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Towards achieving the desired seismic performance for hybrid coupled structural walls

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Abstract. It is widely recognized that the preferred yielding mechanism for a hybrid coupled wall structure is that all coupling beams over the height of the structure yield in shear prior to formation of plastic hinges in structural walls. The objective of the study is to provide feasible approaches that are able to promote the preferred seismic performance of hybrid coupled walls. A new design methodology is suggested for this purpose. The coupling ratio, which represents the contribution of coupling beams to the resistance of system overturning moment, is employed as a fundamental design parameter. A series of nonlinear time history analyses on various representative hybrid coupled walls are carried out to examine the adequacy of the design methodology. While the proposed design method is shown to be able to facilitate the desired yielding mechanism in hybrid coupled walls, it is also able to reduce the adverse effects caused by the current design guidelines on the structural design and performance. Furthermore, the analysis results reveal that the state-of-the-art coupled wall design guidelines could produce a coupled wall structure failing to adequately exhaust the energy dissipation capacity of coupling beams before walls yield.

Keywords: coupled structural walls; inelastic behavior; seismic performance; yielding mechanism; structural design

1. Introduction

Reinforced concrete structural walls, which are often used in mid- to high-rise structural systems in zones of high seismic risk, are efficient lateral load-resisting systems (Massone *et al*. 2012, Wallace *et al*. 2012). Coupled wall systems are comprised of two or more reinforced concrete (RC) structural walls connected in series by coupling beams (Fig. 1). When a coupled wall system is well designed and detailed, the coupling beams are capable of transferring adequate forces between adjacent walls while at the same time contributing significantly to energy dissipation throughout the entire height of the system as they undergo inelastic deformation (Aristizabal-Ochoa 1987). However, in order to provide sufficient stiffness, strength, and ductility under reverse loading, RC coupling beams usually require a dense configuration of steel reinforcement, which complicates the erection of coupled wall systems. It has been reported that current strength-based design methodologies often result in exceptionally high coupling beam shear demands that exceed code prescribed limits (Harries *et al*. 2005).

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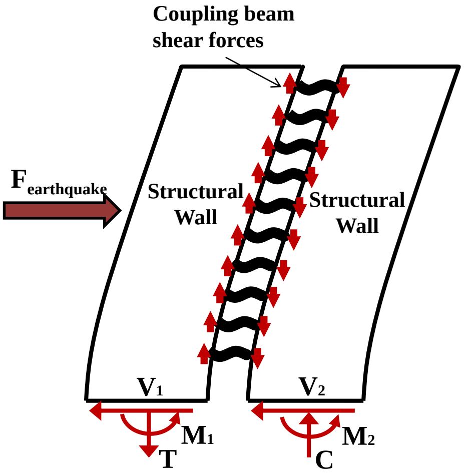


Fig. 1 The force-resisting mechanism of coupled structural walls

Structural steel coupling beams, an alternative to RC coupling beams, possess great ductility and can maintain their load carrying capacity during the large shear distortion that is imposed by the deforming of walls during earthquakes (Cheng *et al.* 2015). Studies (El-Tawil *et al.* 2010) have indicated that the use of steel coupling beams to link RC structural walls is particularly well suited for regions where seismic risk is high. This type of coupled wall structures is referred to as the hybrid coupled wall system in this paper. In recent years, innovative composite materials have been used in coupling beams to achieve enhanced seismic performance, such as high performance fiber reinforced concrete (Hung 2010, Hung and El-Tawil 2011, Lequesne *et al.* 2010, Hung and Su 2013) and concrete filled steel plates (Nie *et al.* 2014, Hu *et al.* 2014).

When a coupled wall system is subjected to earthquake loading, the coupling beam shear forces throughout the height of the structure accumulate and transform into a pair of axial force couple at the base of the system, as shown in Fig. 1. The couple moment generated by this coupling action can resist a significant portion of the total structural overturning moment (OTM) induced by the lateral loading, thereby effectively reducing the base moment demands of individual walls. The proportion of the system OTM resisted by the coupling action can be evaluated using the coupling ratio (CR). For a two-wall system, the CR is defined as

$$CR = \frac{L\sum V_{beam,i}}{L\sum V_{beam,i} + M_1 + M_2} = \frac{L\sum V_{beam,i}}{OTM} \tag{1}$$

where L denotes the distance between the geometric centers of walls, $V_{beam,i}$ denotes the shear force resisted by the i^{st} coupling beam, and M_j denotes the base moment resisted by wall j.

It is widely recognized that the CR is a key parameter in the design and behavior evaluation for coupled wall systems (El-Tawil *et al.* 2010, Hung and El-Tawil 2011, El-Tawil and Kuenzli 2002, Gong and Shahrooz 2001, Harries *et al.* 1993, Hung 2010, Harries *et al.* 2000, Shahrooz *et al.* 1993, Chaallal *et al.* 1996). When a very large CR is used, the coupled walls behave like a single pierced wall; on the other hand, when too small a CR is used, the coupling beams are not able to provide sufficient coupling action, causing the coupled walls to perform like individual walls. El-Tawil and Kuenzli (2002) conducted pushover analyses on 12-story coupled wall systems.

They found that the coupled wall system was able to reduce the wall rotation, story drift, shear distortion, and deflection in a more efficient and economical manner compared to the system with 0% coupling. Harries (2001) suggested CR=66% as a practical upper limit for hybrid coupled walls.

While studies on the effect of CRs on the deformation and internal force of coupled wall systems abound in the literature, there is a lack of studies that correlate the design value of CR with the global yielding mechanism of coupled walls under earthquakes. In addition, it is unknown that whether the current design guidelines are able to enable a coupled wall system to show the desired seismic yielding mechanism. This current report goes beyond all previously published studies to focus on the approaches for facilitating the desired plastic mechanism of coupled wall structures under seismic loading. The paper consists of two main parts. The first part introduces the design methodology employed in the study. The detailed design procedure is demonstrated through six representative coupled walls. In the second part of the paper, the correlation between the design values of CRs and the seismic yielding mechanisms of coupled walls is carefully examined based on the results of extensive nonlinear analyses on the structures.

2. System design considerations

The preferred yielding mechanism for coupled walls is commonly regarded as yielding of the coupling beams throughout the entire height of the structure prior to the onset of plastic hinges at the base of the walls (Harries *et al.* 2005, Paulay and Santhakumar 1976). This yielding mechanism takes advantage of the energy dissipation capacity of coupling beams and reduces the amount of damage to walls under small and moderate seismic hazards. However, the current US design provisions (including ACI-318 (2014), ASCE 7-10 (2010), FEMA-356 (2000)) do not consider the design factors for coupled walls that will facilitate the preferred yielding mechanism. As a result, coupling beams and walls are designed to yield at the same time (Harries *et al.* 2005). The Canadian practices (CSA 2004) uses the wall overstrength factor $\gamma = \sum 1.1 R_y V_n \big/ \sum V_f$ in the wall flexural design to ensure that coupling beams yield before walls reach their flexural capacity (V_n is the coupling beam nominal shear capacity; V_f is the coupling beam shear force determined from factored lateral loading; and R_y is the ratio of expected yield stress to the specified minimum yield stress). However, the use of the factor could induce the following adverse effects on the structural design and performance:

(1) The design force of walls could be significantly magnified due to the overstrength factor, thereby negating the advantage of using a larger design value of CR and adversely affecting the economy of the system.

(2) Since the CR is a fundamental design parameter that significantly influences the economy and seismic performance of a coupled wall system, it is important for the designer to have precise control over the design value of CR. Nevertheless, the application of wall overstrength causes the actual CR of the system to be smaller than the target value under the design earthquake. This could lead to an inaccurate estimate of force demands within the system.

(3) Although the consideration of vertical shear redistribution between beams permitted by Canadian practices (CSA 2004) and AISC Seismic-10 (2010) helps to alleviate the negative influences of wall overstrength, it also increases the likelihood that the resulting wall overstrength factor will be close to unity, consequently preventing the desired yielding mechanism from happening under earthquake shaking.

