The Study of Reinforced Concrete Coupled Walls with the Simulation Approach

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Abstract

The reinforced concrete coupled wall system consists of wall piers and couplings that is one of efficient lateral resistance system during earthquake events. Although many studies have investigated the individual component of the coupled wall (i.e., structural walls and coupling beams) in the past several decades, the test studies are still limited due to the specimen size, and the cost. However, the simulation approach is an alternative method to conduct the investigation of reinforced concrete coupled walls. The previous studies with the modeling method mainly addressed on responses of coupled walls (e.g., drift, rotation and etc.) and rarely focused on the damage progression of the structure. Since the degree of coupling is a significant design parameter of a coupled wall in practice, the study designs one reinforced concrete coupled core wall with three degrees of coupling, including 40%, 50%, and 60%. The coupled wall system consists of two C-Shaped wall piers and coupling beams. The structure is considered as office buildings with 16-story in Los Angeles, CA. The seismic behavior of coupled walls was conducted in the nonlinear static analysis based on the simulation tool of OpenSEES (Open System for Earthquake Engineering Simulation). The simulation results are able to provide enough information to evaluate the damage progression of reinforced concrete coupled walls. On the other hand, the degree of coupling significantly affects the behavior of the coupled wall that includes the response, yielding mechanism, and the damage progression. The coupled wall with a low degree of coupling can show the advantage of the coupled wall compared to the wall with a high degree of coupling.

Keywords: Coupled wall, Degree of coupling, Damage progression, Reinforced concrete. C-Shaped wall

1. Introduction

The reinforced coupled wall system is one of the efficient lateral resistance systems for earthquakes. A coupled wall system consists of two or more wall piers connected by links, or coupling beams (Fig. 1). The moment resistance of a coupled wall is a combination of the flexure resistance of wall piers and the moment couple generated by the coupling beams. To achieve optimal performance, the coupling beams have to be sufficiently stronger and stiffer than wall piers, and also yield prior to wall piers to develop a ductile manner with a characteristic of significantly absorbing energy [1].

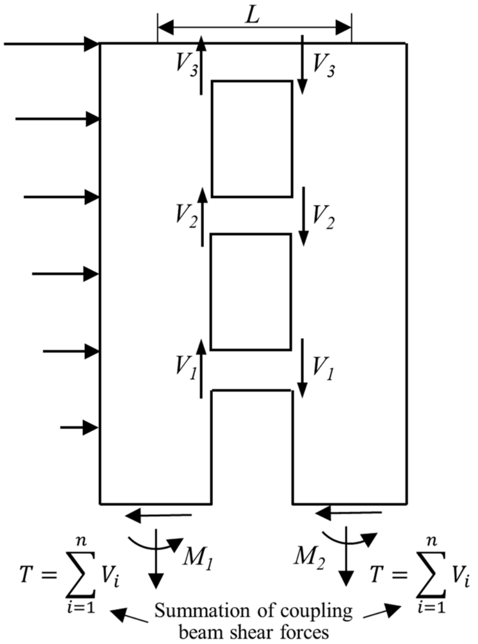


Fig. 1 – Coupled wall system behavior

The degree of coupling (DOC) is often discussed the measurement of the coupled wall defined as the ratio of the total overturning moment resisted by the coupling action to the total structural overturning moment [2]:

$$DOC = \frac{TL}{\Sigma M_w + TL} = \frac{TL}{OTM} \quad (1)$$

Where T is the axial load which results from the accumulative shear in the beams, L is the lever arm between the centroids of wall piers (see Fig. 1), M_w is the overturning moment in individual wall piers, and OTM is the global system overturning moment.

The studies of coupled walls [2-7] indicated that the DOC values significantly affected the behavior of the coupled wall system. The coupled wall with the higher DOC (i.e., 50%) caused the flexural compression failure at wall piers. In contrast, the wall with the lower DOC (i.e., 10%) led to the failure of coupling beams. The study[2] recommended maximum DOC values of 50% and 55% for conventionally reinforced and diagonally reinforced coupling beams, respectively. The degree of coupling of the coupled wall should be less than 70% because of the inefficient and impractical reasons [8].

Performance-based design (PBD) [8-10] popularly is used for coupled wall design in recently. Since the estimation of the damage is related to evaluate the seismic performance and repair cost in PBD, the accurate damage estimation is significantly important for PBD. For estimation of damage in structures, the experimental test data is directly able to provide the information to estimate the damage for the structures. Unfortunately, since the limited test data of coupled walls do not provide a sufficient breadth of information, it is difficult to understand the damage progressions of coupled walls.

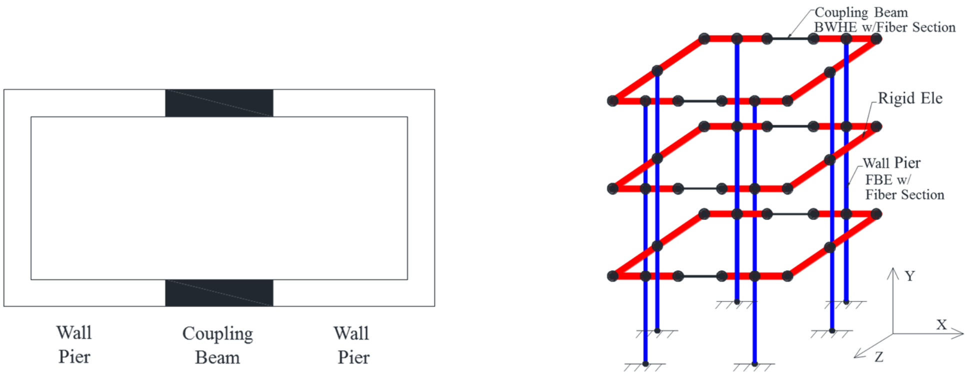
Due to the limited number of coupled wall tests, the numerical simulation is another alternative method to study coupled walls. Simulation studies have demonstrated that the coupled walls with PBD can improve the response of coupled walls [9-11]. Nevertheless, the simulation studies of coupled walls largely focus on global responses. Studies of damage progressions in coupled walls using numerical solutions have received limited attention. Therefore, this study focuses on estimating the damage progressions of coupled walls.

