Exploring the Implication of Multi-plastic Hinge Design Concept of Structural Walls in Dual Systems

N. Samadzadegan
School of Civil Engineering, University of Tehran, Iran

M. Khanmohammadi
School of Civil Engineering, University of Tehran, Iran

SUMMARY:
The results of past researches have shown that higher mode effects can significantly increase the flexural demands in tall cantilever wall buildings. In this paper a new fuse mechanism through height of the walls is explored in order to reduce the effect of higher modes and an optimum arrangement of plastic hinge places is investigated. Therefore, the development of multi-plastic hinge design concept of shear walls are studied in some code conforming designed tall buildings which consist of a core wall/special moment frame dual structural system. The results of comparison in dual system core-wall indicated that with increasing in number of plastic hinges in wall height, drift distribution might tend to be linear, but seismic moment and shear demand significantly differ from code conforming design samples. The results also confirmed that the application of well-designed multi-hinge plastic concept could control the effect of higher modes of response in tall buildings.

Keywords: Shear wall, Higher mode effects, Plastic hinge

1. INTRODUCTION

The performances of shear walls during the past disastrous earthquakes have shown excellent lateral force resisting systems which can effectively reduce lateral displacements of the structures subjected to wind and earthquake (Bozorgnia and Bertero, 2004). As tools for conducting nonlinear analysis have improved and with the advent of performance based design, reinforced concrete walls and core walls are increasingly employed as effective source of lateral force resisting system (Wallace, 2007). In fact, cantilever wall systems for their high lateral stiffness, are very efficient systems to reduce the lateral displacement of structures and also the damages of nonstructural components under moderate or strong ground motions (Tjhin, et al., 2007). It should be noted that such efficacy depends on sufficient strength and also appropriate detailing.

1.1. Design concept of shear walls

In the current seismic design codes, the main idea of designing ductile shear walls is the concentration of nonlinear deformation in plastic hinge zones around the base (Bertero, 1980). The other parts of walls in height are designed based on capacity design approach (EUORO code) or load combination demands (ACI318). Thus, nonlinear deformations in cantilever walls occur in flexure and in regions which are defined as plastic hinges. The mentioned hinges are the main places where energy dissipation is occurred. Moreover, they control the strength and inelastic deformation in the entire structural system. In addition, by establishment of a desirable hierarchy in the failure mechanisms of the system, brittle failure mechanisms, and those with limited ductility are avoided (Paulay and Priestley, 1992).

As a traditional approach in seismic design of regular reinforced concrete vertical buildings, the plastic hinges are assumed to develop at the base of the walls. Proper detailing of reinforcements at the regions of the plastic hinges is required to ensure sufficient capacities; thus, exceeding the deformation capacity in these regions would not happen in strong ground excitations. In order to prepare such a capacity, seismic design codes contain prescriptive provisions to ensure sufficient ductility in plastic hinge zones (Panagiotou and Restrepo, 2009).

1.2. Higher modes effects on cantilever wall systems

Several studies have been conducted on the effects of higher modes on cantilever wall systems. Panagiotou (2009), based on some parametric analyses, suggested that in most wall buildings, including regular tall buildings, the effect of higher modes of response are largely dominated by the second translational mode. In other words, higher modes effects can increase the bending moment demands through the height of the wall. Despite this observation, the codes of the United States have not yet recognized the significance of higher mode effects on the response of the cantilever walls in tall buildings. Seismic design codes, such as ACI-318, are based on the concentration of nonlinear response at the base of the wall and they do not prompt designers to check and detail other parts of the wall to remain elastic (Panagiotou and Restrepo, 2009).

2. STUDY OF A FUSE MECHANISM IN THE HEIGHT OF THE WALL

In this study, the implications of the application of fuse mechanism through the height of the walls are explored. The reason of employing such mechanism is to reduce the effect of higher modes and investigation of optimum arrangement of the plastic hinges. Therefore, the development of multi-plastic hinge design concept of shear walls is proposed in a 16-floor reinforced concrete structure. The building consists of a core wall/special moment frame dual structural system which has been designed based on ACI-318 provisions. Some important characteristics and also the floor plan view of the building are presented in which consists of a core wall/special moment frame dual structural system. This building has been designed according to ACI-318 provisions. Some important characteristics and also the floor plan view of the building are presented in Table 2.1 and Figure 2.1.

