SEISMIC EFFECTS ON COUPLED SHEAR WALL STRUCTURE BY COUPLING BEAMS WITH SIDE BOLTED STEEL PLATES

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ABSTRACT:

Reinforced concrete coupled shear wall structure is an efficient seismic resistant structural system. It has large lateral stiffness and strength, and can provide good control of horizontal displacements and story drifts of buildings under earthquake loads. Reinforced concrete coupling beams, that connect two or more walls in series, play an important role in distributing load and deformation demands throughout the wall system. In this study, nonlinear pushover analysis was conducted for coupled shear wall structure systems with bolted side-plate coupling beams. The objectives of this study are (i) to investigate the seismic response of coupled shear wall system to coupling beams with or without bolted steel plates, and (ii) to provide an improved understanding of retrofitting coupled shear wall structures by plated coupling beams. The behaviors of coupled shear wall structures under pushover loading are discussed in terms of the displacement profiles, target displacements, wall reactions, story drifts over the height, base shear, coupling beam chord rotations, and cracking and yield sequences.

KEYWORDS: Shear wall, coupling beam, steel plate, nonlinear analysis, pushover

1. INTRODUCTION

Coupled shear wall or core wall is an efficient structural system and is commonly employed as a major lateral load-resisting system in tall building structures. A number of coupled individual wall piers can produced a system with large lateral stiffness and strength. By coupling individual flexural walls, the lateral load resisting behavior changes to one where overturning moments are resisted by an axial compression-tension couple across the wall system rather than by the individual flexural actions of walls. The stiffness, strength and ductility of coupling beams have great influences on the overall structural behavior of coupled wall buildings under seismic attack. Local failure of coupling beams may lead to a serious global failure of the whole lateral load resisting system of the building. Under seismic action, the shear and deformation capacities of coupling beams in coupled shear wall or core wall systems are often critical. Fail to provide sufficient ductility to coupling beams may lead to a premature failure of beams under high induced shear or flexural loads (Paulay, 1971 and Wang et al., 1992).

The strengthening techniques have been widely used in the recent years in civil infrastructures such as columns, beams or slabs since their first application in the 1960s (L'Hermite and Bresson, 1967) due to repair or upgrading of the RC structures. Many researchers (Jones et al., 1982; Taljsten, 1995; Oehlers et al., 2000; Lin and Kao, 2003) conducted research on strengthening common flexural beams with bolted or bonded steel plates. The experimental investigations on strengthening RC coupling beams with bolted side steel plates have been conducted by authors. The research shows that external steel plate attachment by bolted connections could considerably improve the strength and deformation capacity of coupling beams under reversed cyclic loadings and steadily sustain most of the shear force after reaching the peak loading of the coupling beam. The good inelastic responses of the strengthened coupling beams support the use of bolted connections for the case of high seismic loading and displacement demands. The behavior of strengthened coupling beams is better with larger ultimate capacity and deformability if the bolt connection group is good with smaller slip under cyclic loading. Based on the experimental results, the envelops of RC coupling beam and bolted side steel plate strengthened coupling beam can be proposed, which are used in nonlinear static pushover analyses for investigating the seismic behaviors of coupled shear wall with bolted side steel plate strengthened coupling beams.

The advent of performance based design has brought the nonlinear static pushover analysis procedure to the forefront. The static pushover procedure has been presented and developed over the past nearly thirty years by Saiidi and Sozen (1981), Fajfar and Gaspersic (1996), and Bracci et al. (1997), among others. In pushover analysis, the magnitude of the structural lateral loading is incrementally increased in accordance with a certain predefined pattern. With the increase in the magnitude of the loading, weak areas and failure modes of the structure could be found. The loading is monotonic with the effects of the cyclic behavior and load reversals being estimated by using a modified monotonic force-deformation criteria and with damping approximations. Static pushover analysis could trace the sequence of yielding and failure on the member and the structure levels as well as the progress of the overall capacity curve of the structure. The method has been described and recommended as a tool for design and assessment purposes by the U.S.A. National Earthquake Hazard Reduction Program 'NEHRP' (FEMA 273) guidelines for the seismic rehabilitation of existing buildings. This analysis procedure is selected for its applicability to performance-based seismic design approaches and can be used at different design levels to verify the performance targets. Moreover, this technique is also recommended in Europe design code, and in China seismic design code.