2. Simulation model

The frame model [7, 9, 10, 12], the multi-springs elements [13], and the continuum finite element method [5, 6, 14] are mainly simulation approaches of the coupled walls. To consider the lower computational demands, and the various complex configurations of coupled walls, this study uses the frame model to simulate the behavior of coupled walls.

2.1 Coupled wall model

A coupled core wall consists of two C-shaped wall piers and coupling beams (see Fig. 2a). The three-dimensional frame model of the coupled wall uses the beam-column elements to represent the behavior of wall piers and coupling beams (see Fig. 2b). The beam-column elements are placed at the centroid of the wall pier geometry and rigid elements model the physical dimension of wall piers and connect with coupling beams. The behavior of the C-Shaped wall piers is simulated by the wide-column model [15]. The behavior of coupling beams is modeled as the finite length hinge zone distributed plasticity beam-column model with fiber sections [16] since the model is the ability to capture the local response of the beam. The rigid elements are used to represent the physical dimension of the wall section and to connect walls to the coupling beam elements. The boundary condition of wall piers is fixed.

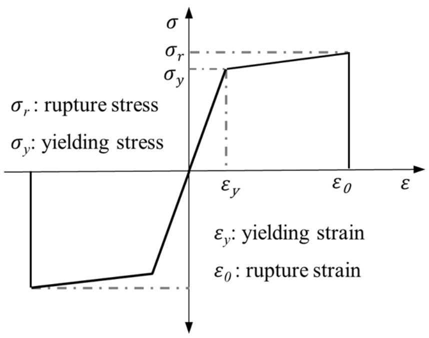


(a) Coupled core wall (b) 3D frame model

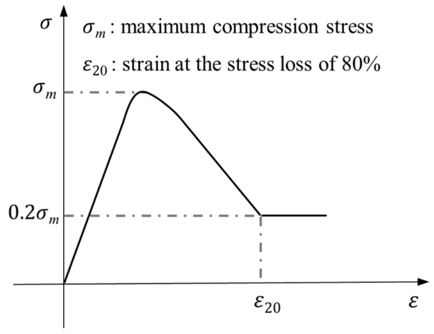
Fig. 2 – 3D Frame Model

The nonlinear analysis is created using the open-source program OpenSEES [17]. The wall pier applies the “ForceBeamColumn” elements (FBE) and the coupling beam is the “BeamWithHinge” element in OpenSEES. The material models of concert and steel fibers are “Concrete02” and “Steel02”, respectively. The five intergradation points is applied in FBE. The material regularization and parameters are applied in the material models [18, 19] to prevent a loss of objective prediction because of the strain-softening behavior under high gravity loads [20].

Fig. 3 shows the damage progression of the coupled wall, including the tension yielding (ε_y), cover spalling (ε = 0.003 of concrete), concrete crushing (ε_{20}), bar buckling and bar rupture (ε_0) for wall piers and coupling beams. Each damage state is based on the relationship between stress and strain at the critical position of the coupled wall.



(a) Reinforced damage



(b) Concrete damage

Fig. 3 – Definition of damage progression

2.3 Validation of simulation models

This section presents the validation of the simulation model to ensure a reasonable prediction. Since the complexity of coupled walls and the limited test data of nonplanar coupled walls, the test specimens of the individual component of wall piers and coupling beams instead of the coupled wall.

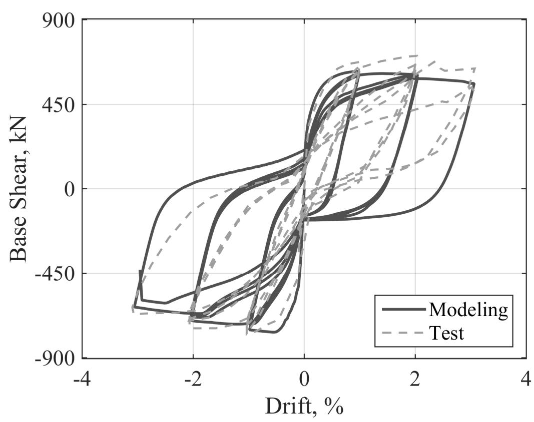
The test data of the structural wall selected T-shaped and C-shaped wall specimens [21, 22] (see Table 1). The ratio of the wall depth to the specimen height is around 3.0 which is a slender wall and the axial ratio is from 5% to 10%. The loading protocol used the cyclic loadings in the coupling direction.

