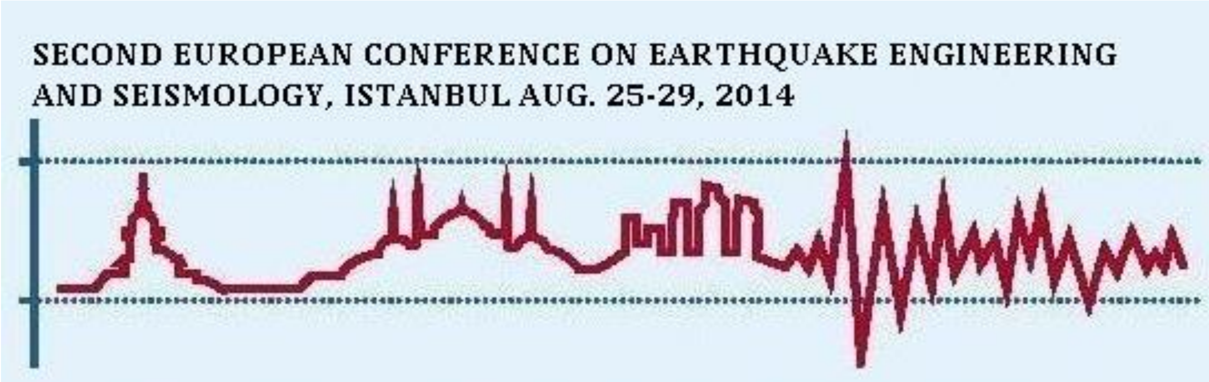

ON THE EFFECTIVENESS OF HYBRID COUPLED WALL SYSTEMS IN 46 STORY TALL BUILDING

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ABSTRACT

Congestion of reinforcement bars has always been an issue for coupling beams if their depth-to-span ratio is not high enough. Alternatively, wide-flanged steel elements can be embedded inside concrete beam to achieve necessary ductility and energy dissipation. This paper summarizes the design procedures and investigates the coupled wall system behavior for both coupling beam alternatives. Their elastic stiffness and load-deformation backbone relations were compared. Then, steel-reinforced and diagonally-reinforced alternatives were evaluated in a tall building coupled wall case for same aspect ratio values. The results of this numerical study point out that providing flexure-controlled steel reinforced concrete coupling beam can achieve at least same energy dissipation for life-safety performance level evaluations.

INTRODUCTION

With rapid urbanization, an increase in the construction of tall buildings has taken place globally. Coupled structural wall system is found to be efficient for reinforced concrete tall buildings in the 45 story range. With coupled wall systems, energy dissipation is scattered over a more extensive region of the structure because inelastic deformations are occurred not only at the bases of walls but also at both ends of coupling beams along the elevation of the shear walls (Figure 1). In idealized case, the coupling beams are assumed to maintain their plastic deformation capacity as the wall piers yield.

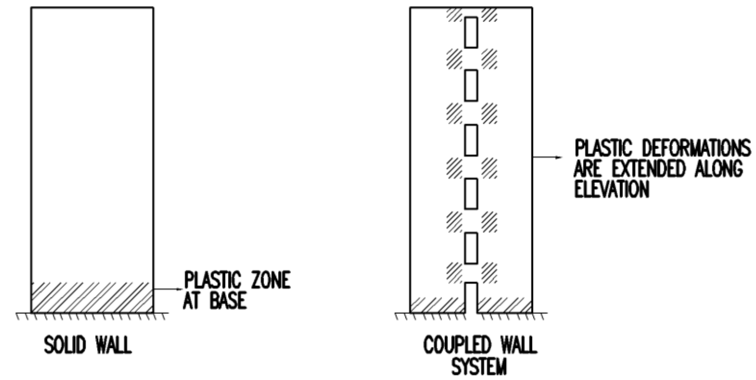

Figure 1. Plastic deformations on (a) solid wall and (b) coupled wall system

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Most commonly encountered practice for coupling beams is providing diagonal bars which are commonly assumed to form a strut-and-tie model, with one group serving as the tension and the other as the compression member (Figure 2).

The use of diagonal reinforcement in coupling beams with aspect ratio (l_n / h) less than 4.0 has been required firstly in ACI 318-99. Two bundles of diagonal rebars are placed such that they intersect at the center of the beam. To increase the compressive and deformation capacities of the diagonal truss members as well as to prevent buckling of the diagonal bars, use of transverse reinforcement around the diagonal bar groups is also required.