In order to minimize the wall overstrength factor, some studies (including El-Tawil *et al.* 2010) recommended minimizing the coupling beam overstrength factor or tailoring beam capacities over the height of the walls. However, only initial guidelines were suggested in these studies, and no definite design parameter has been provided. In order to minimize the adverse effect of wall overstrength while preserving the desired yielding mechanism of coupled wall systems under seismic loading, a simple but reliable design methodology is proposed in this study. The methodology involves the combination of two strategies:

(1) The nominal shear capacity of the coupling beam is designed in a manner such that $\sum V_n / \sum V_f \leq 1.2$. Through enforcing an upper limit to the beam overstrength factor, a more accurate and efficient design can be achieved.

(2) The CR, which reflects the relative stiffness and strength of the coupling beams and walls, is employed as a fundamental design parameter to control the seismic yielding mechanism of coupled walls.

The proposed design methodology and the detailed design procedure are demonstrated in the following sections using six prototype coupled walls.

3. Prototype coupled wall systems

The plan view of the prototype coupled wall systems is shown in Fig. 2. The prototype structures used in this study are based on the research plans for the U.S.-Japan cooperative research program on Composite and Hybrid Structures sponsored by the U.S. National Science Foundation (U.S.-Japan Planning Group 1992). The system is symmetric in both the longitudinal and transverse directions. It consists of a set of C-shaped reinforced concrete structural walls linked by steel coupling beams. The length of the structural walls is 6.45 m in the coupling direction and 9.6 m in the other direction. The clear length of the coupling beams is 1.5 m.

Six coupled wall system designs are generated, including 10-story and 30-story systems with CR design values of 20%, 40%, and 60%, representing low, medium, and high CRs, respectively. The CR design value is defined as corresponding to the system forming a full plastic mechanism. In the 10-story system, the height of the ground floor is 4.6 m, and the story floor-to-floor heights are 3.7 m. In the 30-story system, the height of the ground floor is 3.7 m, and all the other floor heights are 3 m. The different system designs are designated S-N-CR, where N denotes the number of stories, and CR denotes the coupling ratio design value. For example, S-30-40 indicates a 30-story building with 40% coupling.

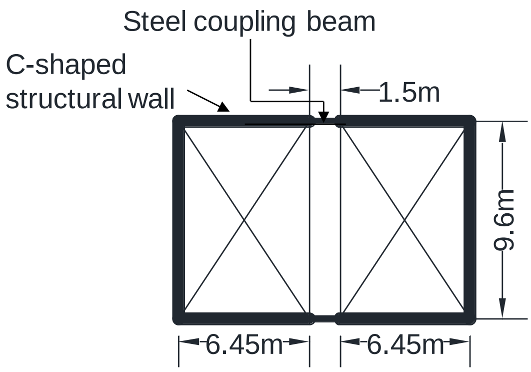


Fig. 2 Plane view of the prototype coupled wall systems

In order to fairly compare the behavior of the various systems and obtain clear conclusions about the effect of varying CR design values on the structural performance and yielding mechanism, the following considerations are taken into account in the design.

(1) All the systems are designed to have identical plane configurations.

(2) For those systems with the same height but different CR design values, they are designed to have identical wall thicknesses, structural weights, and design base shears.

The adequacy of these two considerations is justified later by the reasonable reinforcement amounts used in the designed walls (Section 3.3) and the code-acceptable seismic behavior of the systems (Section 7). The total weights for the 10-story and 30-story systems are 47 MN and 161 MN, respectively. The design base shear will be described in the next section. The selected six coupled wall systems can present the varying yielding mechanisms of general coupled walls because their different CRs and vibration periods can reasonably account for the effect of changes in various design parameters, such as the span length of beams, the depth of walls, and the stiffnesses of beams and walls. Thus, they can adequately serve as the representative examples for the research purpose in this study.

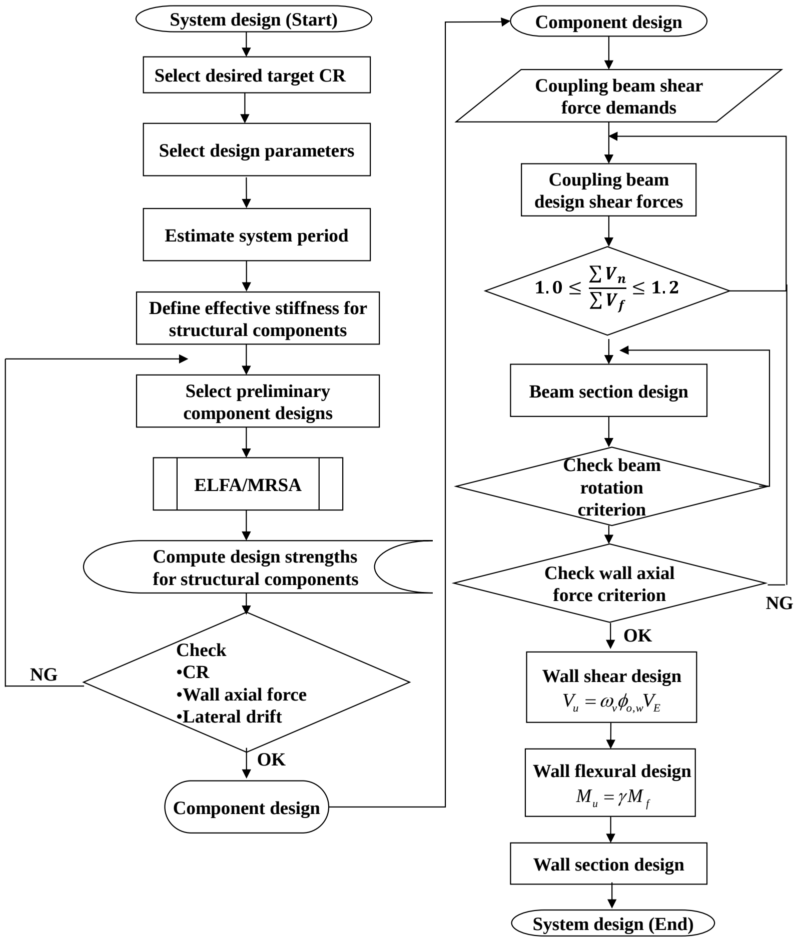


Fig. 3 The proposed design procedure for coupled wall systems

3.1 System design

The prototype structure is assumed to be an office structure in the city of Los Angeles with Site Class D, Seismic Use Group I, and Seismic Design Category D. The short-period and one-second period spectral response accelerations are S_s=2.02 g and S_1=0.76 g, respectively, where g is the acceleration due to gravity. The design response spectrum can then be derived. The prototype systems are classified as Special Composite Reinforced Concrete Shear Walls with Steel Elements in FEMA-450 (2003). The design values reported in Table 4.3-1 of FEMA-450 (2003) are applicable, i.e., the response modification coefficient is R=6, the deflection amplification factor *is* C_d=5, and the system overstrength factor is Ω_o=2.5.

The system design procedure is illustrated in Fig. 3. It is started by selecting a design value of CR. The seismic design loads can be calculated using either the Equivalent Lateral Force Analysis (ELFA) or the Modal Response Spectrum Analysis (MRSA) (FEMA-450 2003). A frame model is constructed to determine the design forces of the structural components under the influence of code specified lateral forces. In order to account for the cracking of concrete and loss of stiffness in the walls due to cyclic loading, reduced section properties are used in the model (Harries *et al.* 2005, El-Tawil *et al.* 2006, ACI-318 2014, CSA 2004, Harries *et al.* 2004, NZS 1995). The effective wall flexural and axial stiffnesses are $0.7EI_g$ and $0.7EA_g$, respectively, except for the plastic hinge zones of the tension wall that has $0.35EI_g$ and $0.35EA_g$; a wall is defined as a tension/compression wall when the coupling action produces a tensile/compressive axial force on it. The strength demands of the coupling beams and structural walls can then be determined using ELFA.