Table 1 – Structural wall specimens for validation

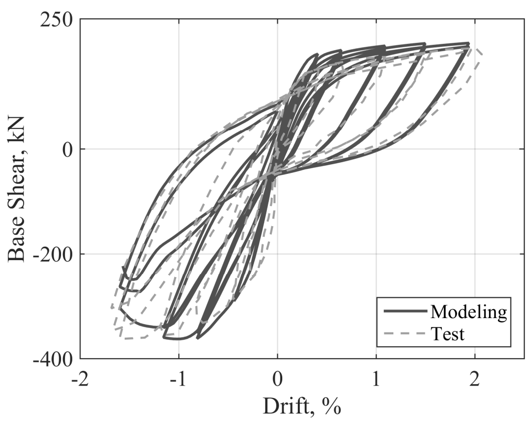
Specimen	Geometry	H/l_w	Strength Ratio Simulation/Test	Drift Ratio Simulation/Test	Failure Mode Test	Failure Mode Simulation
TW2	T-shaped	3.00	1.02	0.95	CB	CB
U2_X	C-shaped	2.93	0.99	0.95	CB	CB

H- Height of specimen, l_w- width of specimen; CB- Crushing and Buckling

Fig. 4 and Table 1 show the simulation results of drift and base strength for TW2 and U2_X. The simulation strength, drift and failure mode obtain good fitness with the test result that indicates the WCM model of the nonplanar is able to predict the reasonable prediction.



(a)U2_X



(b) TW2

Fig. 4 – Validation results of coupled wall specimens

Since the practical design of beam length-to-depth for coupling beams, the test data of coupling beams selected the diagonally reinforced coupling beams with the aspect ratio of greater than 2.0. The selected specimens [23, 24] were shown in Table 2 and the test used the cyclic loading protocol.

Table 2 – Coupling beam specimens for validation

Specimen	l_n/h_b	Reinforcement	Strength Ratio Simulation/Test	Drift Ratio Simulation/Test
DCB1	2.57	Diagonal	1.03	0.97
CB33F	3.33	Diagonal	1.04	1.06

l_n- beam length, h_b- beam height

The prediction of a coupling beam used the BeamWithHinge element of OpenSEES to simulate the nonlinear behavior. Fig 5 and Table 2 show a prediction with reasonable performance in strength and ultimate drift capacity.

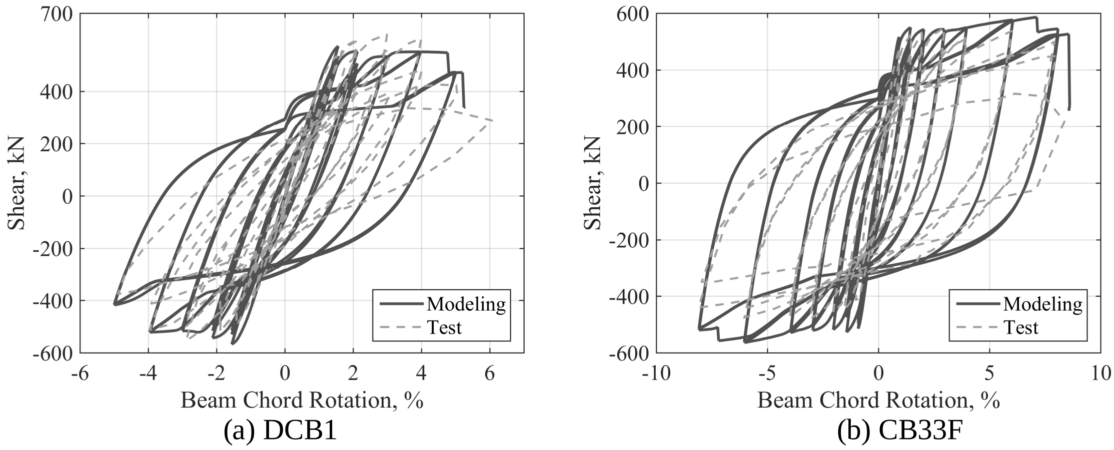


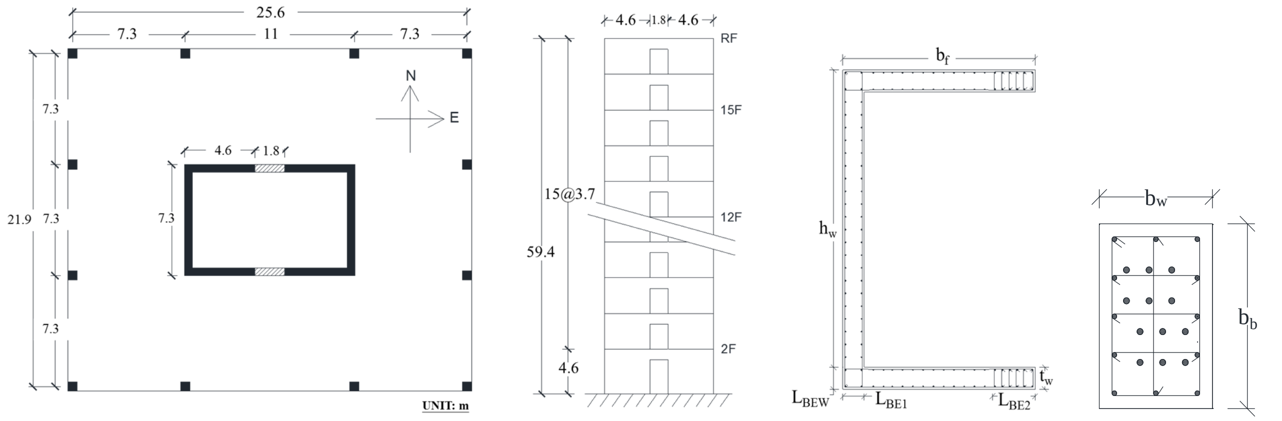
Fig. 5 –Validation results of coupling beam specimens

The section validates the modeling performance of structural wall and coupling beam specimens. The prediction is reasonable compared to the test data. Therefore, the 3D frame model is used to simulate the nonlinear behavior of the coupled wall.