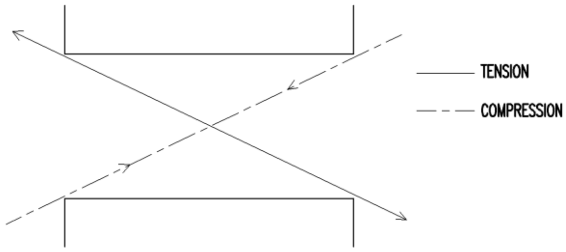

Figure 2. Compression and tension in coupling beam

The procedures for the design of diagonally reinforced concrete coupling beams are given in ACI 318-08 S21.9.7. Specifically, coupling beams with aspect ratio less than 2.0 and expected shear stress greater than a specified upper limit must be reinforced with diagonally placed bars. Previous test results conducted by Barney et al. (1980), is referred for $0.83\sqrt{f'_c \, MPa} A_{cw}$ as an acceptable upper limit for adequate ductility.

Several further experimental researches have been carried out to evaluate the load-deformation response of diagonally reinforced coupling beams (Tassios et al. 1996, Xiao et al. 1999, Galano and Vignoli 2000, Kwan and Zhao 2001, Fortney 2005, Naish et al. 2013). Compared to the beams constructed with conventionally reinforced beams, diagonally reinforced coupling beams were found to have significantly better ductility and energy dissipation properties.

On the other hand, diagonal bundles complicate the constructability; potentially increase construction time and expenses. Moreover, limited shear capacity of reinforced concrete beams lead local designers to develop impractically squat beams (Harries et al. 2000). Recent researches had already stated that, by using steel or steel reinforced concrete (SRC) beam as an alternative to reinforced concrete beams can reduce congestion problems in wall boundaries, also will improve the deformation capacities. (Harries 2000, El-Tawil et al. 2009, Motter et al. 2013). Concrete encasement can also provide fire protection for embedded steel element. Using steel elements to link reinforced concrete shear walls is referred to as a hybrid coupled wall (HCW) system (Figure 3).

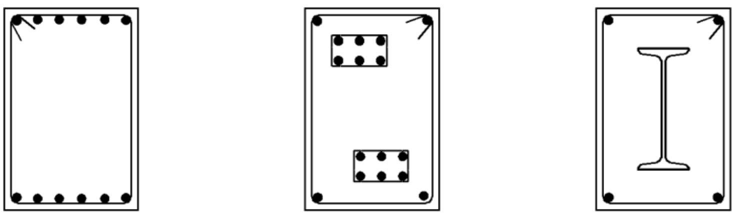

Figure 3. Reinforced concrete coupling beam alternatives (a) conventionally reinforced, (b) diagonally reinforced and (c) steel-reinforced coupling beam

In this numerical research, both pure reinforced concrete coupled wall and hybrid coupled wall systems are reviewed in terms of their assumptions on mathematical modeling, their performances and energy dissipation capabilities under earthquake. Comparative study then verified with a 46-story tall building with non-linear time history analyses. The case structure represents typical reinforced concrete core commercial office building where aspect ratio (span/depth) is over 3.0 due to limited story height.

EFFECTIVE STIFFNESS

In the ASCE Seismic Rehabilitation of Existing Buildings (ASCE 41-06), reinforced concrete beam stiffness values of $0.5E_cI_g$ and $0.4E_cA_{cw}$ are recommended for bending and shear, respectively. Supplement #1 of this document reduces this value down to $0.3E_cI_g$ for diagonally reinforced coupling beams. Previously performed test studies in UCLA on diagonally-reinforced coupling beams state that effective stiffness can be even lower (i.e. $0.2E_cI_g$) for aspect ratio between 2.4 and 3.33 due to slip and extension behavior (Naish et al. 2013). The New Zealand Concrete Structures Standard (NZS-3101 1995) gives following equation which is dependent to beam aspect ratio and ductility (Equation 1).

$$E_cI_{eff} = A \Big/ \left(B + C(\alpha)^{-2}\right) \tag{1}$$

Where α is the aspect ratio of the beam (span to depth), A, B and C are coefficients dependent to ductility. The transition of effective stiffness coefficient in NZS-3101 and their comparison to other codes and studies is summarized below (Figure 4). A report published by PEER (2010) also recommends to adopt Naish et al. (2013) proposal for nonlinear analyses. For linear procedures, Equation 1 can be used.

