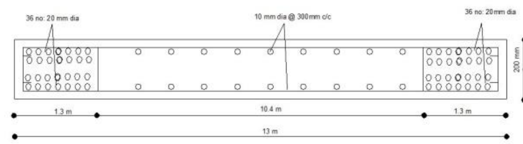



***Fig 2: Sectional plan***

The structural walls for analysis are designated as follows:

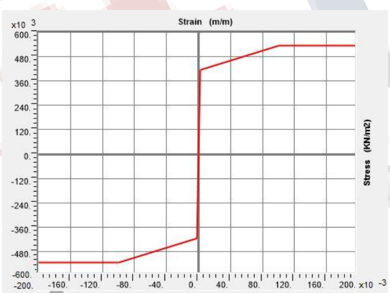
| | |
|---|---|
| SSW 1 : | Structural wall with one row of slits in each storey |
| SSW 2 : | Structural wall with two rows of slits in each storey |
| SSW : | Solid structural wall |

### B. *Modeling of Materials*

Three material types are modelled- Fe 415 for rebar, M 30 concrete for wall portion and boundary portions separately. Non-linear material data suggested by Park et.al. is used for concrete and that suggested by Mander is used for rebar. However, the material data used in this work is a modification of original Park and Mander model. M30 concrete for wall portion is modelled to have a sudden degradation in load carrying capability post yield. Multi linear stress strain data of concrete is assumed for wall end portion. A tri linear stress strain curve is assumed for reinforcement material. The non-linear material data is given in Table I and corresponding stress-strain curves are given in fig. 3.

***Table I: Non-linear material data***

| No: | Material | Stress (MPa) | Strain |
|---|---|---|---|
| 1 | Fe 415 | -535500 | -0.2 |
| | | -535500 | -0.1 |
| | | -415000 | -2.414 E-3 |
| | | 0 | 0 |
| | | 415000 | 2.414 E-3 |
| | | 535500 | 0.1 |
| | | 535500 | 0.2 |
| 2 | M 30 for wall portion | -20038.91 | -8.889 E-3 |
| | | -20038.91 | -1.778 E-3 |
| | | -27579.03 | -9.333 E-4 |
| | | -27579.03 | -8.444 E-4 |
| | | -18388.32 | -4.938 E-4 |
| | | 0 | 0 |
| | | 0.0184 | 4.938 E-10 |
| | | 0.0184 | 4.44 E-3 |
| 3 | M 30 for wall end portion | -21038.91 | -8.889 E-3 |
| | | -21038.91 | -6.667 E-3 |
| | | -30000 | -2.889 E-3 |
| | | -30000 | -1.778 E-3 |
| | | -21449.59 | -5.762 E-4 |
| | | 0 | 0 |
| | | 0.0214 | 5.762 E-10 |
| | | 0.0214 | 4.44 E-3 |



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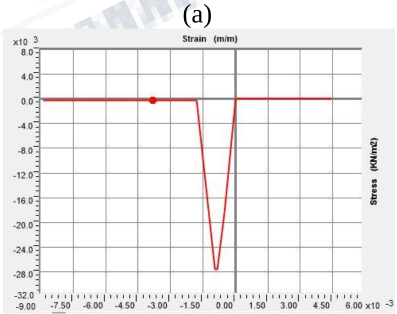

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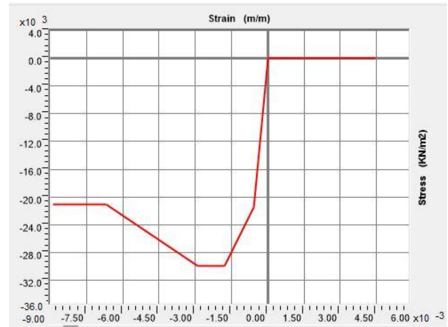


(c)

*Fig. 3: Non- linear material models: (a) steel, (b) M 30 for wall portion and (c) M 30 for wall end portion*

### C. Modeling of Structural Walls: Area Elements

The inbuilt multi-layered, non-linear shell element is used to model wall element in the selected software package. The wall is modelled as a fine mesh of smeared multi -layer shell elements which is based on principles of composite materials and can simulate in-plane and out-of-plane bending and in-plane and out-of-plane bending-shear non-linear behavior. The shell element is composed of many layers of different thickness and different material properties. During analysis, axial strain and curvature of middle layer can be obtained in one element. Then, as per the assumption that plane section remain plane after bending, the strain and curvatures of other layers are calculated. Then the corresponding stresses are calculated by constitutive laws. The multi-layered shell element model of the wall is as shown in Fig. 4.