3. Coupled wall design

The coupled wall system is mostly used for median-to-high buildings in practice [25] and the degree of coupling is significantly important for the behavior of the coupled wall. The coupled wall was designed as a 16-story coupled core wall system building with variable degrees of coupling. Considering the recommended DOC of 55% for a RC coupled wall [2], the study designed the coupled wall with three DOC values of 40%, 50%, and 60%, respectively. The methodology of PBD was used to conduct the design of walls [26]. The details of coupled wall design followed with the previous studies [8, 10, 27, 28].

The coupled wall system is considered as an office building with 16-story where is located in Los Angeles, CA. The first story height is 4.6 m and the typical height of other story is 3.65 m, and the overall height is 59.4 m. The dimension of the structure is 25.6x21.2 m. The coupled core wall consists of two C-Shaped reinforced concrete wall piers and two diagonally reinforced concrete coupling beams (see Fig. 6). A coupled core wall system is located in the center of the building. The study is assumed that the coupled core wall system resists 100% of lateral forces in the coupling direction.



(a) Layout plan of the building (b) Elevation view (c) Wall pier (d) Coupling beam

Fig. 6 – Layout of the coupled core wall

The design of coupled core walls includes three cases of CCW40, CCW50, and CCW60 with DOC of 40%, 50%, and 60%, respectively. The design details of each coupled core wall were shown in Table 3.

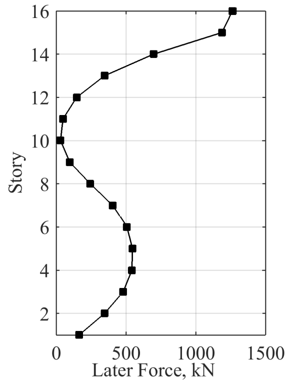
Table 3 – Reinforcement details of coupled wall

	Wall Pier												Coupling Beam						
ID	Story	Dimension			F_{BL}		F_W	F_{BR}		W_B		W_W	Story	Dimension				D	S
		b_f m	h_w m	t_w mm	L_{BE1} mm	L-R	L-R	L_{BE2} mm	L-R	L_{BE} mm	L-R	L-R		L_n m	b_b mm	h_b mm	L-R	α °	L-R
CCW40	**13-16**	4.6	7.3	381	381	6D19	30D13	381	8D25	381	4D19	52D13	**16**	1.8	381	610	6D16	11.7	4D13
	9-12	4.6	7.3	381	508	6D19	30D13	508	8D25	381	4D19	52D13	**7-15**	1.8	381	610	6D19	11.7	4D13
	5-8	4.6	7.3	381	635	6D25	28D13	635	10D25	381	4D25	52D13	**4-6**	1.8	381	610	6D16	11.7	4D13
	1-4	4.6	7.3	381	762	15D29	24D13	762	17D25	381	8D29	52D13	**1-3**	1.8	381	610	4D13	11.7	4D10
CCW50	**13-16**	4.6	7.3	381	381	6D13	30D13	381	6D25	381	4D13	52D13	**14-16**	1.8	381	610	6D19	11.7	4D13
	9-12	4.6	7.3	381	381	6D13	30D13	381	6D25	381	4D13	52D13	**6-13**	1.8	381	610	6D22	11.7	4D16
	5-8	4.6	7.3	381	508	6D19	28D13	508	8D25	381	4D19	52D13	**4-5**	1.8	381	610	6D19	11.7	4D13
	1-4	4.6	7.3	381	635	15D22	22D16	635	14D25	381	8D22	52D13	**1-3**	1.8	381	610	6D13	11.7	4D10
CCW60	**13-16**	4.6	7.3	381	381	4D13	30D13	381	6D25	381	4D13	52D13	**1, 16**	1.8	381	610	6D16	11.7	4D13
	9-12	4.6	7.3	381	381	4D13	30D13	381	6D25	381	4D13	52D13	**12-15**	1.8	381	610	6D22	11.7	4D13
	5-8	4.6	7.3	381	381	6D16	30D13	381	6D25	381	6D16	52D13	**5-11**	1.8	381	610	6D25	11.7	4D13
	1-4	4.6	7.3	381	508	12D19	24D16	508	10D25	381	8D19	42D16	**2-3**	1.8	381	610	6D22	11.7	4D13

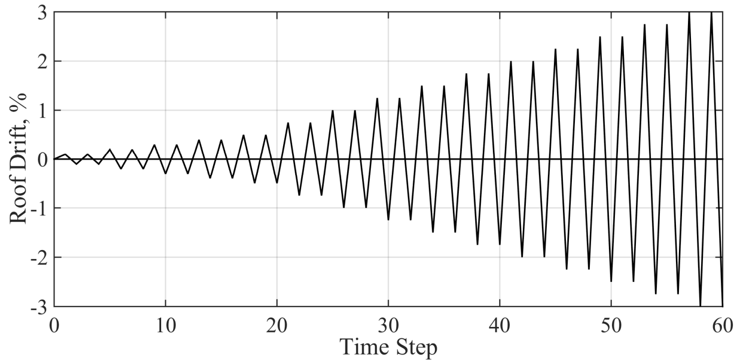
b_f: flange width, h_w: web height, t_w: wall thickness, L_{BE}: length of boundary element, L_n: beam length, b_b: beam width, h_b: beam height; L-R: longitudinal reinforcement, α: diagonal degree, D: diagonal section, S.: all section

4. Analysis of simulation results

The simulation results of coupled walls were conducted in the nonlinear static analyses of monotonic and cyclic loadings. The lateral force was taken from the Modal Response Spectrum analysis of ASCE 7-10 [29] (see Fig. 7a). To observe the complete damage progression of coupled walls (i.e. yielding, cover spalling, concrete crushing and buckling, etc.), the simulation runs until the system fails. The target displacement is 3% roof drift and the details of the cyclic loading were shown in Fig. 7.