Table 2.1. Main characteristics of the building considered

Story height (m)	3.5
Building height (m)	56
Building weight (kN)	85810
T_1 (sec)	2.97
T_1 (sec)	2.47
Core-wall thickness in stories 1-4 (m)	0.4
Core-wall thickness in stories 5-8 (m)	0.3
Core-wall thickness in stories 9-16 (m)	0.25
Core-wall area in stories 1-4 (m^2)	5.96
Core-wall area in stories 5-8 (m^2)	4.455
Core-wall area in stories 9-16 (m^2)	3.65
Core-wall longitudinal reinforcement at base (%)	1.24
Core-wall longitudinal reinforcement at mid-height (%)	0.81
Core-wall longitudinal reinforcement at quarter of wall (%)	0.75

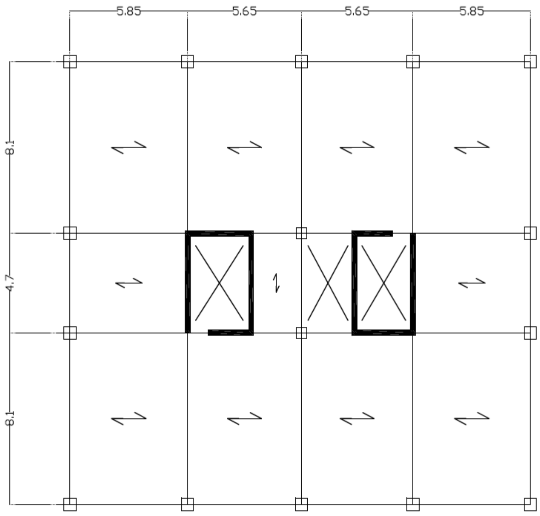

Figure 2.1. Floor plan view of the building

To compare the multi-plastic hinges buildings with the code conforming designed wall samples, the seismic performance of the systems buildings derived through a series of nonlinear static and dynamic analyses. In this regard, the structure is modeled as a nonlinear, three dimensional system in OpenSees. It should be noted that the shear walls are modeled based on the beam-column methods that mechanical properties of walls are concentrated in the geometrical center of a beam-column element. Moreover, Mander et al. nonlinear concrete model (Mander, et al, 1988) is utilized for the purpose of concrete material modeling which is presented in Figure 2.2.

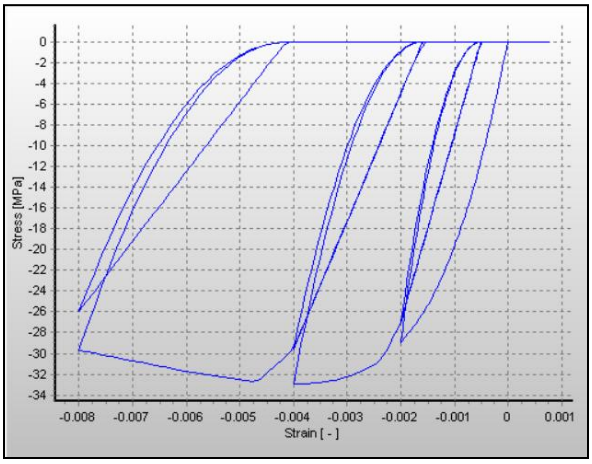

Figure 2.2. Mander et al. nonlinear concrete model (SeismoStruct program)

Menegotto-Pinto steel model (Menegotto and Pinto, 1973) is also used for the material modeling of reinforcements and is presented in Figure 2.3.