In this study, based on the experimental results of bolted side steel plate strengthened coupling beams, the envelops of RC coupling beam and bolted side steel plate strengthened coupling beam are obtained, then nonlinear pushover analyses of the coupled shear wall structure systems with side steel plate bolted coupling beams are conducted. The effect of the coupling beams with and without side bolted steel plates on coupled shear wall system response are investigated. The behavior of coupled shear wall structures under pushover loading is discussed. The discussion addresses displacement profile, wall reactions, story drifts over the height, base shear, coupling beam cracking and yield, concrete crack at critical locations, and system strength. This study provides an improved understanding of retrofitting of coupled shear wall structures.

2. STRENGHTHENING COUPLING BEAMS WITH BOLTED SIDE STEEL PLATE

There are several reasons for strengthening or retrofitting reinforced concrete coupling beams to increase their strength, deformation and energy dissipation capability., such as RC coupling beams in a large number of old coupled shear wall suffer serious material deteriorations due to carbonation, chloride attack of reinforcement, alkali–silica reaction of concrete; due to the inadequacy of the shear design equation in some old design code, coupling beams in such old coupled shear wall structures are likely to be deficient in shear reinforcement; with the economy and technology development, existing building structures located in which be of low to moderate seismicity and has no provisions for resisting earthquake loads, might no longer be considered to be up to the new standard due to increased-load specifications in the seismic code. In this paper, firstly, two typical specimens, one control specimen and the other specimen strengthened with bolted side steel plate, are presented below to show their seismic behaviors.

2.1 Strengthened RC Coupling Beam

Reversed cyclic loading tests were conducted on half-scale coupling beams (Unit 1 and Unit 2), Unit 1 is control specimen and Unit 2 is a strengthened specimen, to investigate the behaviors of the strengthened coupling beams and to obtain the envelopes of load-deformation. As a control reference, Unit 1 was a conventional reinforced coupling beam not strengthened by bolted side steel plates, and the span-to-depth ratio is 2.5.

