SEISMIC BEHAVIOR OF RC DUAL DUCTILITY MODE SHEAR WALLS

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ABSTRACT:
Shear walls are among the most common lateral load resisting systems in medium height buildings. This is due, mostly, to their ability in providing the required level of lateral stiffness and strength for the structure. However, if ductility is the major concern, shear walls are not considered as efficient structural component. The fact is, in a tall shear wall, plastic hinge formation happens only in a fraction of the height of the wall and ductility resources of the rest of the wall remains, mostly, untapped. The experiences with coupled shear walls have shown the potential of dispersion of inelastic behavior over the height of the wall that causes a more desirable ductile behavior and crack pattern for the system. Intuitively, the same concept can be extended to the shear walls with openings. In such cases, both flexural and shear ductility capacity of the system over the height of the wall can be efficiently used to provide us with a dual ductility mode shear wall. In this study a series of inelastic dynamic analysis on coupled shear walls have been carried out to show the potential of dual ductility mode of behavior in responses of such systems subjected to seismic loads. The analysis is based on the equivalent frame approach for modeling the shear walls. The results show much higher performances for dual ductility mode coupled shear walls in comparison with the ordinary ones. Improvement in the behavior of coupled shear wall is quite substantial in deformational and damage aspects of the system. Furthermore, due to damage dispersion and mitigation along the height of the wall, the base shear and base moment of these shear walls reduced.

KEYWORDS:
Dual ductility mode shear wall, opening, reinforced concrete, equivalent frame method, inelastic dynamic

1. INTRODUCTION

Reinforced concrete shear walls are widely used in medium height structures to provide lateral resistance against external horizontal loads. These walls may become imperative from the point of view of economy and control of lateral deflection. But, shear walls are not recognized as ductile systems.
The maximum flexural moment due to horizontal loads happens at the base of the wall. Since bending moment in ordinary shear walls concentrated at base, the plastic hinge formed in a small portion of the height of the wall (So-called L_P), though the ductility resources of the most part of the wall become unused and nearly most of input energy dissipated in flexural manner at the base and most part of the wall dose not participate in this procedure. If the energy dissipation propagates across the height of the wall, one can improve the behavior of the wall considering the necessity for the limitation of the inter-story drifts. Otherwise, the flexural behavior dominates and the mentioned purpose will not occur. (Labafzadeh and Ziyaeifar 2008)
Applying both shear and flexural ductility modes together is the best choice for this idea to reach a *Dual Ductility Mode Shear Walls*. Combining these two modes leads to restrict the inter-story drifts to allowable amounts and utilize shear ductility mode to absorb the input energy along the height of the wall. Several aspects of such system as well as coupled and slit shear walls are shown in Figure 1. (Ziyaeifar 2001)

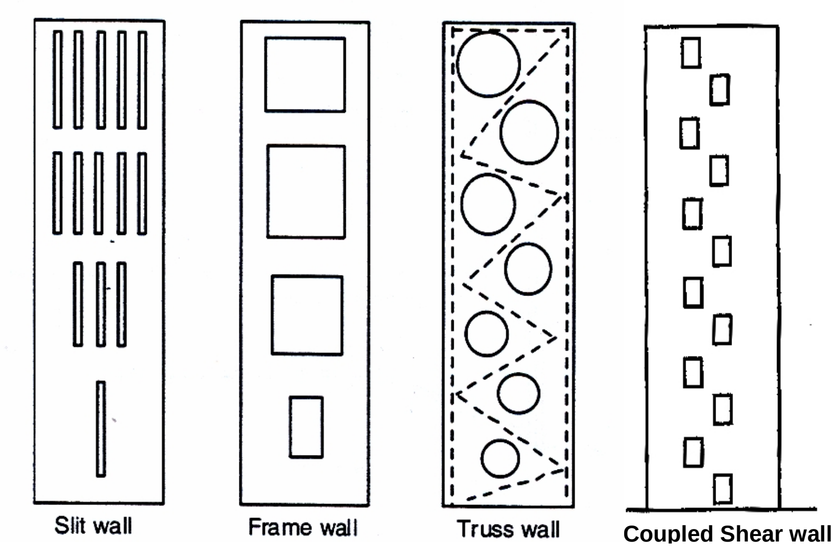

Figure 1 Samples of dual ductility mode shear walls (Ziyaeifar 2001)