The analysis results are checked to ensure that 1) the CR shown by the model coincides with the preselected CR design value, 2) the lateral drift meets the acceptance criterion in the design codes (for example, 0.007 in ACI-318 (2014)), and 3) the wall axial force is less than 35% of the wall axial capacity (FEMA-356 2000). If the criteria are not satisfied, iterated designs, as also needed for the current strength-based design method, are tried until the criteria are satisfied.

3.2 Coupling beam design

In order to achieve a ductile and stable hysteretic behavior, the steel coupling beams are designed to yield in shear in the web before the moment capacity of the full beam section is reached (Harries *et al.* 1993). The AISC Seismic-10 (2010) guidelines for shear links in eccentrically braced frames are applicable for the design and detailing of steel coupling beams. The design procedure leads to steel coupling beams with thin webs and thick, heavy flanges. The shear demands of the coupling beams for the prototype systems are plotted in Fig. 4, where the vertical axis represents the elevation normalized by the height of the building, and the horizontal axis represents the coupling beam shear demand normalized by the maximum coupling beam shear demand in the system. It is found that the pre-selected CR design value has a significant effect on the shear designs of coupling beams along the building height. In particular, the coupled wall systems having the same CR design value exhibit a similar gradient of coupling beam shear demands along the building height. On the other hand, the different structural heights appear to have trivial effects on the shear demand distribution.

The Canadian practice (CSA 2004) and AISC Seismic-10 (2010) allow for a 20% vertical redistribution of shear forces between beams in a design, provided that the sum of the shear capacities of all the coupling beams exceeds the total coupling beam shear demand. Redistribution can improve constructability by permitting designers to use the same beam section over several floor levels of the wall. This is considered in the coupling beam design here.

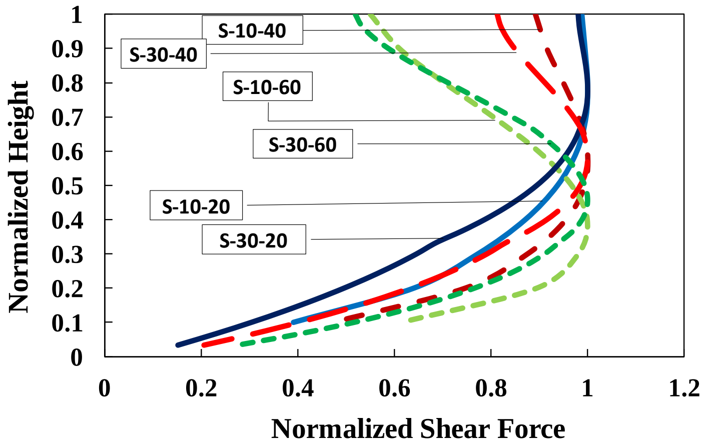
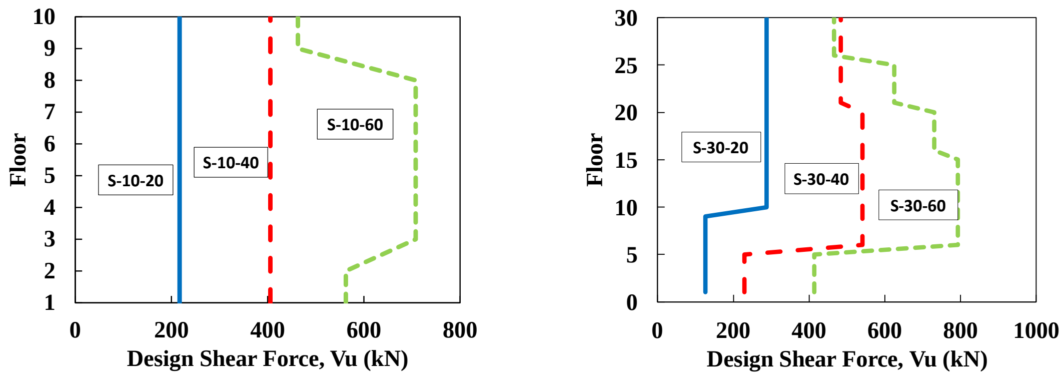


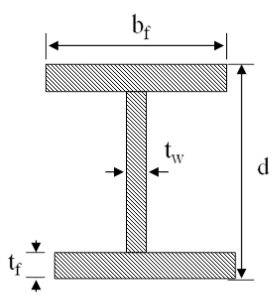
Fig. 4 Normalized shear demands of coupling beams



(a)10-story system (b)30-story system

Fig. 5 The design shear strengths of coupling beams

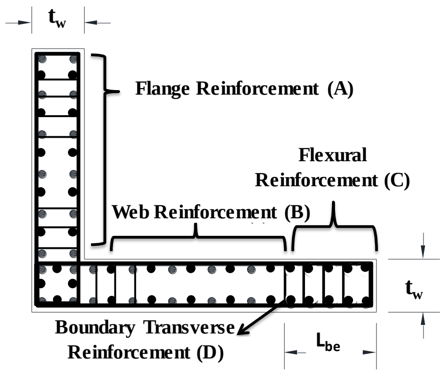
Table 1 Coupling beam designs (unit: mm)



	Floor	d	b_f	t_f	t_w
S-10-20	1-10	229	127	19	6
S-10-40	1-10	279	165	22	10
S-10-60	1-2	368	152	22	10
	3-8	419	152	25	11
	9-10	318	140	25	10
S-30-20	1-10	165	114	25	6
	11-30	305	152	29	6
S-30-40	1-5	241	127	22	6
	6-20	432	152	32	8
	21-30	292	152	25	11
S-30-60	1-5	292	152	25	10
	6-15	457	203	25	11
	16-20	432	152	25	11
	21-25	368	152	25	11
	26-30	318	140	25	10

The beam design shear strengths for the various systems are plotted in Fig. 5. Built-up plate girders are used since suitable sections cannot be found in the tables in (AISC 2011). The resulting ratios of $\sum V_n / \sum V_f$ for all the systems are between 1.0 and 1.2, within the suggested range of overstrength factors. Once the initial coupling beam designs are decided, a numerical model of the coupled wall system is built and analyzed to check if the beam rotation meets the maximum

Table 2 Reinforcement details of structural walls (unit: mm)



System	Floor	Dimensions		A		B		C	D
		t_w	L_{BE}	Horiz.	Vert.	Horiz.	Vert.		
S-10-20	1-5	305	914	#4@102	#5@203	#4@152	#5@152	16#9	#5@76
	6-10	305	914	#4@127	#4@178	#3@127	#4@152	16#8	#4@76
S-10-40	1-5	305	610	#4@102	#5@178	#4@152	#4@152	12#7	#5@76
	6-10	305	610	#4@127	#4@178	#3@127	#4@178	8#5	#4@76
S-10-60	1-5	305	508	#4@102	#5@152	#4@152	#4@178	8#5	#5@76
	6-10	305	508	#4@127	#5@178	#3@127	#4@178	8#5	#4@76
S-30-20	1-5	762	1270	#4@102	#9@152	#4@127	#6@178	16#18	#5@76
	6-10	762	1270	#4@102	#9@152	#4@127	#6@178	16#18	#5@76
	11-15	762	1067	#4@127	#9@178	#4@152	#6@178	14#18	#4@127
	16-20	508	914	#4@178	#9@191	#3@152	#5@178	12#18	#4@127
	21-30	508	813	#4@178	#8@152	#3@152	#5@178	12#14	#3@127
S-30-40	1-5	762	965	#4@102	#9@178	#4@127	#6@203	16#10	#5@76
	6-10	762	965	#4@102	#9@178	#4@127	#6@203	16#10	#5@76
	11-15	762	864	#4@127	#8@152	#4@152	#5@203	16#10	#4@127
	16-20	508	864	#4@178	#8@178	#3@152	#5@203	16#10	#4@127
	21-30	508	610	#4@178	#7@178	#3@152	#4@203	14#9	#3@127
S-30-60	1-5	762	711	#4@102	#9@203	#4@127	#6@229	12#6	#5@76
	6-10	762	711	#4@102	#9@203	#4@127	#6@229	12#6	#5@76
	11-15	762	610	#4@127	#8@178	#4@152	#5@229	10#6	#4@127
	16-20	508	508	#4@178	#8@191	#3@152	#5@229	8#6	#4@127
	21-30	508	508	#4@178	#7@178	#3@152	#4@229	8#6	#3@127

acceptable beam rotation specified in AISC Seismic-10 (2010). If the rotation criterion is not satisfied, the coupling beam design procedure is repeated until it is satisfied. The final design results are presented in Table 1.