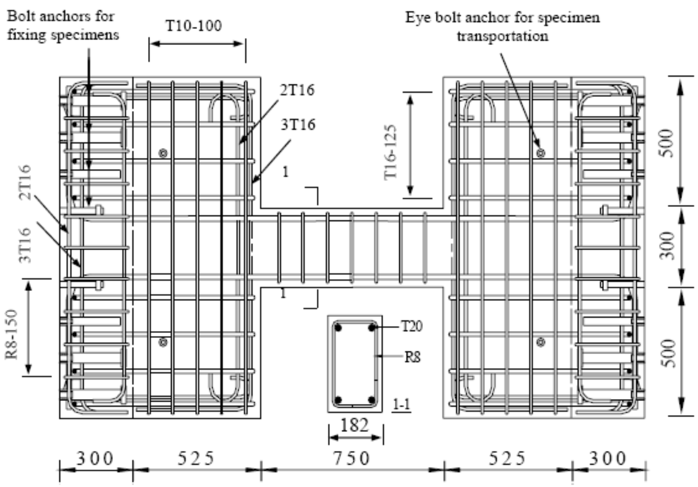

Figure 1 Reinforcement Details of Specimen

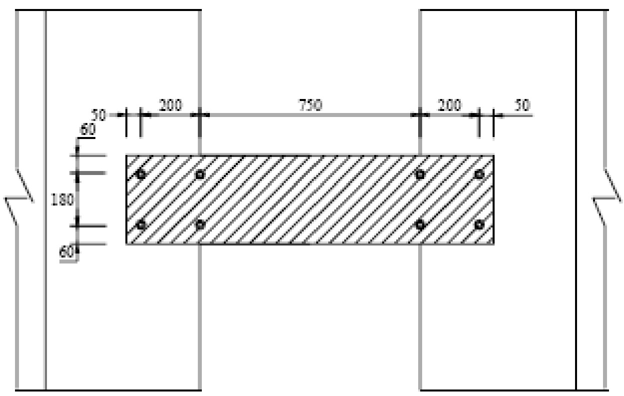

Figure 2 Strengthening Details of Coupling Beam

The control specimen Unit 1 was designed to ensure that shear failure would occur prior to flexural failure. Design compressive strength of concrete in shear walls and coupling beams is about 40MPa and the design strength of reinforcement is 460MPa for high strength deformed bars. In the specimens, the beam compression and tension reinforcements were provided by two 20mm high yield deformed reinforcing bars. The employed arrangements of the reinforcement details of Unit 1 are shown in Figure 1. The steel plates were attached to the side faces of the strengthened specimen by means of bolting. The bolts were designed to transfer all the bending and shear forces from the steel plates to the wall anchors. Coupling beam (Unit 2) strengthened with bolted side steel plates was shown in Figure 2. Steel plates used were 1250mm long, 300mm deep and 6mm thick, matching the depth of the coupling beam. The strengthened coupling beam required anchor sockets at specific locations for the fixing of the external plates. In order to simplify the fabrication, cast in place sockets were used in the test for the mechanical anchorage system. The number of anchor-bolt connections required depended on: the bearing capacity of the concrete, the shear capacity of the anchor-bolts and the shear capacity of the steel plates.

In this connection system, all stress transfers between the plates and the concrete beam must take place through the bolts. The bolt detail was designed to minimize any possible slippage at the connection.

2.2 Shear-Chord Rotation Curves and Force-Deformation Envelopes of RC Coupling Beam

Figure 3 shows the applied shear force against the chord rotation angle for the specimens. It can be seen that the strength and deformation capacity in terms of chord rotation of the plate-strengthened coupling beam were increased when compared with those of the control specimen. The shear force – chord rotation curve of Unit 1 exhibits substantial pinching, especially at large deflection amplitudes. While Unit 2 underwent less serious pinching than Unit 1 due to the steel plates strengthened in the coupling beams. Comparing with those of Unit 1, the ultimate shear V_{max} and the ultimate measured chord rotation angle (θ_u) of Unit 2 were increased by 96% and 90% respectively.

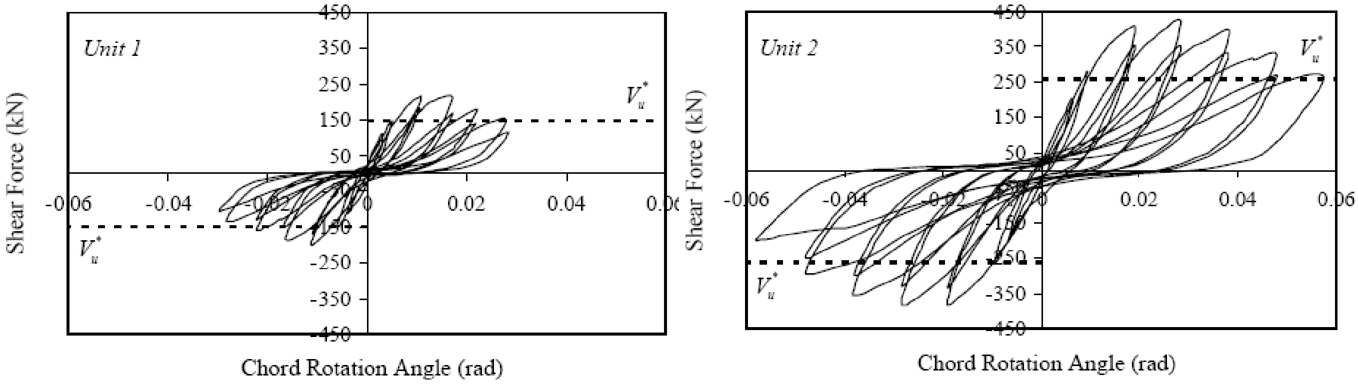

Figure 3 Shear-Chord Rotations Hysteretic Loops of Specimens

The notional stiffness K_0 calculated from experimental results for Units 1 and 2, respectively, is equal to 37.9, and 35.1 (kN/mm). It was noticed that the stiffness among the control specimen and strengthened specimens has little change. Since smaller increase in stiffness induces smaller increase in absorbing forces in coupling beam during a seismic attack, this is desirable and advantageous to have coupling beams with steel plates strengthened to resist loads during a seismic attack. Comparing the strength and deformation of the strengthened coupling beam with those of the control specimen, it could be concluded that the attached steel plates significantly increased both the strength and the deformation capacity of the beams with little increase in the notional stiffness of the beams. However, excessive deformations of the specimens caused crushing of concrete under compression and also cracking of concrete under tension. Failure of the concrete section led to ultimate failure of the beams.