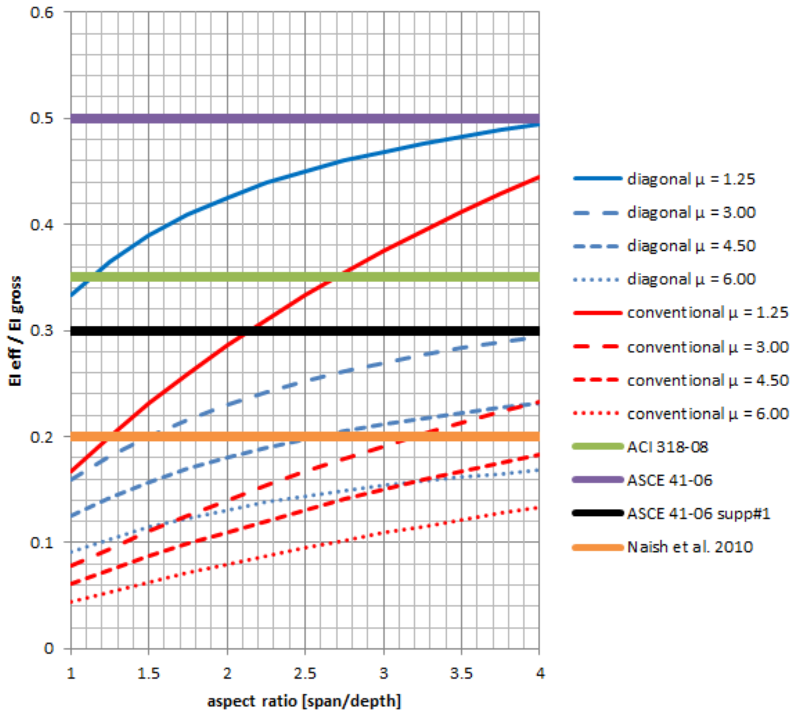

Figure 4. NZS-3101 diagonally-reinforced coupling beam stiffness coefficients vs other provisions and studies

For wide-flanged steel coupling beams, the 2010 AISC Seismic Provisions provide the following equation to estimate the effective moment of inertia (Eq. 2):

$$I_{eff} = 0.60 I_{g,s} \left(1 + \frac{18 E_s I_{g,s}}{(l + 2c)^2 G_s A_w} \right) \tag{2}$$

where $I_{g,s}$ is the moment of inertia of gross steel section, E_s is the elasticity modulus of steel material, G_s is the shear modulus of steel material, A_w is the web area for wide-flanged sections, l is the clear span of the beam and c is the concrete cover in the wall edge. The equation above neglects the contribution of concrete section. Which may lead predicting coupling ratio incorrectly for concrete encased conditions. With concrete encased steel coupling beam would have slightly stronger initial stiffness comparing to steel-only coupling beams.

Recent steel reinforced concrete coupling beam studies (Motter et al. 2013) recommend to consider the aspect ratio when determining the initial stiffness (Eq. 3). This relation is more suggestive since more slip/extension behavior is expected in beams with more squat dimensions.

$$I_{eff} = 0.06 \alpha E_s I_{trans} \tag{3}$$

In this equation α is the aspect ratio of the beam (span to depth), and I_{trans} represents the converted equivalent moment of inertia of the section by using the modulus ratio between concrete and steel material. This equation is adopted in further chapters of this study since it is more consistent for concrete encased steel coupling beams with aspect ratio between 2.4 and 3.33, which are representative values for residential and commercial occupancies, respectively.

STRENGTH-DEFORMATION BACK-BONE CURVES

ASCE Seismic Rehabilitation of Existing Buildings (ASCE 41-06) suggests linearized plastic strength-rotation behavior parameters for coupling beams in order to introduce back-bone curves. If the design conditions are met for diagonally-reinforced coupling beams, total rotations can achieve up to 0.03 rad without strength degradation (Figure 5). 20% of strength loss is expected after this "collapse prevention" limit state rotation value.