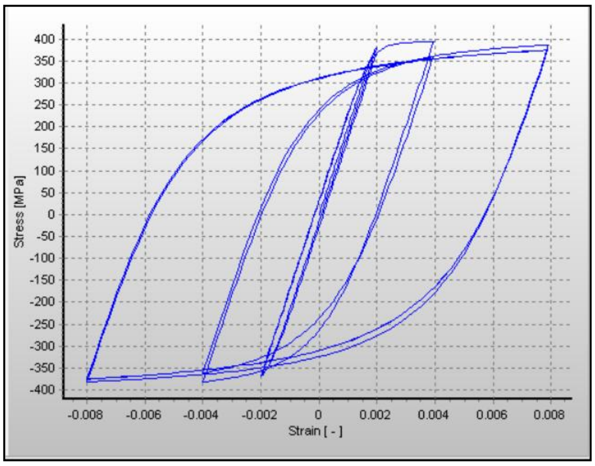

Figure 2.3. Menegotto-Pinto steel model (SeismoStruct program)

Three models are considered in this study to analyze. In the first model, one plastic hinge conforming to ACI-318 provisions is located at the base of the walls. In the second model, another plastic hinge is added to the first model which is located at the mid- height of the wall; thus, a dual-plastic hinge model is made. Finally, in the third model, three plastic hinges are located at the base, 0.25H, and at 0.5H, where H is the total height of the wall. The nonlinear properties of the plastic hinges of walls are assessed through a pushover analysis by SeismoStruct and their moment-rotation equation is defined as Hysteretic Material in OpenSees program. In addition, the Haselton model (Hastelton, et al, 2008) is employed to define hinge properties of the beams and columns of the structure. It should be noted that Haselton is a beam-column element model which is calibrated for predicting flexural response of reinforced concrete frame elements. These properties are defined in OpenSees by Uniaxial Material Clough and assigned to zero-length elements at plastic hinge lacations.

3. SEISMIC ANALYSIS AND GROUND MOTION SELECTION

To compare the response of the systems, a dynamic time history analysis is performed for two earthquake records. Herein, records with the predominant period and large spectral acceleration between zero and the second period of the structure has been used. The reason of using such records is exciting the higher modes of response of the structure. In this regard, RIN228 and Morgan-G06090 records are selected for the analysis.

4. RESULTS OF THE ANALYSIS

Two hysteresis curves as examples of the development of nonlinear response in the plastic hinges of a wall and a beam element of the structure are illustrated in Figures 4.1 and 4.2, respectively.