The envelope curves of specimens are shown in Figure 4, as the applied load increased, concrete was cracked under tension and the chord rotation of coupling beam increased, the load-resisting action of the strengthened beam could be increased through the activation of the steel plates and the anchor-bolt connections. When either compressive concrete crushing or steel plates yielding in tension area and buckling in compression area occurred, the strengthened beams reached their ultimate loads. The average curvature values of the sections spanning between the two reference points with LVDTs can be calculated from testing results. The yield curvature of Unit 1 is about 0.029 rad/m. The increments in curvature were associated with cycles of greater ductility factor. Towards the later stage of loading, the damage of concrete and the buckling of steel plates contributed to the accelerated rate of increase in the curvature in the plastic hinge region.

Load-deformation envelop (moment-curvature and shear-shear distortion envelop) describes the changes in the force capacity with the deformation during a loading process, which is an essential part of the structural nonlinear analysis. Generally, the cross-section fiber modal developed from can be adapted to analyze the moment-curvature relationship, or determine the moment-curvature characteristics from simplified formulations (such as Park et al., 1984). However, due to the bolted side steel plate and the slips of bolt connection group, the above two methods mentioned are not directly applicable, in this study for nonlinear static pushover analysis the moment-curvature characteristics are obtained from experimental test, and tri-liner envelope models are shown in Figure 5, in which Point 1, 2 and 3 are cracking, yield and ultimate point of specimens, respectively. But further researcher should be conducted to study the load-deformation envelop of such strengthened coupling beams with considering involved factors.

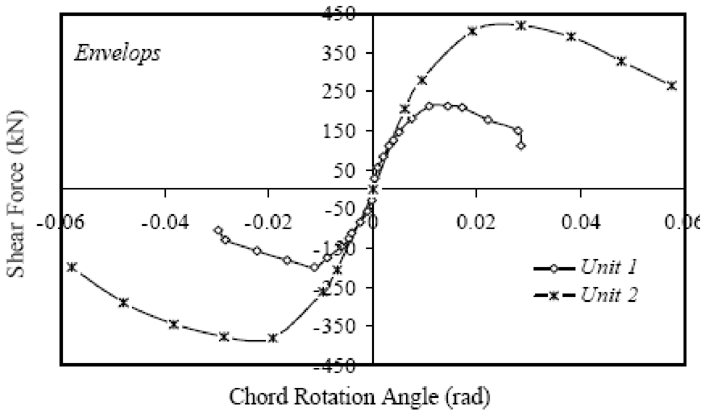

Figure 4. Load-Deformation Envelope

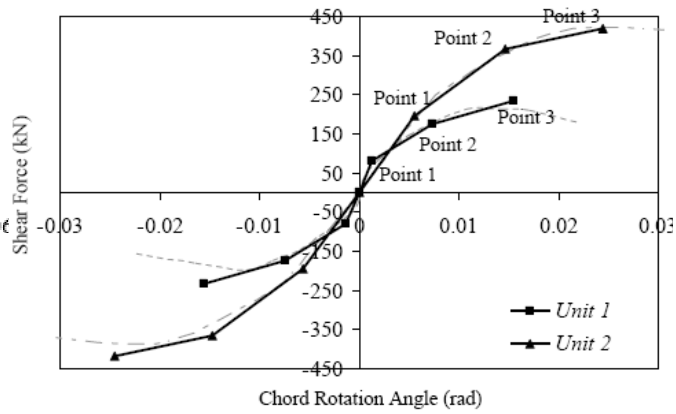

Figure 5. Tri-linear Envelopes of Specimens

3. NONLINEAR ANALYSIS OF COUPLED SHEAR WALLS WITH STRENGTHENED COUPLING BEAMS

The nonlinear static pushover analysis employs simplified nonlinear techniques to quantify seismic behavior. Pushover analysis is becoming popular as it avoids the complexity of a nonlinear time history analysis yet incorporates significant aspects of system degradation that are critical to seismic behavior. However, the pushover method does not directly account for the presence of higher modes, particularly in taller buildings, and is therefore limited to low- to mid-rise buildings whose behavior is dominated by first mode response. The coupled shear walls structures considered herein fall in this category. The nonlinear static analysis of coupled shear walls is conducted based on IDARC procedure in this study.