3.3 Structural wall design

The structural walls are designed as special reinforced shear walls in compliance with ACI 318 (2014). In particular, the design shear of the structural wall is computed using Eq. (2) as recommended by Paulay and Priestley (1992) to ensure a flexural yielding mechanism

$$V_u = w_v \phi_{o,w} V_E \tag{2}$$

In Eq. (2), $\phi_{o,w}$ is the flexural overstrength factor, which is employed to ensure that the plastic behavior of the structural wall is dominated by the flexural pattern. The magnitude of the factor can be taken as 1.25 for walls with common geometries (Paulay and Priestley 1992). Alternatively, it can be taken as the ratio of the maximum probable flexural strength to the design flexural strength of the wall. The latter is particularly more suitable when the wall has a large flange. V_E is the horizontal shear demand derived from code-specified lateral static forces. w_v is the dynamic shear modification parameter that accounts for the influence of high modes on the base shear and can be computed based on the number of floors (*n*) as follows

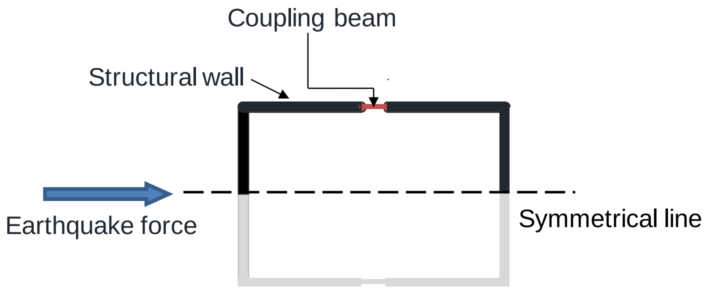
$$\omega_v = 1.3 + \frac{n}{30} \leq 1.8 \tag{3}$$

Moreover, in order to prevent weak floors under seismic loading, the design moment envelope is decided as suggested by Paulay and Priestley (1992) that the design moment in the wall levels of the plastic hinge region be equal to the design base moment, and the design moment above the plastic hinge region be obtained using interpolation. The need for special boundary elements at the edges of structural walls is evaluated according to ACI 318 (2014). Heavy transverse reinforcement is used in the boundary elements to prevent instability of the vertical reinforcement of the boundary element due to concrete spalling and crushing. The design results of the structural walls are summarized in Table 2. It is notable that substantially less wall flexural reinforcement is required in the systems with 60% coupling. It is because when the CR is increased, the lateral force resisting mechanism of a coupled wall system shifts largely from the wall moment resistance to the coupling action.

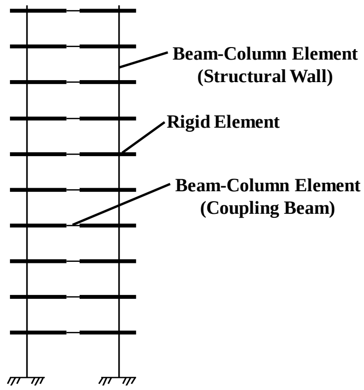
4. Finite element modeling

The behavior of the example coupled wall systems is computationally simulated using OpenSees (2013). Due to the symmetric nature of the system, the numerical analysis is simplified by modeling only half of the structure (Fig. 6(a)). The concrete structural walls and steel coupling beams are represented using nonlinear beam-column elements. The nonlinear beam-column element in OpenSees is capable of analyzing general structural elements subjected to combined forces involving with axial force, shear force, and moment. It also considers spread of plasticity along the element. The behavior of the element section is modeled using fiber sections. In a structural element modeled with fiber sections, the cross section is meshed with sufficient fibers, with each containing an area and a location. Uniaxial material properties are defined numerically and assigned to the fibers. The cross sectional properties including the moment-curvature and the axial force-deformation characteristics as well as their interaction are calculated accordingly by the numerical integration of the stress-strain relationships of fibers. The wall elements are located at the gross section centroid of each structural wall. The modeling of the steel coupling beams accounts for inelastic shear and flexural behavior. The moment of inertia of the full cross-section of the coupling beam is used for bending whereas the full web area is used for shear. Rigid elements, representing the physical size of the wall, are used to connect the coupling beam elements to the structural wall elements, as shown in Fig. 6.

The nonlinear behavior of the concrete material is simulated using the Concrete01 material model, which was developed based on the constitutive law proposed in (Kent and Park 1988). The compressive strength of concrete is 40 MPa. The confinement effect on the concrete strength and ductility is assumed to follow the model proposed by Mander *et al*. (1988) and is accounted for in the analysis by adjusting the material parameters in the unconfined model. The nonlinear cyclic behavior of the steel material is simulated using the Steel01 material model, which employs a bilinear relationship with kinematic plasticity. A615 Grade 60 is used for the steel rebar. The coupling beams are assumed to be made of steel having a material yield strength of 345 MPa. The Young’s modulus and the hardening ratio for the steel material are 200 GPa and 1%, respectively. In addition, a 5% Ralyiegh damping ratio is introduced in the analysis. Gravity loads are applied to the coupled wall models prior to the seismic analysis. The vibration periods for the first three



(a) Plane view of the simplified symmetrical system



(b) Coupled wall model in OpenSees

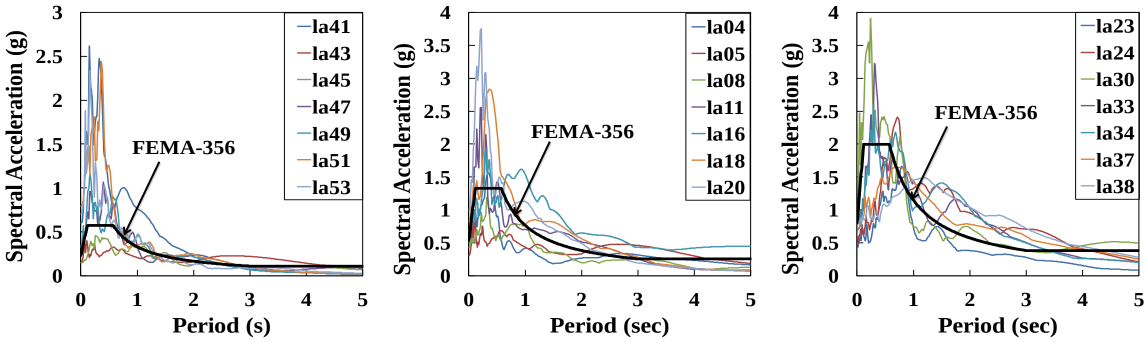
Fig. 6 Numerical model for the coupled wall system

Table 3 Vibration periods of the example coupled wall systems

	Mode 1 (s)	Mode 2 (s)	Mode 3 (s)
S-10-20	0.64	0.11	0.05
S-10-40	0.62	0.12	0.04
S-10-60	0.62	0.12	0.04
S-30-20	2.28	0.50	0.20
S-30-40	2.25	0.51	0.20
S-30-60	2.25	0.52	0.20

Table 4 Ground motion records

50/50		10/50		2/50	
Earthquake	PGA (cm/sec^2)	Earthquake	PGA (cm/sec^2)	Earthquake	PGA (cm/sec^2)
LA41	578.34	LA04	478.65	LA23	409.95
LA43	140.67	LA05	295.69	LA24	463.76
LA45	141.49	LA08	417.49	LA30	972.58
LA47	331.22	LA11	652.49	LA33	767.26
LA49	312.41	LA16	568.58	LA34	667.59
LA51	765.65	LA18	801.44	LA37	697.84
LA53	680.01	LA20	967.61	LA38	761.31