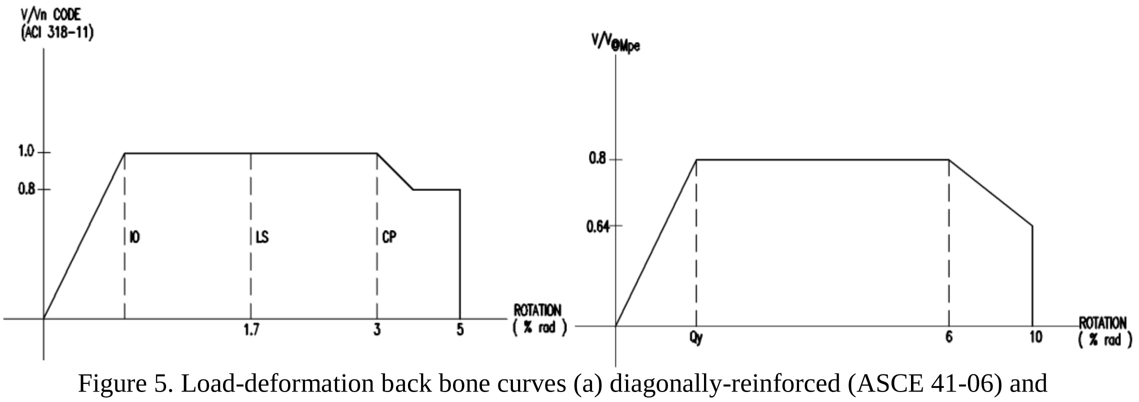

Figure 5. Load-deformation back bone curves (a) diagonally-reinforced (ASCE 41-06) and (b) steel-reinforced concrete coupling beam (Motter et al. 2013)

Naish et al. (2013) beam test results exhibited larger deformation up to 0.06 rad without significant strength degradation. A sudden strength drop down to 30% is observed with their proposal. Nonetheless, the outcome achieved with this study shows that, depending on aspect ratio, diagonally reinforced coupling beams can achieve larger ductility comparing to ASCE 41-06.

For concrete encased steel coupling beam back-bones, yield ordinate point is specified with shear force developed when the expected plastic flexural strength, M_{pe} , is developed at the beam-wall interfaces (Motter et al. 2013). With steel option, a significantly larger rotation up to 0.06rad at beam end can be achieved without any strength degradation (Figure 5b). The performance limit states are not given for this back-bone relation at this stage since a comprehensive fragility curve study needs to be carried out academically. Although, following limit states, which might be slightly conservative, are adopted by the authors of this paper for case-study in next chapter (Figure 6).

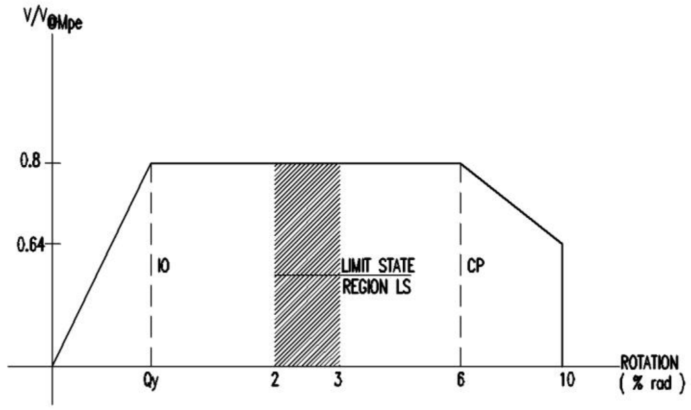

Figure 6. Limit states suggested in this numerical study for back bone developed by Motter et al. (2013)

CASE STUDY: SYSTEM-BASED COMPARISON OF COUPLED WALL ALTERNATIVES ON 46 STORY TALL BUILDING

In this numerical study, both pure reinforced concrete coupled wall and hybrid coupled wall systems are reviewed and in terms of their assumptions on mathematical modeling, their performances, and energy dissipations under earthquake. Comparative study is then verified with a 46-story tall building with nonlinear time history analyses. The case structure represents reinforced concrete core commercial office buildings where coupling beam aspect ratio (span/depth) is generally over 3.0 due to limited story height. Typical floor plan is approximately 36m by 54m; and the concrete core resides in the middle of floor plan and consists of two C-shaped channel and one I-shaped wall piers linked each other with coupling beams.