3.1 Modeling of Coupled Shear Walls in Pushover Analyses

In analysis, Coupling beams and shear walls are modeled using macro elements. Flexural and shear deformations can be considered in the structural macro element, and also axial deformations are considered in the shear wall element. Flexural and shear components in the deformation are coupled in the spread plasticity formulation and are modeled with three parameter Park model to simulate stiffness degradation, strength deterioration, non-symmetric response, slip-lock and a tri-linear monotonic envelope. Axial deformations are modeled using a linear elastic spring element uncoupled to the flexural and shear spring elements.

The moment-curvature envelope of shear wall is computed using fiber model, and the inelastic shear properties are evaluated based on a regression analysis of a large number of test data, the cracking and shear strengths, V_c and V_y are determined from the empirical relation as:

$$V_c = \frac{0.6\left(f_c^{'}+7.11\right)}{M/(VL_w)+1.7} b_e l_w, \quad V_y = \left\{ \frac{0.08\rho_t^{0.23}\left(f_c^{'}+2.56\right)}{M/(VL_w)+0.12} + 0.32\sqrt{f_y \rho_w} + 0.1 f_a \right\} b_e l_w \tag{3.1}$$

Where $M/(VL_w)$ is the shear span ratio, ρ_t is the tension steel ratio, ρ_w is the wall reinforcement ratio, f_a is the axial stress, b_e is the equivalent web thickness, and L_w is the distance between edge columns. The shear deformation could be determined using the secant stiffness as:

$$k_y = \frac{0.5M}{VL_w} k_e \tag{3.2}$$

Where k_e is the elastic shear stiffness (GA/L_w). And the flexural and shear characteristics of coupling beams and strengthened coupling beams with bolted side steel plate are determined from experimental values as shown in Figure 5.

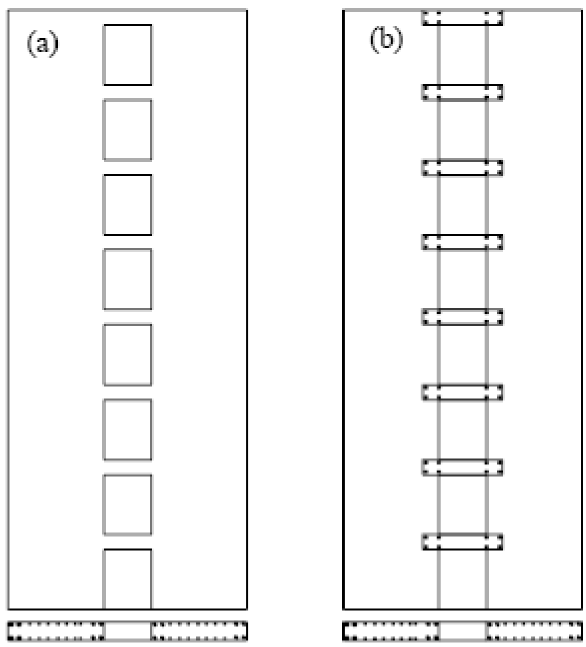

Figure 6. Coupled Shear walls (a), Strengthened Coupled Shear Walls (b)

