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Seismic performance of self-centering hybrid coupled wall systems: Preliminary assessments

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Abstract

Hybrid Coupled Wall (HCW) systems consist of reinforced concrete walls connected with steel coupling beams. HCWs benefit from the superior lateral stiffness of the reinforced concrete walls, while the coupling mechanism reduces the moment demand at the base of the walls. The present study investigates the seismic performance of a new HCW system equipped with friction-damped self-centering coupling beams and examines the efficiency of the new system in reducing residual deformations. The coupling beams of the intended HCW system consist of self-centering links, which can be easily repaired after severe earthquake events. The self-centering system utilized in this study features the following advantages distinguish it from conventional self-centering solutions: (i) it eliminates the coupling beams elongation problem (ii) it facilitates the application of pre-fabricated self-centering components to mitigate uncertainties raised by post-tensioning the connections on site. In this paper, the seismic behavior of the proposed lateral load-bearing system is investigated under several ground motion records and intensities. It is demonstrated that the applied self-centering mechanism has the capacity to minimize earthquake-induced residual deformations and repair time without increasing the damage level expected for the concrete walls in conventional HCWs.

Keywords: Hybrid Coupled Wall Systems, Self-Centering, Reinforced Concrete Walls, Shear Links, Seismic Performance.

1. Introduction

A Hybrid Coupled wall (HCW) system consists of two or more reinforced concrete (RC) walls connected by steel coupling beams. Coupling of RC walls mitigates the moment demand at their base when subjected to lateral loads.

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Furthermore, coupling beams can be designed to act as fuses and dissipate energy by undergoing non-linear deformations. This alleviates the damage concentration at the base of RC walls and distributes the nonlinearity along with the height of the walls during lateral loading. Hence, coupled wall systems have been introduced as efficient lateral force-resisting systems that can be implemented in buildings located in regions prone to moderate to strong earthquakes (El-Tawil et al. 2010; Kolozvari et al. 2018; Ji et al. 2020).

In response to the demand for resilient and sustainable structures, the interest in the development of replaceable steel links for coupling RC pier walls has recently aroused (Ji et al. 2017; Shahrooz et al. 2018; Zona et al. 2016). In this innovative solution, coupling beams include a steel link (fuse) in which the damage is concentrated, while the damaged links can be replaced after severe ground motions. Nevertheless, the replacement of the damaged links may not be practical after severe earthquakes due to considerable residual deformations. To address this problem, some self-centering (SC) coupling beams and links have been introduced in different studies to eliminate the residual deformation and facilitate the repair and replacement of damaged links (Zareian et al. 2020; Huang et al. 2021; Wang et al. 2021; Elettore et al. 2021). However, these studies focused on the SC links, and the seismic performance of HCWs with SC coupling beams has not yet been investigated. Thus, the present study investigates the seismic performance of SC-HCWs and their efficiency in minimizing both seismic damage and repair time. An eight-story building structure is considered as the case study and modeled in OpenSees. Non-linear static and dynamic analyses are performed on two case study HCW systems: one consisting of conventional replaceable steel links and the other taking advantage of SC links.

2. Case study structure

An eight-story building with the plan view shown in Fig. 1(a) is selected for case study purposes. The height of the first story is equal to 3.4 m, while the height of the other stories is 3.2 m. The lateral load resisting system is composed of HCWs in both directions. The permanent and live gravity loads are considered equal to 4.5, and 2 kN/m^2, respectively. The equivalent design earthquake force is determined considering the Type 1 elastic response spectrum with a peak ground acceleration of 0.35g, soil type C, and a building's importance factor of 1 in accordance with the Eurocode 8 (2004). The same building has been designed by Pieroni *et al.*, and further information about the building can be found in Pieroni et al. (2022). However, moment resisting frames used as the lateral load bearing system in that study are replaced with HCWs in this study. The behavior factor is assumed q=5.4 according to the provisions of the Eurocode 8 for coupled wall systems in DCH.

The total overturning moment resisted by a HCW subjected to lateral loading consists of the moment reactions developed at the base of the wall piers and the coupling action induced by the coupling beams. The ratio of the overturning moment resisted by the coupling action to the total overturning moment, *i.e.,* the coupling ratio, is assumed equal to 60%. The compressive strength of concrete and yield strength of rebars are f'_c=28 and f_{yr} =400 MPa, respectively. The design of the RC piers complies with the requirements of the Eurocode 8 (Part 5) (2004), AISC 341-16 (2016), and ACI 318-19 (2019).

The coupling beams of the HCWs consist of two wide-flange sections anchored to the pier walls (side beams) and a central link. The side beams are designed such that they remain elastic and concentrate the non-linear deformations in the links. Two design scenarios are considered in this study with respect to the central links. In the first and reference scenario, the coupling beams include conventional replaceable steel links (Ji et al. 2017) as shown in Fig. 1(b). The HCW with replaceable links is referred as R-HCW. The steel links of the R-HCW are designed to meet the requirements of AISC340-1 (2016) for the links of eccentrically braced frames. The length of the links also meets the limitation of AISC 341-10 for shear links ($e/(M_P/V_P)<1.6$, where e, M_P, and V_P denote the length, plastic flexural, and plastic shear strength of the links. In the second design scenario, the coupling beams include the SC shear link depicted in Fig. 1(c). The HCW with SC links is referred as SC-HCW.