(a) 50/50 (b) 10/50 (c) 2/50

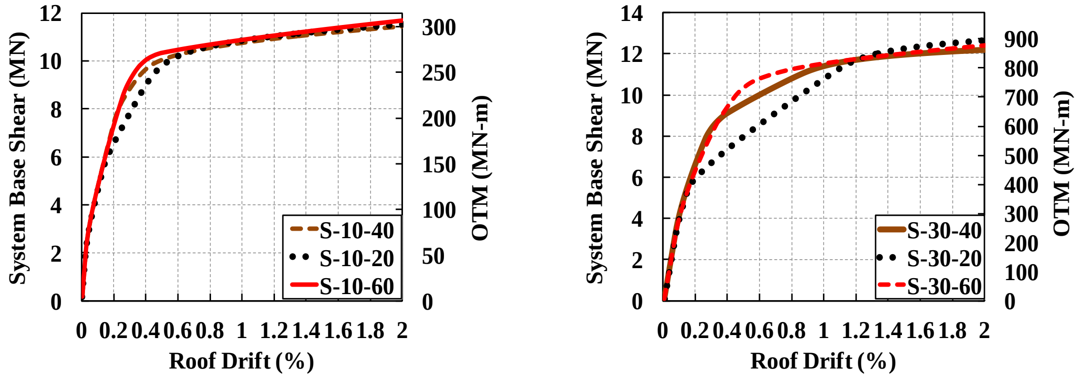
Fig. 7 Elastic acceleration response spectra of the 21 ground motion records

modes of the example coupled wall systems are summarized in Table 3. It is interesting to note that the variations in the CR design values have an insignificant influence on the vibration period of the system. The results imply that the vibration periods are governed by the wall designs, which are designed to be identical for the systems having the same height but different CRs in order to obtain a clear conclusion of this study.

Although the model described above is able to account for the general nonlinear behavior of coupled wall systems including material nonlinearities and P-Delta effects, it does have a number of limitations. For example, the model cannot account for concrete splitting, rebar slip and buckling, or the effects of low-cycle fatigue fractures on the bar response. Nevertheless, as long as these limitations are kept in mind, the developed model can still yield valuable insight into the structural response of a coupled wall system under earthquakes, especially at the system level, which is the focus of the study.

5. Evaluation procedure

The behavior of the coupled wall systems is studied using both nonlinear pushover analysis and nonlinear dynamic analysis. For the nonlinear dynamic analysis, three suites of time history ground motion records from the SAC (Structural Engineers Association of California, Applied Technology Council, and California University for Research in Earthquake Engineering) steel



(a) 10-story systems (b) 30-story systems

Fig. 8 Pushover behavior

project are used. The three suites, which represent three main seismic hazard levels, namely, 50%, 10%, and 2% probabilities of exceedance in 50 years (hereafter referred to as the 50/50, 10/50, and 2/50 events, respectively), are adopted to evaluate different performance levels of the designed coupled wall systems including immediate occupancy (IO), life safety (LS), and collapse prevention (CP). Each suite contains seven ground motion records. The peak ground accelerations (PGA) of the ground motion records are summarized in Table 4. The 5% damped response spectra of the ground motions are plotted in Fig. 7. Several response parameters of the systems are evaluated to verify the adequacy of the design method. The average of the maximum responses under the seven ground motions is employed as the representative value for a particular hazard level (FEMA-356 2000).

6. Results of nonlinear static analyses

Figs. 8(a) and 8(b) show the relationships between the base shear and roof drift for the 10-story and 30-story systems, respectively. The nearly identical initial and residual responses of the coupled wall systems with varying CRs implies that the behavior of coupled wall systems under these two response stages is majorly governed by the wall designs, and the variations in the CR design values have an insignificant influence. The influence of a larger CR is found to increase the yield base shear and the yield displacement of the system. In other words, increasing the CR helps sustain the elastic behavior of the system at a larger system response. The results also indicate that the variations in the CR have a greater influence on the pushover curve for the tall system than the short system, signifying that too short a system will not greatly benefit from coupling.

As can be seen in Fig. 8, the yielding mechanism shown by the systems with 20% coupling leads to two obvious yield points in the pushover curve. Via examining the simulation output, it is suggested that the first reduction in the lateral stiffness of the system is due to the development of the coupling beam plastic mechanism whereas the second reduction is due to the formation of wall plastic hinges. On the other hand, there is only one prominent yield point in the pushover curves of the systems with 60% coupling, which is caused by the nearly simultaneous yielding of the coupling beams and structural walls.

7. Results of nonlinear time history analyses

In this section, the adequacy of the designs of the various systems is justified by comparing the seismic responses of the designed coupled wall systems with the acceptance limits stipulated in current design provisions and guidelines. Then, the seismic yielding mechanisms of the systems are evaluated.

7.1 Story drift, coupling beam rotation, and wall rotation

Fig. 9 shows the story drift demands of the various systems under different seismic hazards. The story drift demands at the LS and CP performance levels are 1.5% and 2.5%, respectively, which are considered to be acceptable by ASCE 7-10 (2010).

The coupling beam rotation demands for the example systems are presented in Fig. 10. The demands at different performance levels satisfy the acceptance criteria specified in FEMA-356 (2000) with the exception of the case of S-30-20 at the CP performance level, which is slightly beyond the specified acceptable value of 0.14 rad.

Fig. 11 shows the wall rotation demands for the example coupled walls. In comparison with the permitted wall plastic hinge rotations for the IO, LS, and CP performance levels in FEMA-356 (2000), all the systems meet the criteria.