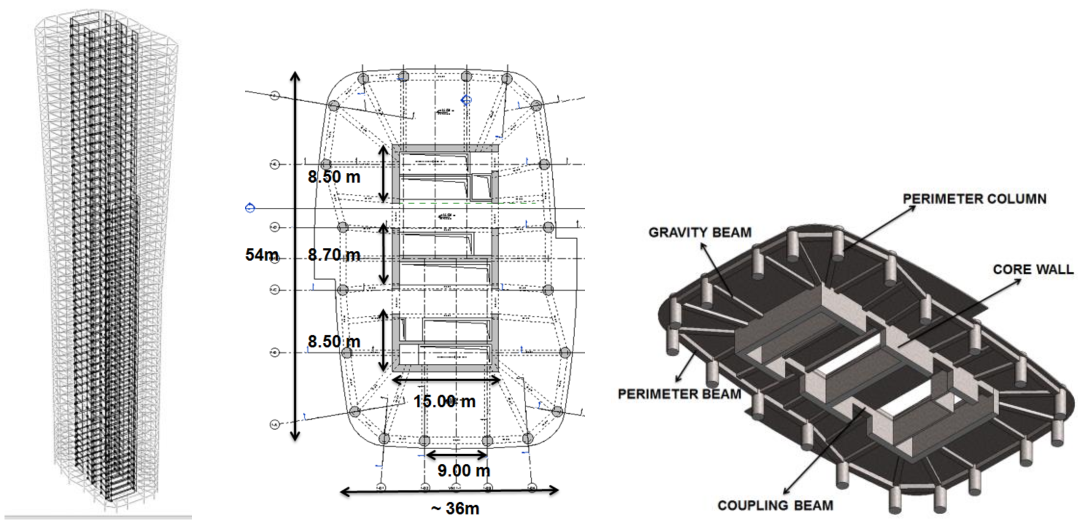

Figure 7. 46 story reinforced concrete core wall building (a) perspective view; (b) typical plan and (c) structural key elements

The occupancy of the building will be for banking and financial purposes; therefore, according to Seismic Design Code for Tall Buildings in Istanbul, the building is considered as "special building" with increased performance objectives: Life-safety under maximum considered earthquake, which has site specific PGA of 0.53g in unreduced response spectrum. The main objective for such building is to provide essential energy-dissipative structural system under high seismic demands.

Coupling beams are located on lobby entrances and their depths are restricted due to architectural reasons and also for mechanical-electrical coordination. Beam span length and depth are 3.60m and 1.05m, respectively. Beam widths are same as connecting walls' thicknesses. It is aimed to compare the efficiencies of diagonally-reinforced and steel-reinforced coupling beam alternatives with same aspect ratios.

Paulay and Binney (1974) theoretically predicted the ultimate shear capacity of diagonally reinforced coupling beams using a simple model that assumes all load resisted by diagonal compression and tension carried by the diagonal reinforcement. ACI 318-08 also determines and checks the strength of beams with diagonal reinforcement (Eq. 4).

$$V_n = 2A_{vd} f_y \sin\alpha \leq 0.83\sqrt{f'_c \, MPa} A_{cw} \qquad (4)$$

Where A_{vd} and A_{cw} are the diagonal bundle rebar area and coupling beam gross cross section area, respectively. f_y and f'_c represents steel yield stress and concrete compression strengths, respectively. Without confined concrete's contribution into diagonal's compressive capacity, the corresponding beam requires minimum of 24 amount of 32mm diameter rebar within each 13 degree diagonal bundle. The congestion of diagonals at mid-span and also at beam-wall interface can be observed in Figure 8a. In steel-reinforced concrete coupling beam alternative, a minimum required of 0.0222m3 section modulus was provided with a 850mm deep 450mm width built-up wide-section having flange and web thicknesses of 50mm and 30mm, respectively (Figure 8b).