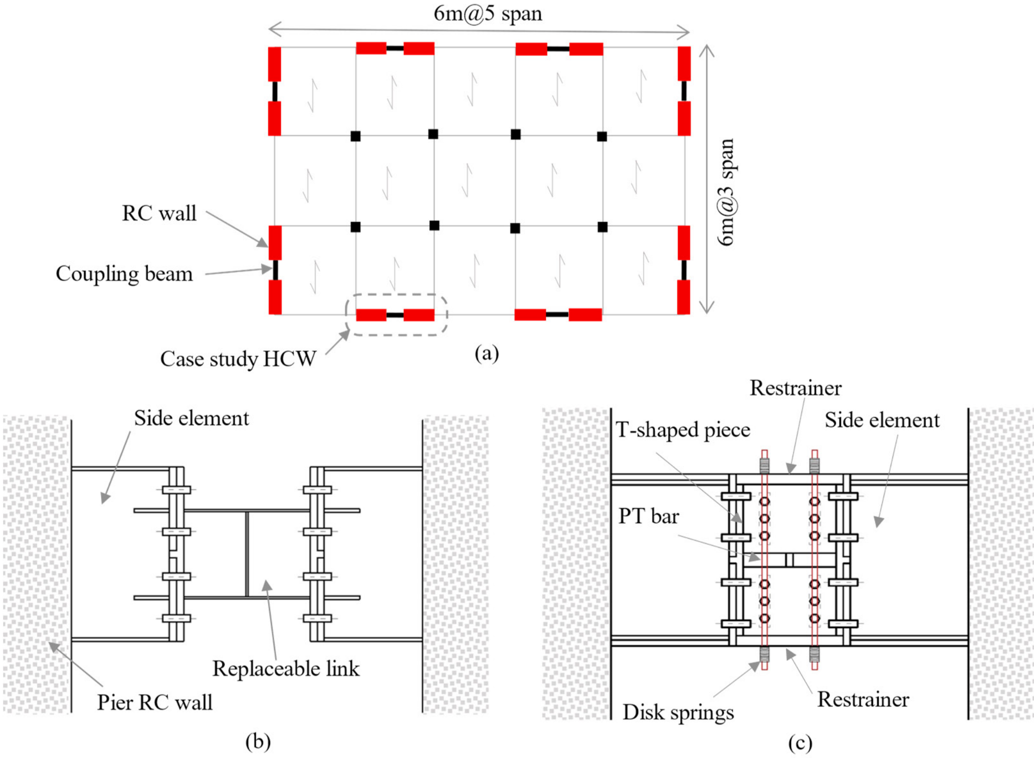

Fig. 1. (a) Plan of the archetype building; (b) R-HCW coupling beams; (c) SC-HCW coupling beams.

A friction-damped self-centering link configuration similar to the one proposed by Huang and Wang (2021) is implemented in this study. This configuration features vertical post-tensioned (PT) bars providing the restoring force and a friction slip mechanism providing energy dissipation capacity. The proposed configuration is formed of two T-shaped pieces which are fixed to the adjacent structural members and two restrainers. The restrainers are fabricated by welding one end of two frictional plates to an anchorage plate. Four PT bars are used to clamp the top and bottom restrainers to the T-shaped pieces and maintain the integrity of the SC links. The SC links configuration is illustrated schematically in Fig. 1(c). Additional details of the SC link can be found in Huang and Wang (2021). However, the configuration proposed by Huang and Wang is slightly updated in this research by adding disk springs in parallel and series to calibrate both the resistance and stiffness of SC links.

The SC links are designed with activation forces nearly identical to the shear yield strength of the counterpart links in the R-HCW. The size and post-tensioning force of the bolts clamping the friction plates are selected to achieve an energy dissipation capacity factor between 60-70% for the SC links. This factor is defined as $\beta=F_f/(0.5F_{PT0}+F_f)$, where F_f and F_{PT0} are the friction resistance and the initial post-tensioning force in the SC links (Huang et al. 2021). The energy dissipation capacity considered in this study allows for enough energy dissipation without undermining the recentering capability of the links.

3. Non-linear numerical modeling

2D non-linear models of the R-HCW and SC-HCW are created in OpenSees (McKenna et al. 2000). The RC wall piers are modeled using the Shear-Flexure Interaction Multiple-Vertical-Line-Element-Model (SFI-MVLEM) from the OpenSees elements library. The SFI-MVLEM uses 2D macroscopic fiber-based model formulation, and it incorporates biaxial constitutive RC panel behavior (Kolozvari et al. 2015). This model accounts for the axial-shear coupling, which is critical for modeling the RC walls subjected to lateral loading. This modeling approach has been validated for RC pier walls in coupled systems, and the modeling parameters suggested by Kolozvari et al. (2018) are implemented in this study. The pier walls are discretized to 19 fibers (panels) in the transverse direction to represent the walls' cross-section and reinforcement arrangement in boundary and web areas.