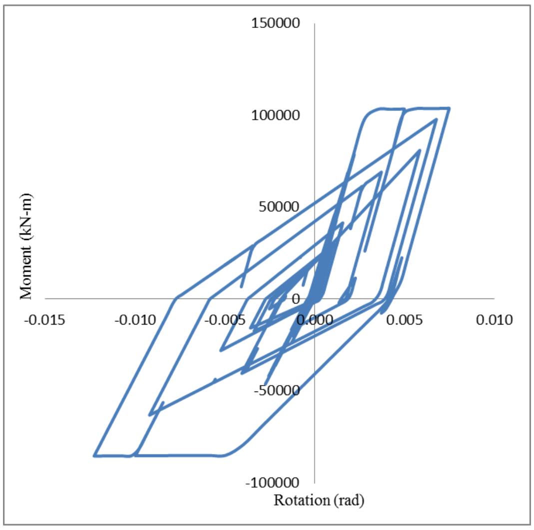

Figure 4.1. Sample of a hysteresis curve of a wall hinge

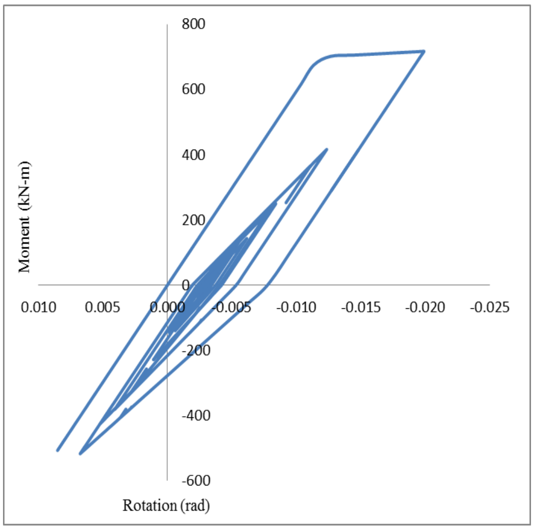

Figure 4.2. Sample of a hysteresis curve of a beam hinge

The bending moment envelopes for the Single Plastic Hinge (SPH), Dual Plastic Hinge (DPH), and the Three Plastic Hinge (TPH) design approaches obtained from nonlinear dynamic time history analysis for RIN228 and Morgan-G06090 records are shown in Figure 4.3. A main finding of the analysis is the conspicuous reduction observed in bending moment demands in DPH and TPH in comparison to SPH approach. This reduction is more significant at the mid-height of the building where the high flexural demands can possibly lead to undesirable nonlinear response. Thus, it seems that the increase in bending moment demands at the mid-height of the walls in tall buildings which is possibly caused by the second mode of response can be avoided with the application of multi-plastic hinge design concept for walls.

Moreover, the higher amount of reduction of bending moments in TPH concept compared with DPH concept suggests an optimum arrangement of plastic hinges in the case of three plastic hinges at base, quarter and the mid-height of the wall.

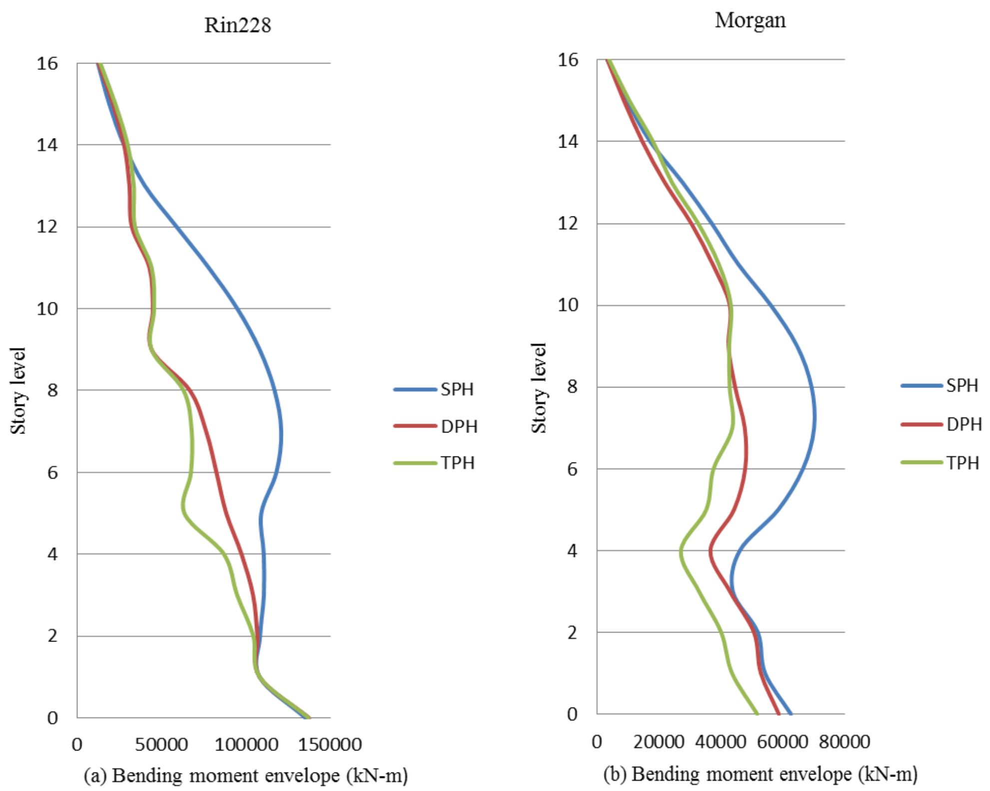

Figure 4.3. Bending moment envelopes for records (a) Rin228; (b) Morgan

Figure 4.4 represent the shear force envelopes obtained for the building in each design approach. It is observed in this figure that multi-plastic hinge design concepts can partially reduce the shear forces in cantilever walls. However, these approaches do not result in significant reduction of shear forces around the mid-height of the wall.