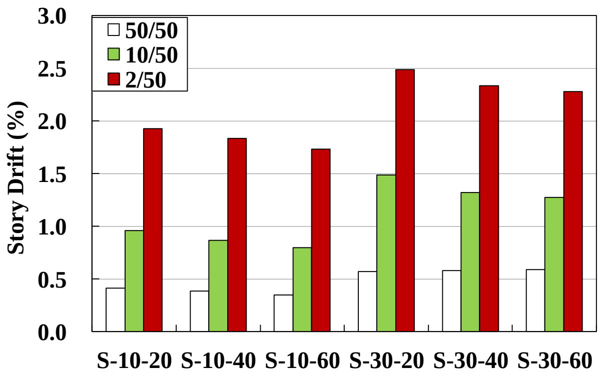


Fig. 9 Story drift demands

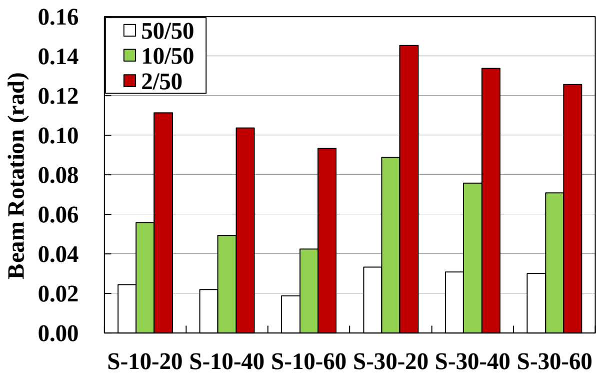


Fig. 10 Coupling beam rotation demands

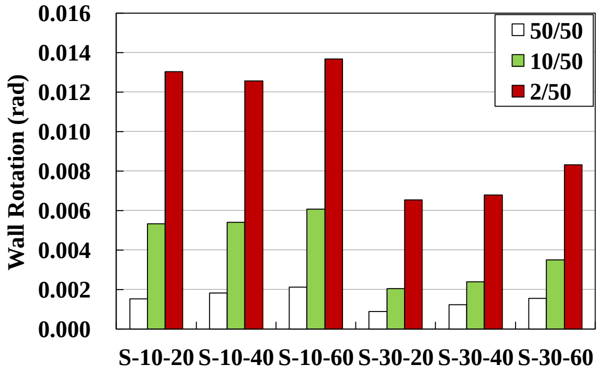


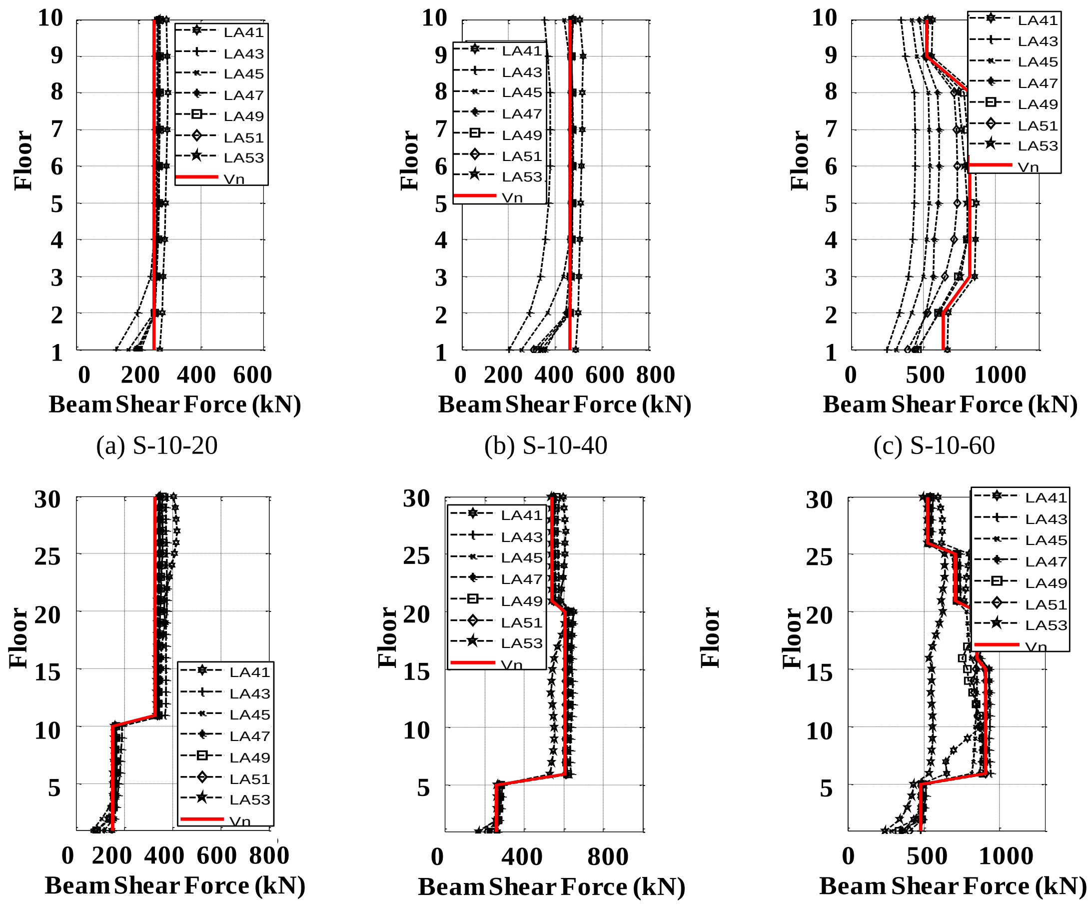
Fig.11 Wall rotation demands

The adequacy of the system designs is verified through the seismic responses of the various systems that satisfy the relevant design provisions. In addition, it is also justified by the fact that the observed effects of CRs on the system response agree with the reported trends in literature (El-Tawil *et al*. 2010); namely, a larger CR leads to a smaller story drift and beam rotation demands and causes a larger wall rotation demand.

7.2 Seismic yielding mechanisms

Figs. 12 and 13 show the nominal shear capacities of the coupling beams along with the maximum shear forces in the coupling beams caused by the 50/50 and 10/50 earthquakes, respectively. It can be seen in Fig. 12 that the shear capacities are essentially reached in the coupling beams of the 20%-systems under the 50/50 event. The results show that although the systems are designed for the 10/50 events, many of coupling beams yield under 50/50, especially for those in the systems with lower coupling. It can be partially attributed to the fact that the walls have a substantially larger stiffness and strength than coupling beams. In addition, the current design method does not consider the effect of shear magnification caused by the dynamic effect (Paulay and Priestley 1992). When the seismic hazard level is increased to 10/50, the analysis results in Fig. 13 indicate that the majority of the coupling beams in the example coupled wall systems have fully exploited their shear capacities.

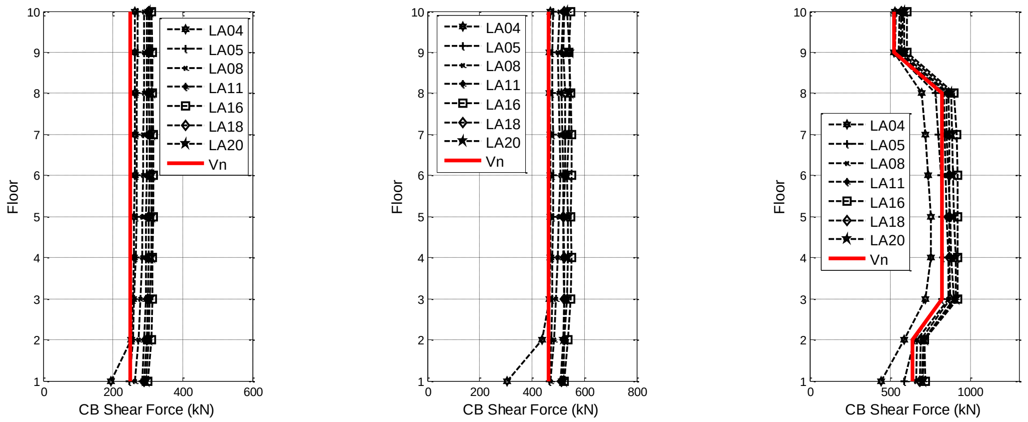
In order to facilitate the utilization of the energy dissipation capacity of a coupled wall system under seismic action, it is desirable that all coupling beams have yielded in shear before plastic hinges occur in structural walls. Figs. 14 and 15 show the coupling beam yielding status at the point when the wall plastic hinge occurs under representative cases; the black solid circles in the coupling beams denote that the beams have yielded in shear. It can be seen that while nearly all the coupling beams in the 20%- and 40%-systems have sufficiently exploited their energy dissipation capacities, many coupling beams in the 60% systems are still in the elastic stage when the plastic hinge forms at the base of the wall. In particular, the locations of the coupling beams that remain elastic are generally those designed to have the largest nominal shear capacity in the system. The results imply that even though the state-of-the-art coupled wall design guidelines account for the wall overstrength, the coupling beam shear redistribution, and the shear demand gradient of coupling beams along the building height, they might still fail to generate a coupled wall structure that can sufficiently exploit the energy dissipation capacity of the coupling beams prior to the development of plastic hinges in structural walls.