In many structural walls a regular pattern of openings will be required for architectural purpose. Coupled shear walls are a form of construction often used mostly in moderately high multistory reinforced concrete buildings.
Using openings in a regular and rational arrangement leads to efficient structural systems, particularly suited for ductile response with very good energy-dissipation characteristics. The main reason for this implication is that the connecting beams are considerably weaker than the walls and have the ability to dissipate the energy over the entire height of the structure if detailed suitably. (Paulay and Priestly 1992; Chaallal and Ghlamallah 1996)
Several theoretical and experimental researches have been devoted to assess the behavior of coupled shear walls (Schnobrich 1977; Fintel and Ghosh 1974; Wight 1988; Agrawal et al. 1981; Subedi 1991; Chaallal 1992). However, Paulay (1971) carried out a noticeable research which has a considerable contribution to the understanding of hysteretic behavior of coupled shear wall systems and the ability of such walls in distributing the inelastic behavior over the height of the wall.
In addition, some experimental and theoretical investigations have been conducted to study the behavior of slit shear walls (Omori et al. 1966; Mutoh et al. 1968; Mutoh 1973; Kwan and Lu 1993; Lu and Wu 1996; Kwan and Tian 1998; Lu et al. 1999). The research performed by Kwan et al. (Kwan, Dai and Cheung 1999) on RC shear wall with one and two bond of slits indicated that yielding of the connecting beams can significantly reduce the deflection response of the slit shear wall structure.
Intuitively, the same idea can be applied for all the shear walls with any openings. In order to provide a dual ductility mode shear wall, it is necessary to employ both flexural and shear ductility capacity of the system concurrently over the height of the wall.
This paper aims to compare the seismic behavior of ordinary RC shear wall with the ones with openings using equivalent frame approach in order to show the capability of these types of walls in generating the ductile shear walls.

2. ANALYTICAL METHOD AND PROCEDURE

The most common methods used for analysis of shear walls are finite element method, continuous approach and equivalent frame method. In the finite element method the whole structure is modeled using plane stress elements for the walls, frame elements for the coupling beams and plate elements for the floor slabs. (Zienkiewicz et al. 1971) The behavior of dual ductility mode shear walls was investigated using finite element methods and the ability of such walls in creation of ductile shear wall was demonstrated. (Labafzadeh and Ziyaeifar 2008)
Various forms of plane stress elements have been developed to model the walls; these include lower order elements with or without rotational degrees of freedom (MacLeod 1969; Girijavallabhan 1969), higher order elements (Chan and Cheung 1979) and finite strip elements (Cheung and S. Swaddiwudhipong 1978) etc.

Analysis of coupled shear wall structures can be performed by means of the continuous medium technique, in which a continuous medium of equivalent properties replaced for the coupling beams. (Tso and Rutenberg 1977) On the other hand, in the equivalent frame method (Candy 1964; MacLeod 1967) both the walls and the coupling beams are modeled by frame elements. In this method, it is assumed that the sectional properties are concentrated in the vertical centerline of the cantilever wall.
To study the nonlinear behavior of reinforced concrete shear wall with openings, coupled shear walls as a common type of these walls are modeled through equivalent frame approach using DRAIN-2DX program. (Parakash, Powel and Campbell 1993) The coupled shear wall is idealized as a frame using beam-column elements which is composed of two wide columns connected by the coupling beams. In this research two type of coupled shear wall (CSW) on rigid base were selected. CSW1 model is similar to one used by Chaallal and Ghlamallah (1996). However, the concrete model used in this research (Fig. 2) is trilinear model to predict the behavior of the concrete more perfectly and differs with the bilinear model used in previous research by Chaallal et al. Model nonlinearities are considered using the extended Takeda model of the moment-rotation relationship of R/C members. (Takeda et al. 1970)