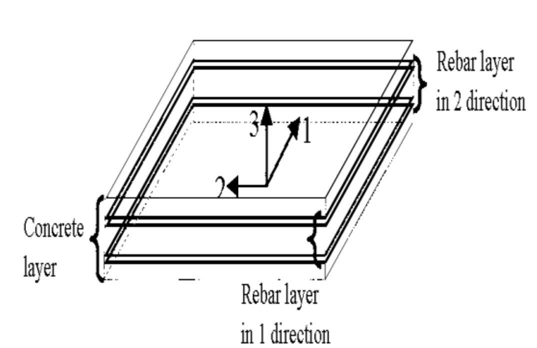



*Fig. 4: Non-linear multi-layered shell element*

## IV. ANALYTICAL STUDY OF STRUCTURAL WALLS WITH SLIT

Firstly, the Eigen Value (Modal) analysis and then inelastic dynamic analysis are carried out for the structural wall with slits and a solid structural wall, whose geometry and reinforcement details are as given in Fig. 1 and 2.

As per the modal analysis, the fundamental natural periods for SSW 1 and SSW 2 are 0.59410 s and 0.76071s respectively, while that for SSW is 0.59001s. The natural period of SSW 2 is 0.17s times longer than SSW.

Inelastic dynamic response analysis diagrams are obtained by applying four exemplary earthquake wave data namely El Centro (USA 1940), Athens (1999), Parkfield (USA 1985) and Northridge (USA 1994) earthquakes to the model. The earthquake details are given in Table II

***Table II: Earthquake details***

| No: | Earthquake | Duration (s) | PGA (g) | PGA at instant (s) |
|---|---|---|---|---|
| 1 | Athens | 45.99 | 0.326 | 6.82 |
| 2 | El Centro | 53.76 | 0.35 | 2.14 |
| 3 | Parkfield | 43.96 | 0.43 | 7.52 |
| 4 | Northridge | 59.98 | 0.843 | 4.22 |

The U S Geological Survey has developed an Instrumental Intensity Scale similar to Marcella Intensity to relate it with PGA. The Instrumental Intensity with PGA perceived shaking and potential damage is reproduced in Table III for quick reference.

***Table III: PGA related to intensity of ground motion***

| Instrumental Intensity | PGA (g) | Perceived Shaking | Potential Damage |
|---|---|---|---|
| I | <0.0017 | Not felt | None |
| II-III | 0.0017-0.014 | Weak | None |
| IV | 0.014-0.039 | Light | None |
| V | 0.039-0.092 | Moderate | Very light |
| VI | 0.092-0.18 | Strong | Light |
| VII | 0.18-0.34 | Very strong | Moderate |
| VIII | 0.34-0.65 | Severe | Moderate to heavy |
| IX | 0.65-1.24 | Violent | Heavy |
| X | >1.24 | Extreme | Very heavy |

The El Centro accelerogram is shown in figure 5

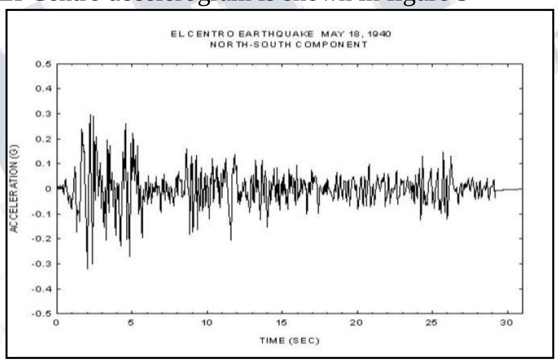
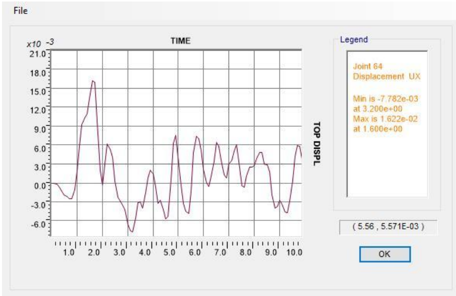
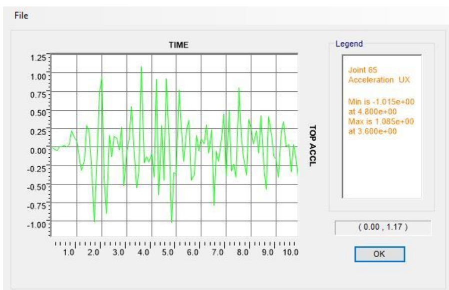



***Fig. 5: El Centro accelerogram***

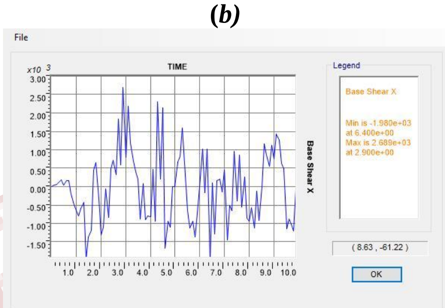
The time histories of top storey displacement, top storey acceleration, base shear and base moment of SSW 1 subjected to El Centro accelerogram is shown in Fig. 6.