(a) Lateral forces



(b) Time history

Fig. 7 – Details of the nonlinear static analysis

According to the simulation results, investigation of coupled core walls mainly includes the prediction of the degree of coupling and damage progression of coupled core.

4.1 Degree of coupling

Fig. 8 shows the DOC of three coupled walls with the roof drift under the monotonic loading. The calculation of the DOC follows with Equation (1). The average DOC of CCW40, CCW50, and CCW60 are 40%, 47%, and 57% between the post-yield point and before the significant decrease of the shear resistance. These are able to generally meet the design requirements of 40%, 50%, and 60%. For the DOC along with the roof drift, the value is according to the elastic properties of the coupled wall before the yield point of the structure. As the coupled walls occur the significant damage in wall piers and coupling beams, the reduction of resistance leads to a change of the DOC. When the concrete crushing of the wall piers causes the degradation of the wall pier resistance, the coupling beam remains the same shear resistance. Therefore, the decrease of the overturning moment with the same contribution of coupling beams apparently increases the DOC value.

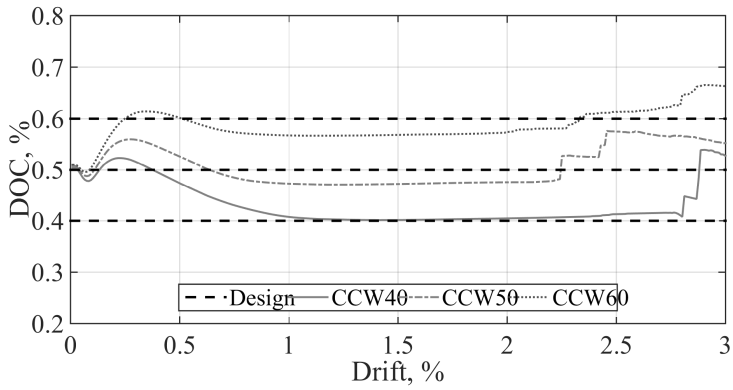


Fig. 8 – Simulation DOC of CCW40, CCW50, and CCW60

4.2 Damage progression

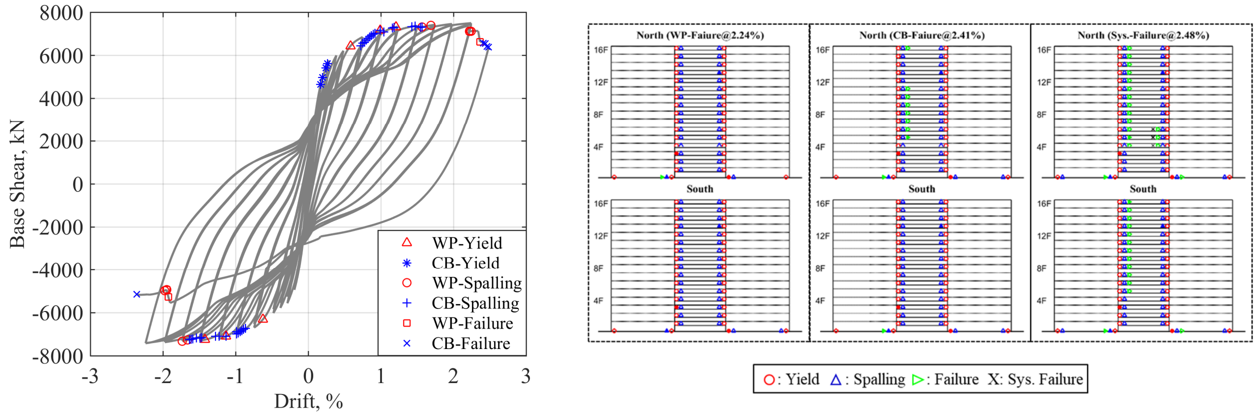
The section discusses the damage progression of coupled core walls with the cyclic loading analysis. The damage progression is associated with the roof drift. The left subfigure of Fig. 9-11 shows the relationship of the base shear and the roof drift with the damage state. The right subfigure presents the damage distribution with the roof drift. The three-dimension coupled core wall is in terms of two two-dimension coupled walls to represent the damage state in the coupling direction which are the north and south sides. The north side of the coupled wall represents the top part of the plan view in a coupled core wall and the south side is the bottom of the plan view.

4.2.2.1 CCW40

Fig. 9 shows the damage progression of CCW40 with the roof drift. Coupling beams yielded at a drift of 0.17%, followed by wall pier yielding at a drift of 0.58%. Coupling beams occurred the cover spalling at 0.75% drift. The wall pier initiated the cover spalling and almost coupling beams were cover spalling before the cover spalling of wall piers at a drift of 1.57%. At a roof drift of 2.24%, the base shear reached the maximum base shear of 7495 kN.