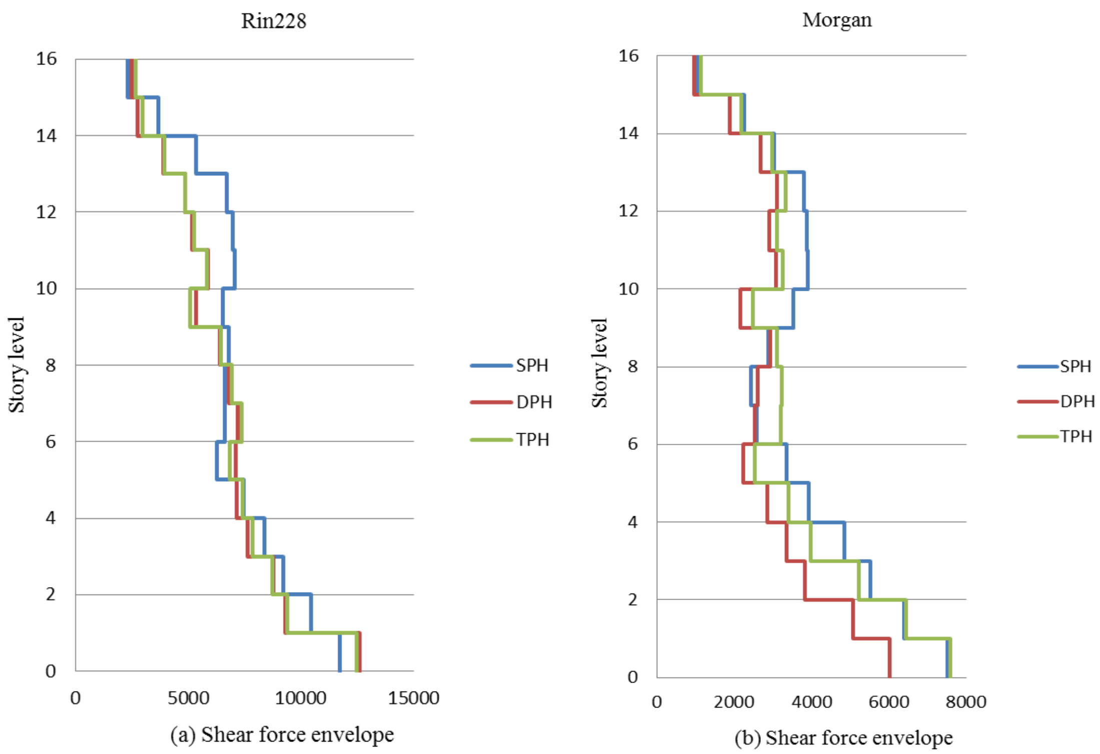

Figure 4.4. Shear force envelopes for records (a) Rin228; (b) Morgan

The inter-story drift distribution in the height of the cantilever wall building is illustrated in Figure 4.5. Regarding to the figure, one can conclude that there are no significant changes or reduction at the height of the building.