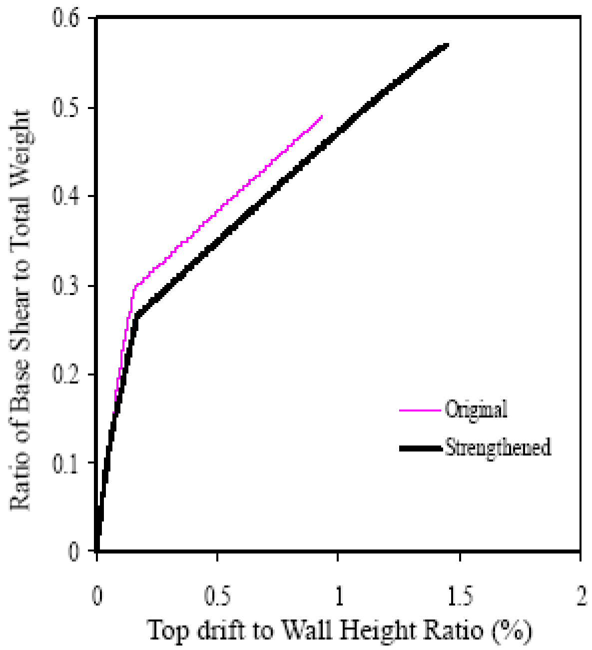

Figure 7. Curve of Base Shear with Top Drift of the Coupled Shear Walls

In the study, a half-scale eight-story coupled shear wall structure is designed as shown in Figure 6., the story height is 1.5m, the width of one shear wall is 1.5m, the thickness of shear is 182mm, the size and reinforcement of coupling beams are the same as that of experimental specimen. Each story suffers 10kN/m^2 dead load of 1.5m width. The coupling beams were strengthened along total height of shear wall.

3.2 Results of Pushover Analyses

In analysis, P-△ is considered and modal adaptive force distribution, in which the mode shapes are combined using the SRSS method and scaled according to their modal participation factor, is adopted to subject to coupled shear walls and strengthened coupled shear walls. Figure 7. shows the strength capacity of coupled shear walls. At the collapse situation, base shear force and top displacement of strengthened coupled shear walls increase 17% and 54%, respectively, comparing with those of original coupled shear walls. If number the coupling beams from bottom to top as 1 to 8, it is found that the sequence of yield coupling beams in original coupled shear walls is 7, 3, 4, 2, 5, 6, 1, 8, but the sequence of yield strengthened coupling beams in strengthened coupled shear walls is 3, 4, 2, 5, 1, 6, 7, 8. The ratio of base shear forces of first coupling beam yield in original coupled shear walls and strengthened coupled shear walls is 1: 1.27, it is found that the beginning yield of coupling beams in strengthened coupled shear walls is delayed. The lower initial stiffness, higher yield and ultimate deformations of strengthened coupling beams make that the strengthened coupled shear wall structure has better seismic performance by larger top displacement with smaller base shear force when compared with those of original coupled shear wall structure.

Figure 8(a) shows the comparison of story drift ratio when No.4 coupling beam yielded in original and strengthened coupled shear walls. The yielding of No.4 coupling beam in strengthened coupled shear walls is earlier than that in original coupled shear walls, and the base shear force is also lower, so at that time the story drift ratios of strengthened coupled shear walls is smaller than those of original coupled shear walls. But when shear wall in first story begun cracking, although the ratio of base shear forces in original coupled shear walls and in strengthened coupled shear walls is 1:0.86, the story drift ratios of strengthened coupled shear walls is larger than those of original coupled shear walls as Figure 8(b) shown. The reason for this is that the total lateral stiffness of strengthened coupled shear wall is lower when strengthened coupling beams have yielded.