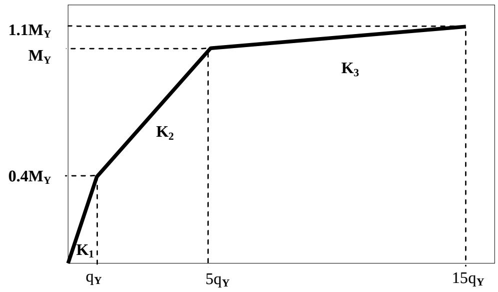

Figure 2 Trilinear model of the moment-rotation relationship of R/C members

CSW2 is the wall with stronger link beam. To investigate the behavior of these types of walls it is necessary to model an ordinary shear wall (OSW) as a bench mark. All the walls are considered in this study is assumed to be part of an office building, the plan view of which is presented in Fig. 3. It is designed to resist all the combination of gravity and seismic loads specified by the National Building Code (NBC) of Canada. (Chaallal et al. 1996)

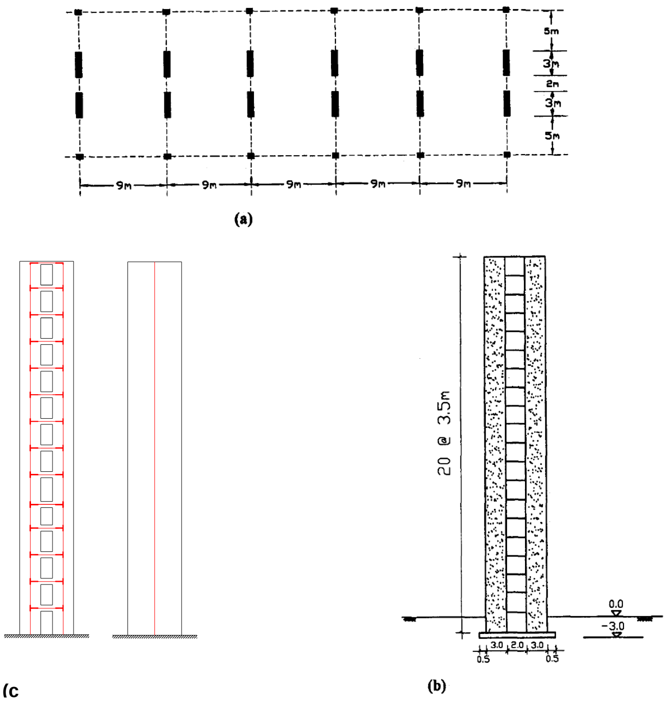

Figure 3 Geometric and analytical Model: (a) Plan View; (b) Typical CSW; (c) Analytical model

Implicit step by step Newmark-β integration procedure is used for the nonlinear dynamic analysis. In order to optimize the solution and makes it accurate, a time step of 0.0025 sec was utilized. The equation which governs the dynamic equilibrium at any time *t* is written in an incremental form as follows:

$$M\Delta\ddot{u} + C\Delta\dot{u} + K\Delta u = \Delta p(t) \tag{2.1}$$

in which M= structure mass matrix; C= viscous proportional damping matrix; K= instantaneous structure stiffness matrix; $\Delta\ddot{u}$, $\Delta\dot{u}$, Δu = incremental nodal acceleration, velocity, and displacement vectors, respectively; $\Delta p(t)$ = incremental applied loading vector which is considered as $Mr\Delta\ddot{u}_g(t)$; r = coupling vector; and $\Delta\ddot{u}_g(t)$ = incremental ground acceleration vector. In this study the lump mass concept is used. The damping matrix C is computed as:

$$C = aM + bK \tag{2.2}$$

The mass and stiffness coefficients in the above equation are determined so that the first two elastic mode critical damping ratio becomes equal to 3%.