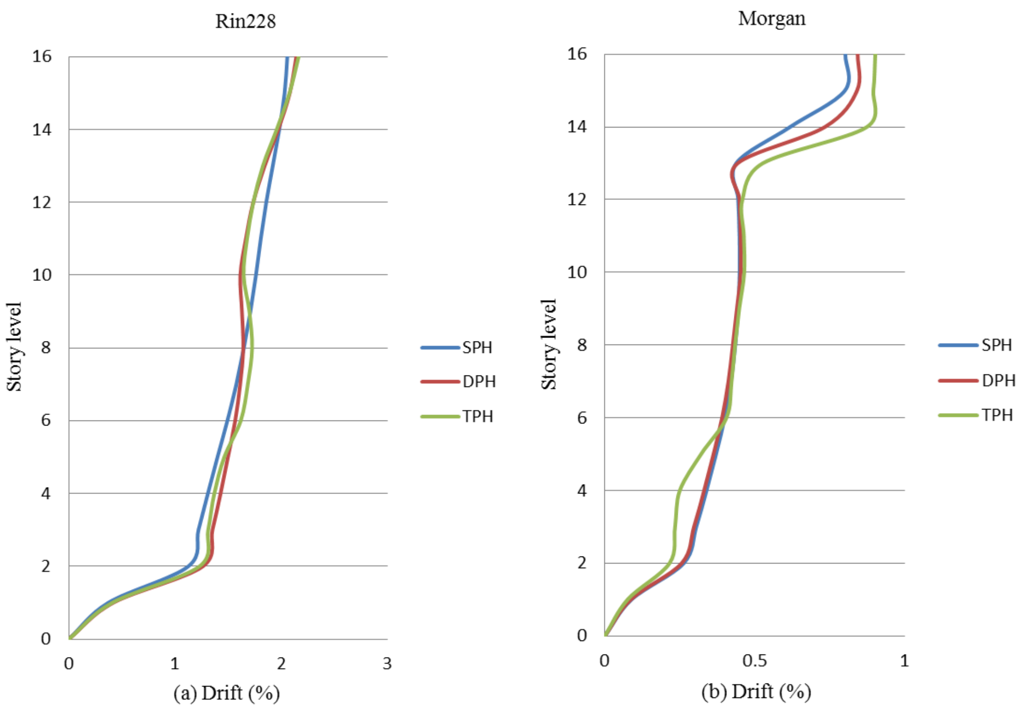

Figure 4.5. Shear force envelopes for records (a) Rin228; (b) Morgan

6. CONCLUSIONS

In This study, the efficacy of a fuse mechanism by developing the plastic hinges at the height of the shear wall is investigated. The reason of using the mechanism is reducing the effects of higher modes on the nonlinear dynamic response of cantilever-reinforced concrete wall buildings. Designing these types of buildings according to ACI-318 may result in some unintended distribution of nonlinear deformations in the height of the wall. The reason is that proper detailing to ensure the sufficient ductility is not addressed in the design procedure of the Code. Thus, the application of multi-plastic hinge design concept of the walls significantly reduces the bending moment demands at the height of the wall. Such reduction in bending moment demands can be probably increased by the effects of higher modes especially in tall buildings. In addition, the reduction of bending moment demands brings a reduction in the amount of longitudinal reinforcement in a significant portion of the walls.

REFERENCES

ACI 318-08 (2008). Building code requirements for structural concrete and commentary, ACI Committee 318, Farmington Hills, USA.

Bertero, V.V. (1980). Seismic behavior of reinforced concrete wall structural systems, *Istanbul the 7th World Conference on Earthquake Engineering*. **Vol.6:** 323-330.

Bozorgnia, Y., Bertero, V.V. (2004). Earthquake Engineering From Engineering Seismology to Performance-Based Engineering, CRC Press, New York, USA.

Haselton, C.B., Liel, A.B., Lange, S.T., Deierlein, G.G. (2008). Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings, Pacific Eerthquake Engineering Research Center, report 2007/3, University of California, Berkeley.

Mander J.B., Priestley M.J.N., Park R. (1988). Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering*, **Vol. 114:** No. 8, 1804-1826.

Menegotto M., Pinto P.E. (1973). Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behaviour of elements under combined normal force and bending. Symposium on the Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads, International Association for Bridge and Structural Engineering, Zurich, Switzerland.

Panagiotou, M., Restrepo, J.I. (2009). Dual-plastic hinge design concept for reducing higher-mode effects on high-rise cantilever wall buildings, *Earthquake Engineering and Structural Dynamics* **38:** 1359–1380.

Paulay, T., and Priestley, M.J.N. (1992). Seismic Design of Reinforced Concrete and Masonry Buildings, John Wiley & Sons, New York, USA.

Tjhin, T.N., Aschheim, M.A., Wallace, J.W. (2007). Yield displacement-based seismic design of RC wall buildings. *Engineering Structures* **29:** 2946-2959.

Wallace, J.W (2007). Modeling issues for tall reinforced concrete core wall buildings, *The Structural Design of Tall and Special Buildings* **16:** 615–632.