After the loading cycle of a drift 2.24%, the concrete crushing of the north inner side of the left wall pier caused a 5% reduction of the base shear. Then, the south inner side of the left wall pier also occurred the concrete crushing at a drift of 2.36% and the base shear reduced to 6628 kN.

At a drift of 2.41%, the north side of the middle height coupling beam appeared the concrete crushing. Although most coupling beams of the left side occurred the concrete crushing at a drift of +2.48%, the base shear only dropped to 6570 kN which is less than 1% of reduction. The concrete crushing of coupling beams didn't significantly affect the base shear. Finally, the concrete crushing of the inner side of the right wall pier at a drift of -2.48% and the base shear dramatically degraded 34% to 4929 kN and was considered to have collapsed. The system collapse of CCW40 is due to the concrete crushing of the inner sides of the wall pier bases and few coupling beams.



(a) Drift and base shear (b) Damage distribution

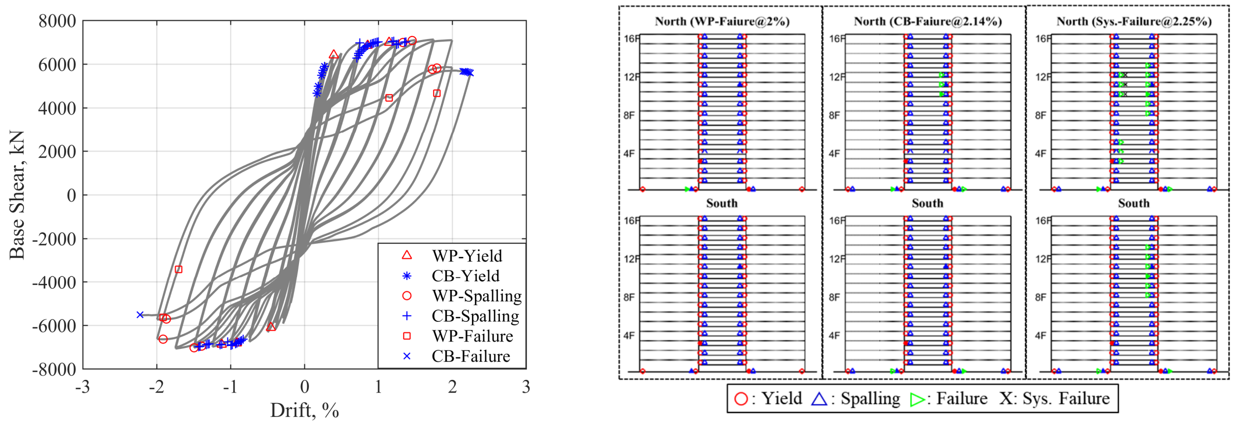
Fig. 9 – Damage progression of CCW40

4.2.2.2 CCW50

Fig. 10 shows the damage progression for CCW50 with the roof drift. Coupling beams firstly yielded at 0.17% drift, followed by wall pier yielding at 0.40%. Coupling beams initially occurred the cover spalling at a drift of 0.75%. The maximum base shear is 7135 kN at a drift of 1.75% after the cover spalling of all coupling beams.

As the concrete crushing of the internal side of the left wall pier base in the north side at the first cycle of a roof drift 2%, the base shear only dropped 6% from 7099 to 6672 kN. As the second cycle of 2% drift, all internal sides of wall piers crushed to cause a substantial reduction of the base shear to 18% from 6672 to 5858 kN. After the concrete crushing at the inner side of wall piers, the right coupling beams of the story 10, 11 and 12 at the north side of the coupled wall initially crushed at 2.14% drift and the base shear is almost close the bottom line of the system failure.

Finally, at a drift of 2.25%, all inner sides of wall pier bases and over one-third of coupling beams crushed, the system resistance reduced 23% to 5502 kN that was considered to have collapsed.



(a) Drift and base shear (b) Damage distribution

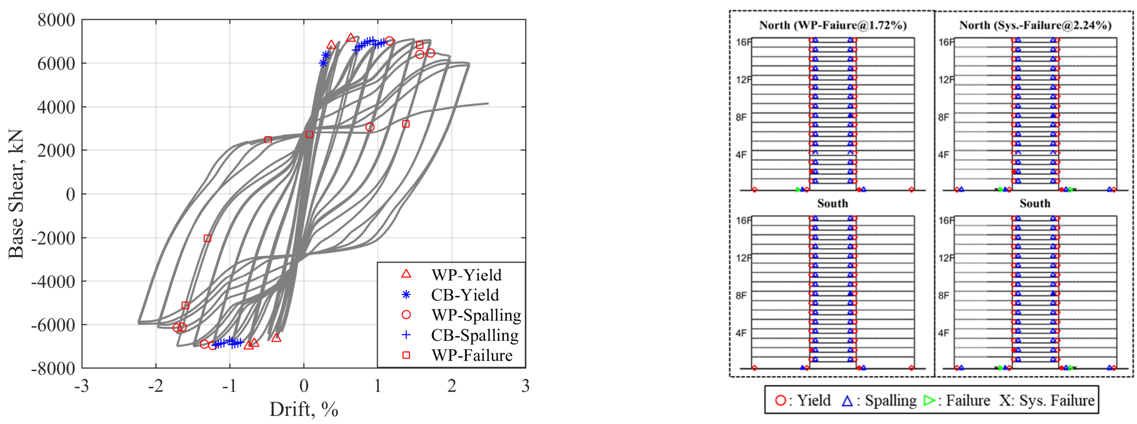
Fig. 10 – Damage progression of CCW50

4.2.2.3 CCW60

Fig. 11 shows the damage progression of CCW60 with the roof drift. Most coupling beams yielded at a drift of 0.26%, followed by the wall pier yielded at 0.37%. Coupling beams initially occurred the cover spalling at a drift of 0.71%. The maximum base shear is 7215 kN with a drift of 0.75%. After the cover spalling of most coupling beams at a drift of 1.16%, the wall pier base appeared the cover spalling.