3. NUMERICAL RESULTS

In order to study the seismic behavior of dual ductility mode shear walls, a set of seven earthquake records were utilized as input accelerograms and scaled so that all the record have the same PGA equal to 0.4g. The details of the selected records are presented in Table 3.1. A series of linear and nonlinear dynamic analysis have been performed on a variety of shear walls mentioned in previous section.

Table 3.1 Characteristics of earthquake records used

Earthquake	**Year**	**PGA (g)**	**Duration (sec)**
El Centro	1940	0.319	31.2
Taft	1952	0.179	54.38
San Fernando	1971	1.16	41.8
Santa Barbara	1978	0.203	12.57
Tabas	1978	0.852	23.82
Northridge	1994	0.500	40
Kobe	1995	0.343	48

Dissipated elasto-plastic energy over the height of the wall, the implicit center of dissipated energy, Story drift and displacement, base shear and base moment were considered as the response of structures.

The distribution of the dissipated energy over the height of the shear walls due to El Centro record is presented in Fig.4 as a typical result of the analysis. It is pointed out that most of input energy, dissipated at the lower part of OSW which leads to concentrate the damages at the small fraction of the wall. This is also confirmed by the implicit center of dissipated energy. Furthermore, dual ductility mode shear walls (DDSW) prevent the accumulation of the damages at special portion of the wall by spreading out the dissipated energy over the height of the wall, so the ductility resources of all part of wall can be utilized to have a more desirable ductile behavior.

Comparing the distribution of the dissipated energy in CSW1 and CSW2 indicates that the implication presented in this paper as dual ductility mode shear walls can be achieved if both flexural and shear ductility mode behaviors employed together. Although in CSW1 the input energy dispread over the entire height of the wall but the connecting beams are so weak that the flexural ductility at the base of the wall with extreme moment and rotation remains untapped. So the beams should be stronger at the lower part than the upper fraction of the wall,

in order to make use of both flexural and shear ductility mode simultaneously.
The intersorry drift and maximum story displacement of the selected shear walls are illustrated in Fig.5 and 6 due to El Centro earthquake as typical results. It is obvious that CSW2 as a kind of DDSWs has smaller amount of interstories drifts and story displacements in compare with other walls.

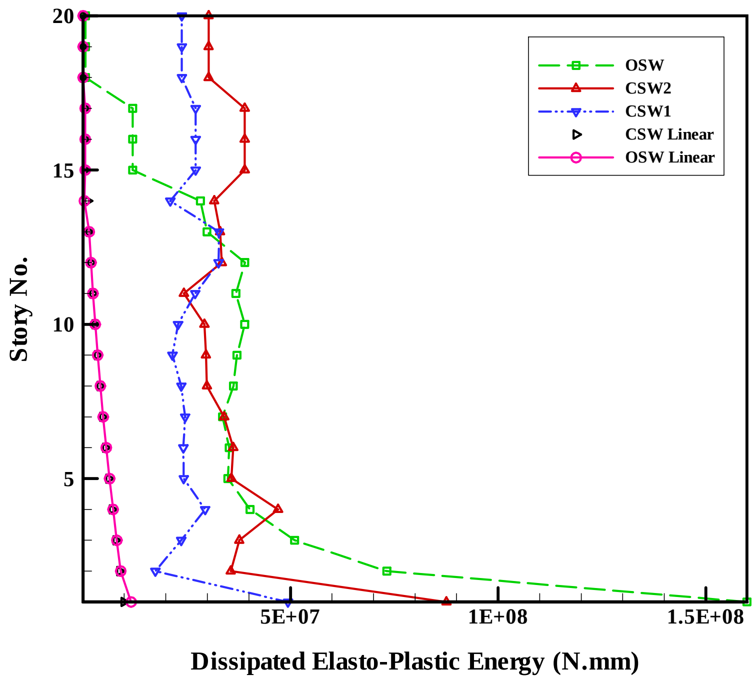

Figure 4 Distribution of Elasto-Plastic Energy over the height of the walls due to El Centro record (linear and nonlinear analysis)