(a) S-10-20 (b) S-10-40 (c) S-10-60

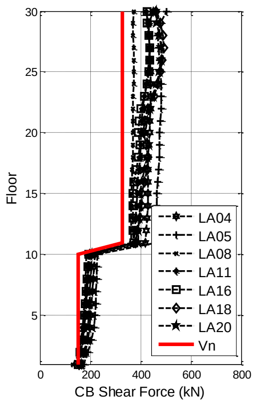
(d) S-30-20 (e) S-30-40 (f) S-30-60

Fig. 12 Maximum coupling beam shear forces under 50/50 events

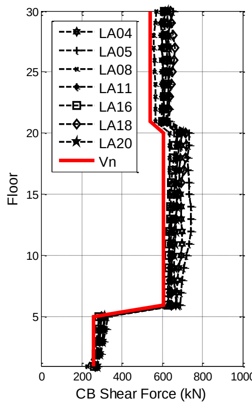


(a) S-10-20 (b) S-10-40 (c) S-10-60

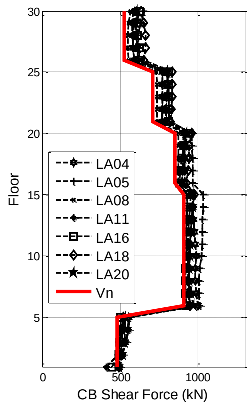
Fig. 13 Maximum coupling beam shear forces under 10/50 events



(d) S-30-20

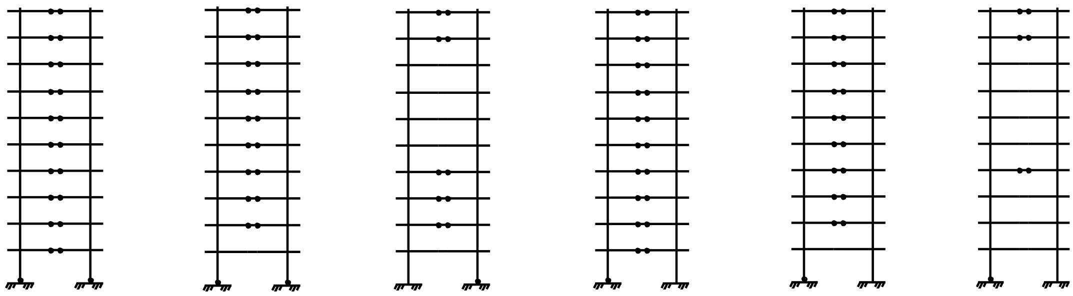


(e) S-30-40



(f) S-30-60

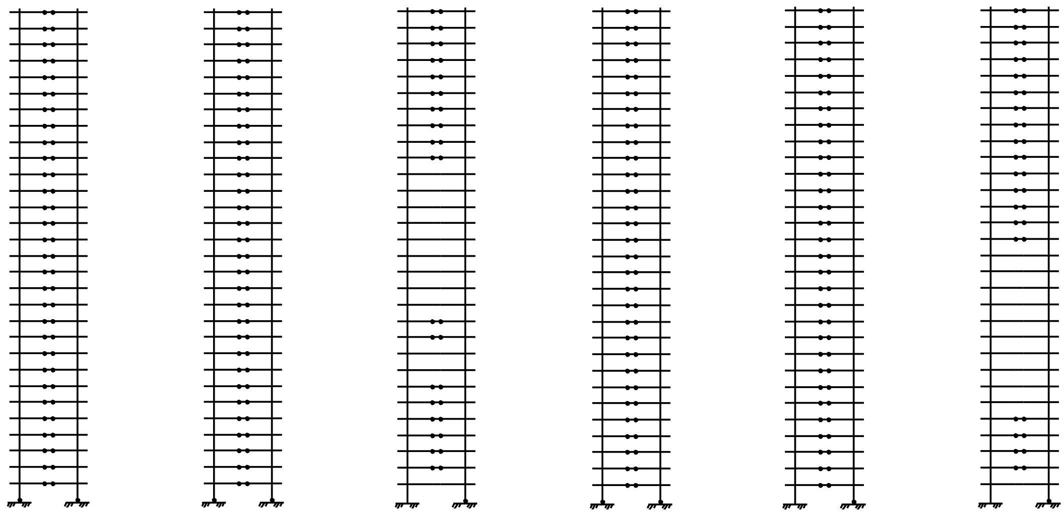
Fig. 13 Continued



S-10-20 S-10-40 S-10-60 S-10-20 S-10-40 S-10-60

(a) 10/50 (LA11) (b) 2/50 (LA34)

Fig. 14 Coupling beam yielding status of the 10-story systems



S-30-20 S-30-40 S-30-60 S-30-20 S-30-40 S-30-60

(a) 10/50(LA04) (b) 2/50 (LA30)

Fig. 15 Coupling beam yielding status of the 30-story systems

The effect of the varying CR design values on the yielding mechanism is quantified using the coupling beam yielding ratio (CBYR) and summarized in Table 5. The CBYR is defined as the number of the yielded coupling beams to the total number of the coupling beams at the point when the wall plastic hinge occurs. It can be seen in Table 5 that the CBYRs for a certain coupled wall system under the 10/50 and 2/50 events are approximately the same. For the 20%-systems, the average CBYRs are 100%, i.e., that all the coupling beams have yielded in shear before the wall plastic hinge occurs, exhibiting the preferred yielding mechanism. When the CR design value is increased to 40%, although the average CBYRs decrease for both the 10-story and 30-story systems, they are still maintained at a high level of 90%. However, for the systems with 60% coupling, their average CBYRs are less than 60%. In particular, the average CBYR for the S-10-60 is as low as 15%. Again, the results indicate that a coupled wall system that is designed in accordance with the state-of-the-art design guidelines might not exhibit the preferred yielding mechanism under earthquake forces. Furthermore, the results reveal that the CR design value is an important factor in influencing the seismic yielding mechanism of coupled wall systems.

Table 5 also provides information regarding the yielding status of structural walls under multiple hazard levels. The data show that the 10/50 events cause the wall plastic hinge to occur in most of the 10-story systems (those cases with reported CBYRs in Table 5). On the other hand, in many cases under the 10/50 events, the structural walls in the 30-story system (those cases denoted by *) remain essentially elastic. In the 2/50 earthquakes, the wall plastic hinges occur in all the systems.

Table 5 Coupling beam yielding ratios

Hazard Level	**Ground Motion**	**S-10-20**	**S-10-40**	**S-10-60**	**S-30-20**	**S-30-40**	**S-30-60**
2/50	LA23	100%	90%	20%	100.00%	100.00%	90.00%
	LA24	100%	90%	0%	100.00%	100.00%	96.67%
	LA30	100%	90%	50%	100.00%	100.00%	63.33%
	LA33	100%	90%	10%	100.00%	100.00%	53.33%
	LA34	100%	90%	30%	100.00%	100.00%	76.67%
	LA37	100%	90%	0%	100.00%	90.00%	16.67%
	LA38	100%	90%	0%	100.00%	90.00%	26.67%
Average under 2/50		**100.00%**	**90.00%**	**15.71%**	**100.00%**	**97.14%**	**60.48%**
10/50	LA04	*	*	*	100.00%	100.00%	60.00%
	LA05	*	90%	20%	100.00%	100.00%	96.67%
	LA08	100%	90%	0%	*	*	*
	LA11	100%	90%	50%	*	*	*
	LA16	100%	90%	0%	*	*	26.67%
	LA18	100%	90%	0%	*	53.33%	13.33%
	LA20	100%	90%	20%	100.00%	66.67%	40.00%
Average under 10/50		**100.00%**	**90.00%**	**15.00%**	**100.00%**	**80.00%**	**47.33%**
Average overall		**100.00%**	**90.00%**	**15.38%**	**100.00%**	**90.90%**	**55.00%**

Note: “*” denotes the case when the wall plastic hinge has not occurred

8. Implication of CR design values for system yielding mechanisms

When a coupled wall system is subjected to an earthquake, the proportion of the resistance provided by the coupling action to the overturning moment (i.e., the CR) is not constant during the earthquake. Rather, it varies with the instantaneous system response. For a coupled wall system having the desired system plastic mechanism, it is found that the relationship between the roof drift response and the resulting CR, obtained using nonlinear pushover analysis, can be adequately expressed as in Fig. 16. The CR curve in Fig. 16 can be divided into three different stages, i.e., the ascending portion, the descending portion, and the plateau. When the system starts to deform, the coupling beam shear force increases rapidly, leading to the ascending CR value. After most coupling beams yield in shear, the CR exhibited by the system reaches the maximum value, CR_{MAX}. As the system response continues to increase, the wall base moment magnifies more rapidly than the moment resulting from the coupling action, leading to the degradation of CR. With the initiation of the plastic hinge in the structural wall, the contribution of the coupling action to the resistance of the overturning moment gradually becomes constant. As the system exhibits the full plastic mechanism, the CR curve becomes flat, and a local minimum CR, CR_{FPM}, is reached, where the subscript FPM is the abbreviation of full plastic mechanism. Then, the CR slightly rises with the increasing system response due to the overall hardening effect of the system.