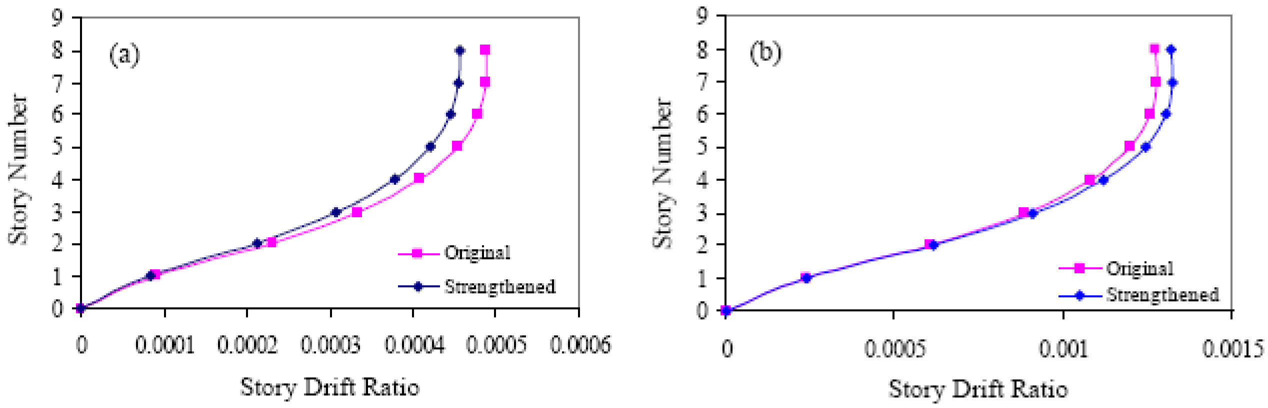

Figure 8. Comparisons of Story Drift Ratio

4. CONCLUSIONS

Based on the experimental testing, the nonlinear structural behaviors and the characteristics of load-deformation envelope of strengthened coupling beam with bolted side-steel plates are obtained, and the pushover analyses of the strengthened coupled shear walls have been conducted in this study. It is found that, due to lower initial stiffness, higher yield and ultimate deformations of the strengthened coupling beams, the strengthened coupled shear wall structure has better seismic performance by larger top displacement with smaller base shear force when compared with those of original coupled shear wall structure.

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REFERENCES

Paulay T. (1971) "Coupling beams of reinforced concrete shear walls" *Journal of the Structural Division*, Proceedings of the ASCE, **ST(3)**, pp843-862

Wang W.H., Fu X.D. and Ni Y. (1992) "Behavior of ceramite concrete coupling beams in shear wall structures under reversed cyclic loading' (in Chinese) *Journal of Building Structures*, **13(1)**, pp71-78.

L'Hermite R. and Bresson J. (1967) "Concrete reinforced with glued plates" RILEM International Symposium, Synthetic Resins in Building Construction, Paris, 1967; pp175-203.

Jones R., Swamy R.N. and Ang T.H. (1982) "Under- and over-reinforced concrete beams with glued steel plates" *The International Journal of Cement Composites and Lightweight Concrete*, **4(1)**, pp19-32.

Taljsten B. (1995) "Strengthening of structures using epoxy bounded steel or fibre reinforced plastic plates" IABSE Extending the Lifespan of Structures, August 1995, San Francisco, pp1173-1178.

Oehlers D.J., Nguyen N.T. and Bradford M.A. (2000) "Retrofitting by adhesive bonding steel plates to the sides of RC beams, Part 1: Debonding of plates due to flexure" *Structural Engineering and Mechanics*, **9(5)**, pp491-504.

Lin W.S. and Kao C.C. (2003) "Nonlinear finite element 2d analysis for RC beams strengthened by epoxy bonded steel plates" *The Chinese Journal of Mechanics-Series A:* **19(4)**, pp409-419.

Saiidi M, Sozen MA. (1981) "Simple nonlinear seismic analysis of R/C structures", *Journal of the Structural Division*, ASCE 1981;**107(ST5)**:937–51.

Fajfar P, Gaspersic P. (1996) "The N2 method for the seismic damage analysis of RC buildings". *Earthquake Engineering and Structural Dynamics* 1996;**25**:31–46.

Bracci JM, Kunnath SK, Reinhorn AM. (1997) "Seismic performance and retrofit evaluation of reinforced concrete structures". *Journal of Structural Engineering*, ASCE 1997;**123(1)**:3–10.

FEMA. NEHRP guidelines for the seismic rehabilitation of buildings. FEMA 273, Federal Emergency Management Agency, 1996.

Park, Y. J., Ang, A. H.-S., and Wen, Y. K. (1984), "Seismic Damage Analysis and Damage-Limiting design of R/C Buildings", Civil Engineering Studies, Technical Report No. SRS 516, University of Illinois, Urbana.

Valles R.E., Reinhorn A.M., Kunnath S.K., Li C. and Madan A. (1996), IDARC2D: A Program for the Inelastic Damage Analysis of Buildings. Technical Report NCEER-96-0010, 1996.