***(a)***




***(b)***

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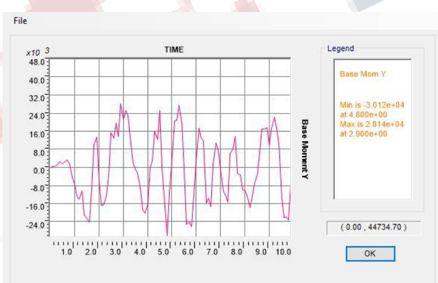


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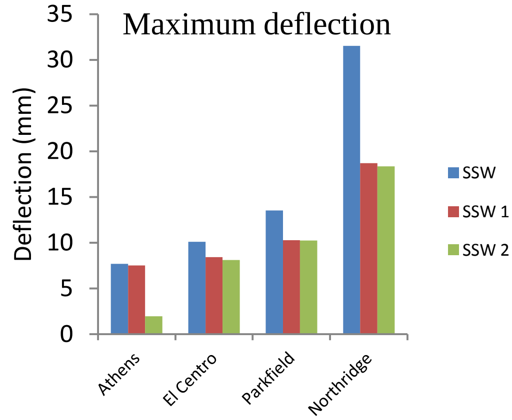
***Fig 6: Time history of responses***

The response of the structures subjected to various earthquakes is given graphically in figure 7.

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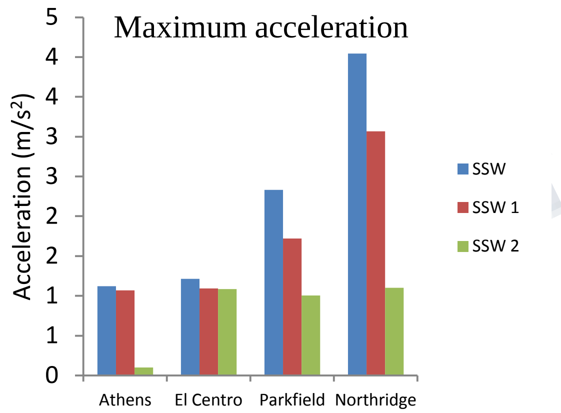


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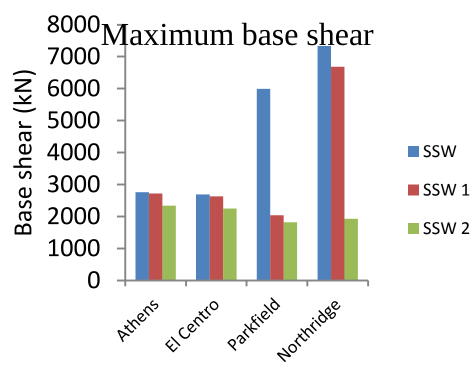
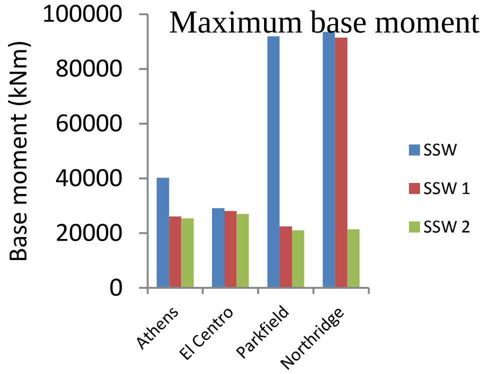



(c)




(d)

***Fig 7: Structural Response***

The top storey deflection plot for SSW, SSW1 and SSW2 for various earthquake histories indicate that slit shear walls are showing better performance. SSW1 subjected to Athens earthquake is showing 1.9% reduction in peak deflection value, whereas peak of SSW2 is about 70% less. The built-up inertia force is less in upper storeys of slit shear wall, which resulted in less deflection value.

The maximum acceleration response of structures is also giving a positive feedback for slit shear wall. The peak acceleration response reduced from 3.6% for SSW1 subjected to Athens earthquake and the trend followed in all other earthquakes also. For SSW2 subjected to Athens earthquake, the peak acceleration response reduced to 12% and the trend continued.

The base shears and base moment values for SSW, SSW1 and SSW2 also shows the same trend. The values are found decreased to 1.7% and 2.19% for SSW1 and: 15% and 16% for SSW2; subjected to Athens and El-Centro accelerogram. The base moments for SSW1 and SSW2 are 3,29% and 7% lesser than that for SSW, subjected to El-Centro time history. For other earthquake time histories, the base moment values are unexceptionally high: which may be either due to high intensity of Parkfield and Northridge earthquake histories or due to resonance.

## V. CONCLUSION

This study aimed to investigate seismic behavior of RC structural wall with the objective of studying their seismic performance with respect to solid structural wall. As per the analysis it is concluded that, under dynamic loading RC structural walls with slits are exhibiting better performance than solid ones.

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