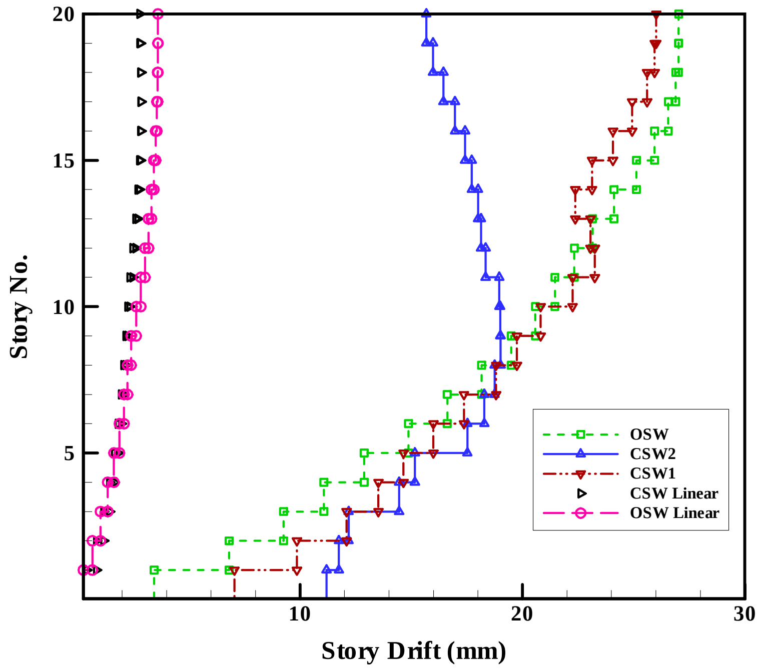

Figure 5 Interstory drifts due to El Centro record (linear and nonlinear analysis)

Time histories of base shear and base moment for OSW and CSW2 due to El Centro earthquake are shown in

Fig.7 and 8. Reducing the base shear and moment of the walls due to seismic loads are other advantages of DDSWs. So it can be stated that not only the ductility but also the damping ratio of these kinds of walls are more than other shear walls.

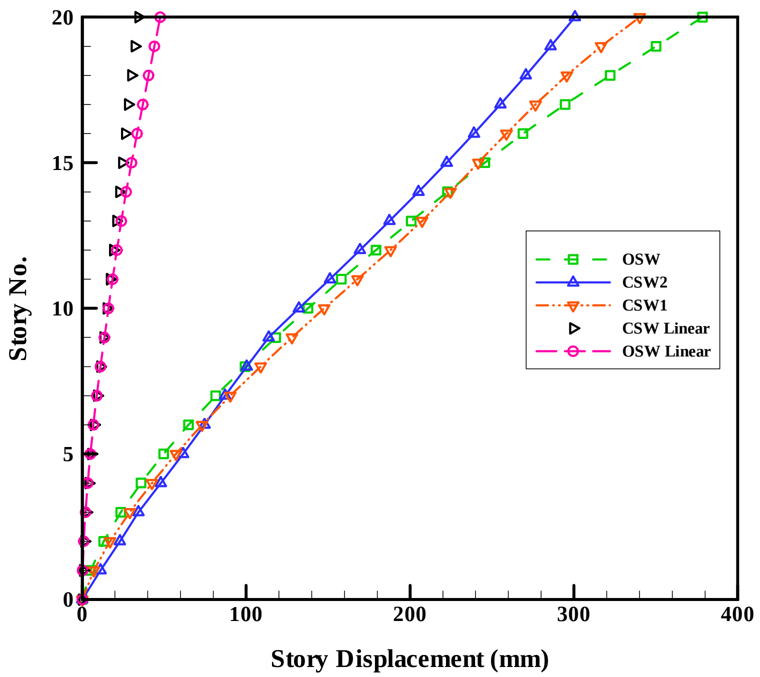

Figure 6 Maximum story displacements due to El Centro record (linear and nonlinear dynamic analysis)