Fig. 17 shows the CR curves for the example systems obtained using nonlinear pushover analysis. It can be seen that as the CR design value becomes larger, the difference between the values of CR_{MAX} and CR_{FPM} becomes less, suggesting that the coupling beams and the structural walls yield at closer roof drift responses. In particular, it can be seen in Fig. 17(a) that as soon as the CR curve of the S-10-60 arrives at CR_{MAX}, it enters the plateau, a CR curve substantially deviating from the ideal one described in Fig. 17. Thus, when a system with an excessively large CR design value is subjected to earthquakes, wall plastic hinges might have occurred before most coupling beams yield due to the dynamic effects, as also evidenced by the small CBYRs of the 60%-systems in Table 6. It is worth noting that the CBYR of the S-10-60 is as small as 15%. The results presented in Fig. 17 and Table 6 suggest that low-story coupled walls with a large CR design value have poor seismic performance in terms of the system plastic mechanism.

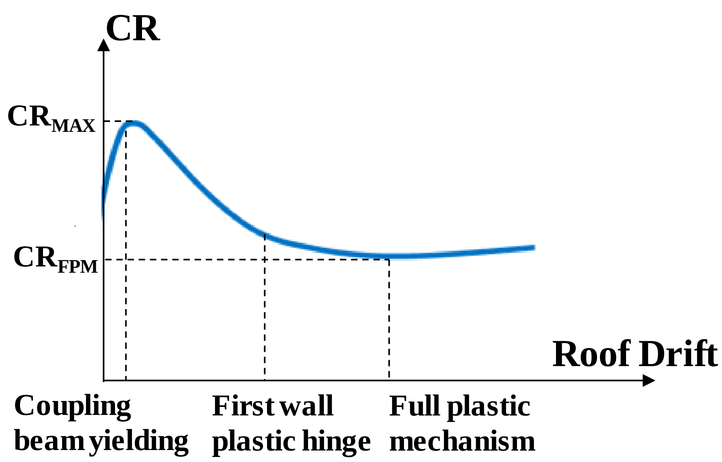
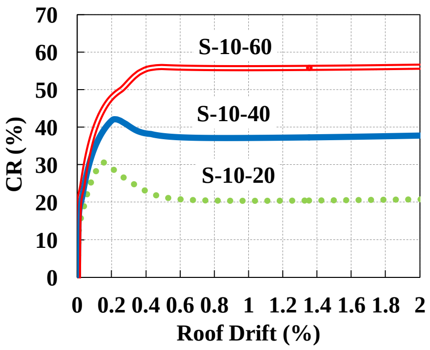
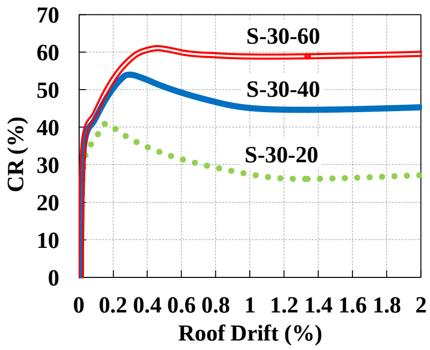


Fig. 16 The relationship between the CR and the roof drift for a coupled wall system showing the ideal plastic mechanism



(a) 10-story system



(b) 30-story system

Fig. 17 Relationship between CR and roof drift

Table 6 CR_{MAX} and CR_{FPM} values

Systems	CR Design Value (%)	CR_{MAX} - CR_{FPM} (%)	Dynamic CBYR (%)
S-10-20	20	10.2	100
S-10-40	40	5.1	90
S-10-60	60	0.3	15
S-30-20	20	14.8	100
S-30-40	40	9.4	91
S-30-60	60	2.2	55

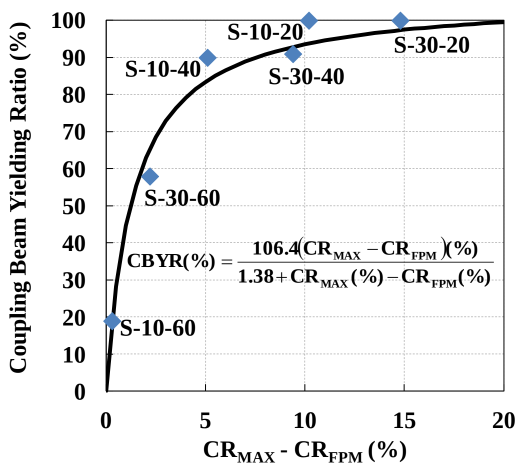


Fig. 18 The influence of the value of (CR_{MAX} - CR_{FPM}) on the CBYR

Although Table 6 shows that the CBYR generally decreases as the CR design value increases, only the CR design value is an insufficient indication to accurately predict the value of the CBYR of the system. It is found in the study that the exhibited CBYR of a coupled wall system under earthquakes is closely related to the value of (CR_{MAX} - CR_{FPM}) obtained using nonlinear static analysis, as shown in Fig. 18. An adequate correlation between the values of (CR_{MAX} - CR_{FPM}) and the CBYRs can be established using nonlinear regression analysis as

$$\mathrm{CBYR}(\%) = \frac{106.4\left(\mathrm{CR}_{\mathrm{MAX}} - \mathrm{CR}_{\mathrm{FPM}}\right)(\%)}{1.38 + \mathrm{CR}_{\mathrm{MAX}}(\%) - \mathrm{CR}_{\mathrm{FPM}}(\%)} \tag{4}$$

Based on the analysis results of 126 scenarios considered in this study, it is suggested that the value of (CR_{MAX} - CR_{FPM}) be larger than 5% in order for a coupled wall structure to exhibit the preferred yielding mechanism under earthquake loading.

9. Conclusions

An innovative design methodology capable of facilitating the preferred yielding mechanism in hybrid coupled walls under earthquake loading was proposed. The method was suggested in this study to resolve the adverse effect associated with the wall overstrength factor that was greatly relied on by the current strength-based design approach to achieve the preferred seismic yielding mechanism. The success of the method relied on the selection of an appropriate CR design value as well as the enforcement of an upper limit on the wall overstrength factor. The design method allowed the designer to have effective control over the CR without introducing additional design parameters, making it attractive from the design point of view. In addition, the adverse effect of the wall overstrength factor in the current strength-based design approach was greatly reduced. The effects of CR design values on the seismic yielding mechanism of coupled walls were investigated using nonlinear pushover analyses and nonlinear time history analyses on six prototype hybrid coupled wall structures with varying CR design values and structural heights that were able to present the seismic behavior of general coupled walls. The performance of the systems under 50/50, 10/50, and 2/50 seismic events was considered.

The adequacy of the proposed design methodology is justified by the acceptable seismic responses of the designed prototype systems that satisfied the response criteria stipulated in the current design provisions and suggestions. Quantifying effects of CR design values and structural heights on the seismic yielding mechanism of hybrid coupled walls under different seismic hazard levels were provided. It was found that even though the state-of-the-art coupled wall design guidelines accounted for the wall overstrength, the coupling beam shear redistribution, and the shear demand gradient of coupling beams along the building height, they could generate a coupled wall structure failing to adequately exploit the energy dissipation capacity of beams prior to the development of wall plastic hinges. In order to achieve the preferred seismic yielding mechanism, the CR design value had to be chosen with caution. A nonlinear regression model was established to correlate the value of (CR_{MAX} - CR_{FPM}) and the coupling beam yielding ratio. In order to facilitate the preferred seismic yielding mechanism, it was suggested that the design value of (CR_{MAX} - CR_{FPM}) should be larger than 5%. Moreover, while preventing early damage to structures in earthquakes, a CR design value of 40% was also generally applicable for coupled walls to achieve the desired yielding mechanism and the optimal structural efficiency. In particular, a CR ranging between 30% and 40% was suitable for short systems, and a range between 40% and 50% was appropriate for tall ones.

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