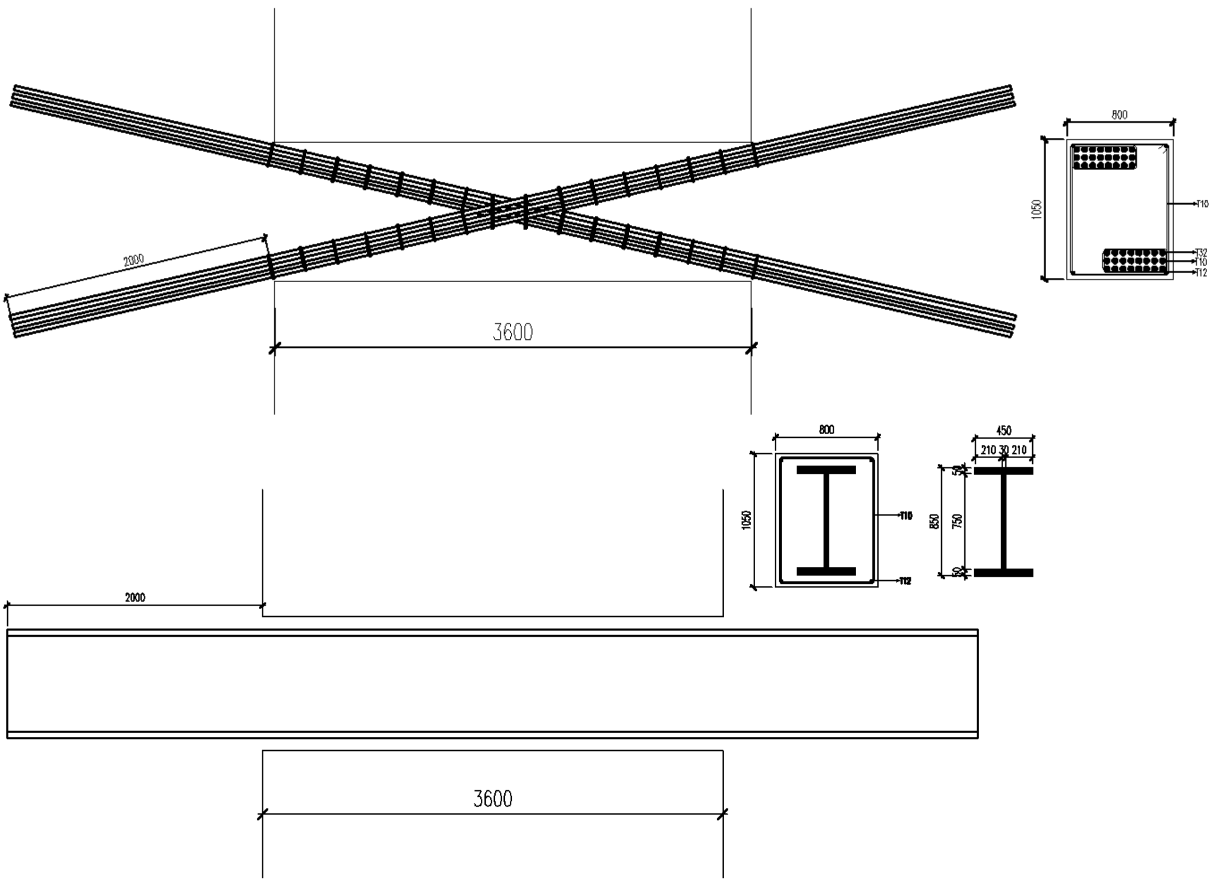

Figure 8. Design results of coupling beam alternatives (a) congestion of rebars in diagonally-reinforced case and (b) concrete encased built-up steel section

Coupling beam load-deformation relation then adopted per ASCE 41-06 for diagonally-reinforced case. Proposed back-bone curve for SRC alternative was developed based on proposal given by Motter et al. (2013). Figure 9 below shows the significant difference between both alternatives in terms of strength and ductility. The initial stiffness of SRC is slightly stronger compared to diagonally-reinforced coupling beam. On the other hand, this would not affect linear coupling ratio of the entire structure significantly.