As all coupling beams and most wall pies reached the damage state of the cover spalling, the internal side of the left north wall pier base initially crushed at the first cycle of 1.75% drift. The base shear only dropped 1.5% from 7055 to 6961 kN. As the second cycle of 1.75% drift, all internal sides of wall piers crushed to cause a bigger reduction of around 11% from 6961 to 6405 kN. Even though the concrete crushing of all internal wall pier bases initiated, the loss of the resistance strength didn't have a significant degradation compared to CCW50 (i.e., the reduction of 18%).

After the concrete crushing of the inner side of wall piers, the system still remains its base shear of 5872 kN (i.e., 82% of the maximum base shear) at a roof drift of 2.24%. Then, while the loading cycle of 2.5% drift wasn't completed, the external side of the right wall pier base crushed and the system resistance dramatically dropped to 4159 kN. The concrete crushing of the whole right wall pier bases caused the collapse of the system, but the coupling beam didn't crush. The system collapse of CCW60 is generally due to the concrete crushing of inner sides of the wall pier base and one external side of the right wall pier base.



(a) Drift and base shear (b) Damage distribution

Fig. 11 – Damage progression of CCW60

4.3 Damage progression and degree of coupling

Table 6 shows the relationship of the damage progression and the DOC of the coupled wall. For the damage progression of wall piers, the drift of the yielding, cover spalling and failure (i.e., concrete crushing) decrease along with the increase of the DOC. The reason is that the design of coupled walls with high DOC is the concept of a strong coupling beam and weak wall piers.

For the damage progression of coupling beams, the roof drift of yielding, cover spalling, and the failure didn't have a trend with the DOC. The reason is due to the coupling beams of each case didn't be designed as the same capacity, but the variable capacity of each beam based on the beam shear distribution. For CCW60, the failure of beams didn't happen until the wall pier failure, due to the design concept of weaker wall piers and strong beams. In words, the coupled wall with too high DOC may not be able to perform the advantage of coupled walls.

For the failure of the coupled walls, as the concrete crushing occurred at the inner side of the wall piers, degradation of the system resistance for CCW40, CCW50, and CCW60 are 34%, 18%, and 11%, respectively. The trend meets the design concept of a coupled wall with the degree of coupling. The information indicates that the C-Shaped wall pier of the system with a low DOC performs better resistance compared to the wall with a high DOC. On the other hand, the component failure of the coupled wall is directly related to the parameter of the DOC. CCW40 and CCW50 include the concrete crushing of wall piers and coupling beams, and CCW60 only involves the concrete crushing of wall piers.

The damage progression order of three coupled walls generally follows as a similar order that is yielding of coupling beams, yielding of wall piers, cover spalling of coupling beams, cover spalling of wall piers, failure of wall piers, failure of coupling beams, and system failure. The only difference is CCW60 without the failure of coupling beams. The DOC of a coupled wall doesn't obviously affect the damage progression order.

Table 4 – Damage progression of coupled walls

Damage Progression	Wall Pier			Coupling Beam		
	CCW40	**CCW50**	**CCW60**	**CCW40**	**CCW50**	**CCW60**
Yield	0.58%	0.40%	0.37%	0.17%	0.17%	0.26%
Spalling	1.57%	1.33%	1.16%	0.75%	0.75%	0.75%
Failure	2.24%	2.00%	1.72%	2.41%	2.14%	-
System Collapse	-	-	2.24%	2.48%	2.25%	-

5. Conclusion

This study investigated the behavior of the reinforced concrete coupled core wall with the nonlinear static analysis. The simulation method of the 3D frame model with the simulation tool of OpenSEES was able to model a reasonable prediction compared to the test results. The coupled core wall system was designed as a 16-story reinforced concrete office building with three degrees of coupling of 40%, 50%, and 60% (i.e., CCW40, CCW50, and CCW60). The simulation results of three cases CCW40, CCW50, and CCW60 have summarized the following conclusions.

The simulation method of the 3D frame model was able to simulate the expected degree of coupling for three coupled walls with a DOC of 40%, 50%, and 60%. Three coupled walls show the preferred yielding mechanism which most coupling beams yield before the wall piers. The coupled wall with the preferred mechanism easily develops a ductile manner with a characteristic of significantly absorbing energy. That also meets the previous study that the degree of coupling should be less 70% [8].

Three coupled walls under the cyclic loadings indicate that: 1) the damage progression of wall piers with the roof drift decreases along with the increase of DOC. The system with the high DOC increases the axial load to cause the stiffer behavior of the system, and drift of damage progression is smaller compared to the system with low DOC; 2) the damage progression of coupling beams with the roof drift didn't show the obvious trend with the DOC, except yielding; 3) the DOC value of the coupled wall significantly affects the damage progression of the system. The coupled wall with a low DOC (i.e., 40% and 50%) can perform the advantage of the coupled wall.