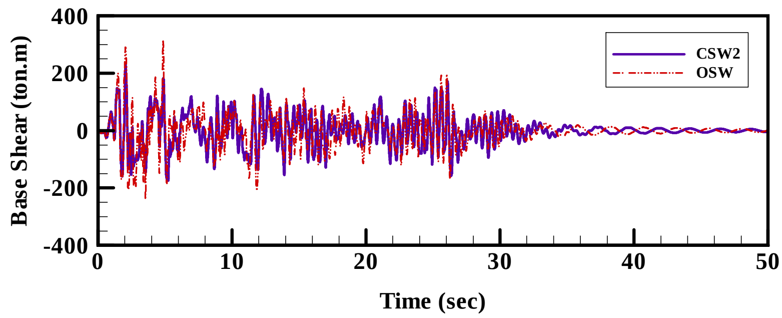

Figure 7 Time histories of base shear for OSW and CSW2 due to El Centro record

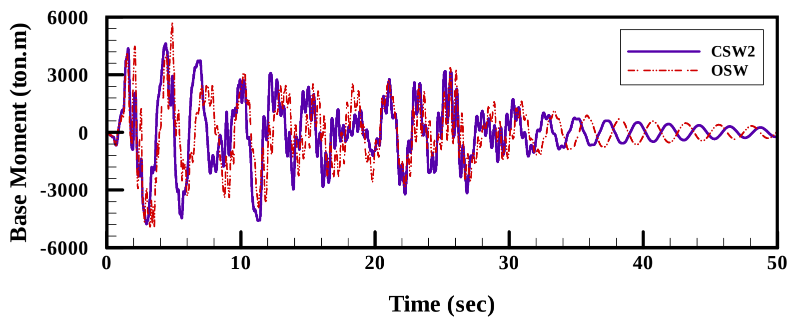

Figure 8 Time histories of base moment for OSW and CSW2 due to El Centro record

The summary of the typical results for the seismic response of DDSW due to El Centro earthquake are presented in Table 3.2.

Table 3.2 Comparison of the Response of ordinary shear wall and dual ductility mode shear wall

Response	*OSW*	*CSW1*	*CSW2*
$\mathbf{Drift_{avg}}$	19.2 *mm*	19.5 *mm*	16.6 *mm*
$\mathbf{Drift_{max}}$	27.0 *mm*	26.0 *mm*	19.0 *mm*
Top Displacement	378.5 *mm*	340.2 *mm*	300.6 *mm*
Total Elasto-Plastic Input Energy	$7.13{*}10^8$ *N.mm*	$5.28{*}10^8$ *N.mm*	$7.33{*}10^8$ *N.mm*
Implicit Center of Dissipated Energy	$0.32H_t^*$	$0.51H_t$	$0.48H_t$
Base Shear	316.4 *ton*	149.1 *ton*	231.3 *ton*
Base Moment	5719.2 *ton.m*	2270.2 *ton.m*	4776.8 *ton.m*

*H_t: *Total height of the wall*

4. CONCLUSION

Using openings in RC shear walls leads to efficient structural systems with very good energy-dissipation characteristics which is entitled Dual Ductility Mode Shear Wall here. In order to present the ductile behavior of such walls, a parametric study based on equivalent frame approach was carried out. The findings of this investigation provide better perception of seismic response of these walls.

The results of inelastic dynamic analysis on a variety of shear walls indicate that rational arrangement of openings can improve the dynamic characteristics of these walls such as ductility and damping ratio. This is occurred by utilizing the whole potential of dispersion of inelastic behavior over the height of the wall.

As the implicit center of dissipated energy is in upper height for DDSW than OSW, it is pointed out that the input energy of earthquake can be dissipated in DDSWs without any damage localization at the special part of the wall.

Decreasing in the story displacements, interstory drifts, base shear and moment are the other advantages of DDSWs caused by increasing in ductility and damping ratio.

These kinds of walls are not only provide better structural behavior, but also are suitable for architectural purpose and can be employed in the buildings without any more economical costs.

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