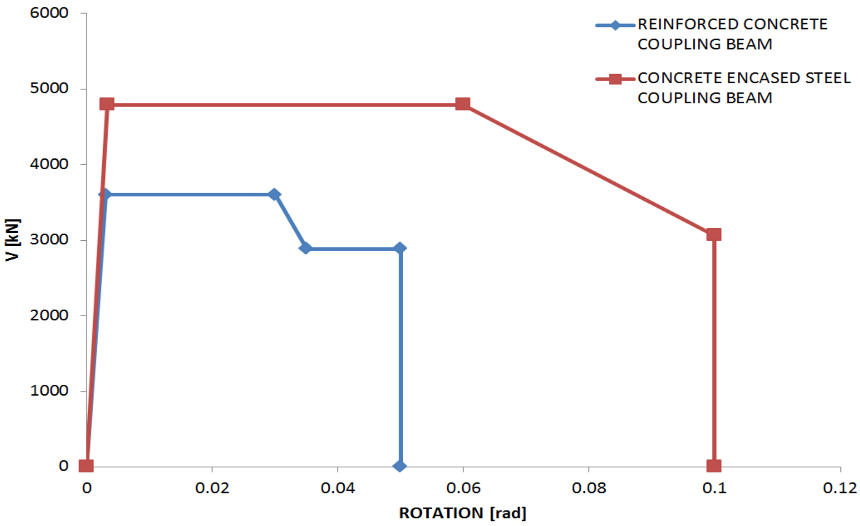

Figure 9. Shear vs. rotation capacity curves of coupling beams

Nonlinear time-history analyses then carried out in order to evaluate both alternatives for life-safety performance level under MCE. It is observed that element’s hysteretic loops and their energy dissipations are almost similar since there was not any strength degradation encountered since all elements were able to achieve life-safety performance.

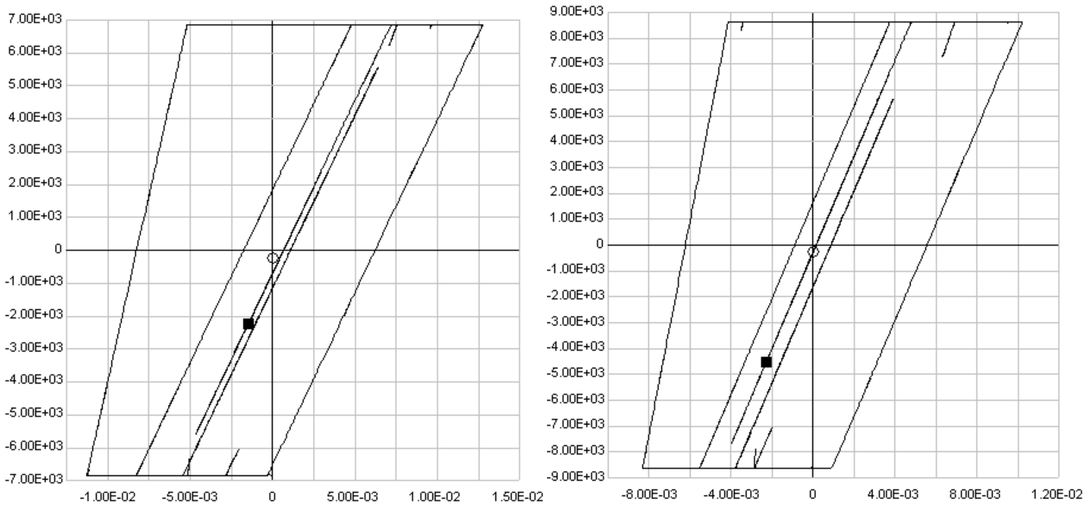

Figure 10. Coupling beam 14th floor hysteretic loops (a) diagonally-reinforced and (b) SRC coupling beam x axis rotation [rad] y axis moment [kNm]

CONCLUSIONS

In this paper, diagonally-reinforced concrete coupling beams and steel-reinforced concrete (SRC) coupling beams modeling parameters were investigated and reviewed component-wise. Their load-deformation back-bone relations were compared. Comparing to diagonally-reinforced alternative, SRC option has significantly larger deformation capabilities without strength degradation.

While diagonals with low angle cause implementation problems on site, providing minimum required embedment length for steel-reinforced concrete coupling beams is a must for adequate ductility. At least same strength can be achieved by steel-reinforced coupling beams with a lower depth. Furthermore, SRC coupling beams can provide higher ductility under higher seismic-demands.

Nonlinear time-history analyses then carried out in order to evaluate both alternatives for life-safety performance level under MCE. It is observed that element's hysteretic loops and their energy dissipations are almost similar since there was not any strength degradation encountered since all elements were able to achieve life-safety performance.

Although diagonally reinforced beams theoretically can achieve approximately same strength, the placement of required amount of rebars at aspect ratio higher than 3.0 is questionable. Therefore, it is strongly recommended to provide steel only or SRC coupling beams instead of diagonally reinforced beams where demands are high and aspect ratio is greater than 3.0

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REFERENCES

ACI Committee 318. (2011). Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (318R-08R), *American Concrete Institute,* Farmington Hills, Mich.