6. References

[1] Paulay T, Binney J (1974): Diagonally reinforced coupling beams of shear walls. *ACI special publication*, 42.

[2] Harries KA (2001): Ductility and deformability of coupling beams in reinforced concrete coupled walls. *Earthquake Spectra*, **17**(3), 457-478.

[3] Shiu K-N, Aristizabal-Ochoa J, Barney G, Fiorato A, Corley W (1981): Earthquake resistant structural walls: Coupled wall tests. *Rep. to National Science Foundation*, Construction Technology Laboratories, Portland cement Association, Skokie, IL.

[4] Ozselcuk A (1989): Experimental and analytical studies of coupled wall structures. *Ph.D. Dissertation*, University of California, Berkeley, Berkeley, CA.

[5] El-Tawil S, Kuenzli CM (2002): Pushover of hybrid coupled walls. II: Analysis and behavior. *Journal of Structural Engineering*, **128** (10), 1282-1289.

[6] Hassan M, El-Tawil S (2004): Inelastic dynamic behavior of hybrid coupled walls. *Journal of Structural Engineering*, **130** (2), 285-296.

[7] Eljadei AA, Harries KA (2014): Design of coupled wall structures as evolving structural systems. *Engineering Structures*, 73, 100-113.

[8] Harries KA, Moulton JDl, Clemson RL (2004): Parametric study of coupled wall behavior-implications for the design of coupling beams. *Journal of Structural Engineering*, **130** (3), 480-488.

[9] Harries KA, McNeice DS (2006): Performance-based design of high-rise coupled wall systems. *The Structural Design of Tall and Special Buildings*, **15** (3), 289-306.

[10] Xuan G, Shahrooz B, Harries K, Rassati G (2008): A performance-based design approach for coupled core wall systems with diagonally reinforced concrete coupling beams. *Advances in Structural Engineering*, **11** (3), 253-268.

[11] Harries KA, Shahrooz BM, Brienen P, Fortney PJ, Rassati GA (2006): Performance-Based Design of Coupled Wall Systems. *Composite Construction in Steel and Concrete V*, South Africa.

[12] Turgeon J (2011): The seismic performance of coupled reinforced concrete walls. *M.S. Thesis*, University of Washington, Seattle, WA.

[13] Lu X, Chen Y (2005): Modeling of coupled shear walls and its experimental verification. *Journal of Structural Engineering*, **131**(1), 75-84.

[14] Hung C-C, El-Tawil S (2011): Seismic behavior of a coupled wall system with HPFRC materials in critical regions. *Journal of Structural Engineering*, **137**(12), 1499-1507.

[15] Beyer K, Dazio A, Priestley MJN (2008): Inelastic Wide-Column Models for U-Shaped Reinforced Concrete Walls. *Journal of Earthquake Engineering*, 12, 1-33.

[16] Deierlein GG, Reinhorn AM, Willford MR (2010): Nonlinear structural analysis for seismic design. NEHRP Seismic Design Technical Brief No 4, NIST GCR 10-917-5, *NIST*, Gaithersburg, MD.

[17] Mazzoni S, McKenna F, Scott MH, Fenves GL (2006): Open System for Earthquake Engineering Simulation (OpenSEES) User Command-Language Manual. *Pacific Earthquake Engineering Research Center*, University of California, Berkeley.

[18] Pugh JS (2012): *Numerical simulation of walls and seismic design recommendations for walled buildings. Ph.D. Dissertatio*n, University of Washington, Seattle, WA.

[19] Coleman J, Spacone E (2001): Localization issues in force-based frame elements. *Journal of Structural Engineering*, **127**(11), 1257-1265.

[20] Bažant ZP, Planas J (1998): *Fracture and Size Effect in Concrete and Other Quasibrittle Materials*. CRC Press.

[21] Thomsen IV J, Wallace J (1995): Displacement-based design of reinforced concrete structural walls: Experimental studies of walls with rectangular and T-shaped cross sections. *Rep No CU/CEE-95*-06, Clarkson University, Potsdam, NY.

[22] Ile N, Reynouard J (2005): Behaviour of U-shaped walls subjected to uniaxial and biaxial cyclic lateral loading. *Journal of Earthquake Engineering*, **9**(01), 67-94.

[23] Ishikawa Y, Kimura H (1996): Experimental study on seismic behavior of RC diagonally reinforced short beams. *Eleventh World Conference on Earthquake Engineering,* Acapulco, Mexico.

[24] Naish D, Fry A, Klemencic R, Wallace J (2013): Reinforced Concrete Coupling Beams--Part II: Modeling. *ACI Structural Journal*, **110** (6), 1067-1075.

[25] Lehman JA, Turgeon AC, Birely CR, Hart KP, Marley DA, Kuchma LN, Lowes (2013): Seismic Behavior of a Modern Concrete Coupled Wall. *Journal of structural engineering*, **139** (8), 1371-1381.

[26] FEMA (1997): NEHRP guidelines for the seismic rehabilitation of buildings. Applied Technology Council, FEMA-273, Redwood City, CA.

[27] El-Tawil S, Fortney P, Harries K, Shahrooz B, Kurama Y, Hassan M, Tong X (2010): *Recommendations for Seismic Design of Hybrid Coupled Wall Systems*, SEI/ASCE.

[28] ACI (2011): Building code requirements for structural concrete (ACI 318-11) and commentary. *ACI*, Farmington Hills, MI.

[29] ASCE (2010): Minimum design loads for buildings and other structures. *SEI/ASCE 7-10,* Reston, VA.