AISC. (2005). Steel Construction Manual, 13th edition, *American Institute of Steel Construction,* Chicago, IL.

AISC. (2010). Seismic Provisions for Structural Steel Buildings, *American Institute of Steel Construction,* Chicago, IL.

ASCE/SEI 41-06 (2007). Seismic Rehabilitation of Existing Buildings. American Society of Civil Engineers, Reston, VA, 428 pp.

Barney, G. B., Shiu, K. N., Rabbat, B. G., Fiarato, A. E., Russel, H. G., and Corley, W. G. (1980). Behavior of Coupling Beams under Load Reversals. *Bulletin RD068.01B*, Portland Cement

Computers and Structures, Inc (CSI). (2013). Perform 3D, Nonlinear Analysis and Performance Assessment for 3D Structures, Berkeley, CA.

El-Tawil, S., et al., (2010). Recommendations for Seismic Design of Hybrid Coupled Wall Systems, American Society of Civil Engineers, Virginia.

Fortney, P. (2005). The Next Generation of Coupling Beams, *PhD dissertation,* University of Cincinnati, Cincinnati, OH, 2005, 370 pp.

Galano, L., and Vignoli, A. (2000). Seismic Behavior of Short Coupling Beams with Different Reinforcement Layouts. *ACI Structural Journal*, V.97, No. 6, Nov-Dec., 876-885.

Gong, B. and Shahrooz, N.M. (2001a). Concrete-Steel Composite Coupling Beams. I: Component Testing. *Journal of Structural Engineering*. 127:6, 625-631.

Gong, B. and Shahrooz, N.M. (2001b). Concrete-Steel Composite Coupling Beams. I: Subassembly Testing and Design Verification. *Journal of Structural Engineering*. 127:6, 632-638.

Harries, K. A., Gong, B., and Shahrooz, B. M. (2000). Behavior and Design of Reinforced Concrete, Steel and Steel-Concrete Coupling Beams. *Earthquake Spectra*, EERI.

Kwan, A. K. H., and Zhao, Z. Z. (2001). Testing of Coupling Beams with Equal End Rotations Maintained and Local Joint Deformation Allowed. *Structures and Buildings*, Thomas Telford, London, 152, No. 1, 67-78.

Motter, C.J.; Wallace, J.W.; Fields, D.F.; Hooper, J.D.; Klemencic, R. (2013). Design Recommendations for Steel Reinforced Concrete (SRC) Coupling Beams. UCLA-SGEL Report 2013-06, University of California, Los Angeles, Los Angeles, CA.

Naish, D.,Fry, A., Klemencic, R., Wallace, J. (2013a). Reinforced Concrete Coupling Beams – Part I: Testing. *ACI Structural Journal*. 110:6, 1057-1066.

Naish, D.,Fry, A., Klemencic, R., Wallace, J. (2013b). Reinforced Concrete Coupling Beams – Part II: Modeling. *ACI Structural Journal*. 110:6, 1057-1066.

Paulay, T. (2002).The Displacement Capacity of Reinforced Concrete Coupled Walls. *Engineering Structures* 24, 1165-1175.

Paulay, T., and Binney, J.R. (1974). Diagonally Reinforced Coupling Beams of Shear Walls. *Shear in Reinforced Concrete*, SP-42, American Concrete Institute, Farmington Hills, Mich., 579-

PEER/ATC-72-1. (2010). Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings. *Pacific Earthquake Engineering Research Center (PEER) and Applied Technology Council (ATC) Joint Task Force*.

Seismic Design Code for Tall Buildings in Istanbul (Draft) (2008). Kandilli Observatory and Earthquake Research Institute, Bogazici University, Istanbul, Turkey.

Tassios, T. P., Moretti, M., and Bezas, A. (1996). On the Coupling behavior and Ductility of Reinforced concrete Coupling Beams of Shear Walls. *ACI Structural Journal*, V.93, No. 6, Nov-Dec., 711-720.

Toprak, A.E., Bal, I.E., Gulay, F.G., (2012). Numerical Evaluation of Plastic Region Propogation in Coupled Wall Systems, 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24-28 September.