Elastic BeamColumn Elements are implemented to model the side elements of the coupling beams as they are expected to remain elastic. To account for the shear deformation of the side elements, a zero-length elastic shear spring with the stiffness of their cross-sections is set at their connection to the pier walls. Central links of the R-HCW are modeled using Two-Nodes Link Elements. The links' mechanical behavior is determined by the Unidirectional materials assigned to the springs representing the links' degrees of freedom. The axial and flexural springs are assumed elastic, while the shear springs are non-linear. Giuffré–Menegotto–Pinto hysteretic model (OpenSees Steel 02 material) is used to characterize the non-linear shear behavior of the links. The modeling parameters suggested for steel links and obtained from the calibration of this modeling approach against the available experimental results (Okazaki et al. 2005) are applied in this study. The same modeling approach is implemented to model the SC links in SC-HCW. However, Giuffré–Menegotto–Pinto hysteretic model assigned to the shear springs of the two-node links is replaced with the Self-Centering Uniaxial material from the OpenSees material Library.

4. Non-linear analyses and performance assessments

The non-linear models of the R-HCW and SC-HCW are analyzed, and the results are compared to investigate how effectively the seismic behavior of coupled wall systems can be improved by the application of a self-centering mechanism.

4.1. Non-linear Static (Push-Over) Analyses

Fig. 2 shows the overall drift (the ratio of the roof displacement to the height of the case study building) versus the pier walls' base shear for both R-HCW and SC-HCW obtained from push-over analyses. The incipient points of links' non-linear behavior, cracking and crushing of concrete, and the yield of the pier wall reinforcements at different levels are also superimposed in this figure.

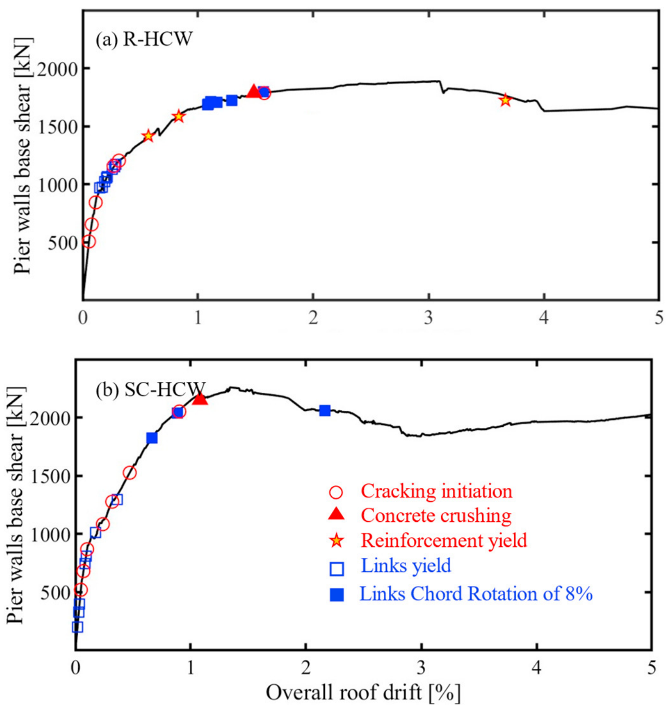

Fig. 2. Push-over curves obtained for (a) R-HCW and (b) SC-HCW

As expected, the tensile cracks in RC walls proceed to other damage states. Concrete tensile cracking strain is assumed equal to 0.015% in this study. However, coupling beam links of both R-HCW and SC-HCW yield in all stories before other damage states, which is aligned with the target of the applied design procedure.

4.2. Incremental Dynamic Analyses (IDAs)

Incremental Dynamic Analyses (IDAs) are performed to assess the seismic performance of the SC-HCW compared with the R-HCW. A set of 30 ground motion records are chosen to conduct IDAs. This set is selected such that the average spectral acceleration of the set matches the design spectral values in the range of periods between $0.25T_1$ and $2T_1$, where T_1 is the fundamental vibration period of the case study building. The spectral acceleration at the fundamental period $S_a(T_1)$ is selected as the Intensity Measure (*IM*). The fundamental periods of R-HCW and SC-HCW are very similar, and the average value ($T_{1,avg}=0.7$ *sec)* is considered as T_1 for both systems. The IDAs are performed by scaling the ground motion records to increasing *IM* values from 0.4*g* to 2*g*.

Fig. 3(a) shows the median, the 16th and 84th percentile of the maximum story drifts vs. IM. The figure shows that the use of SC links increases the maximum earthquake-induced story drifts. However, the rate of this increase is negligible. Fig. 3(b) shows the beneficial effects of using the SC links in effectively reducing the roof residual displacement, although it is not fully eliminated due to the damage to the pier walls. The difference between the limited residual drifts at different levels of the SC-HCW and the residual story drifts recorded for the HCW is highlighted in Fig. 4(a).

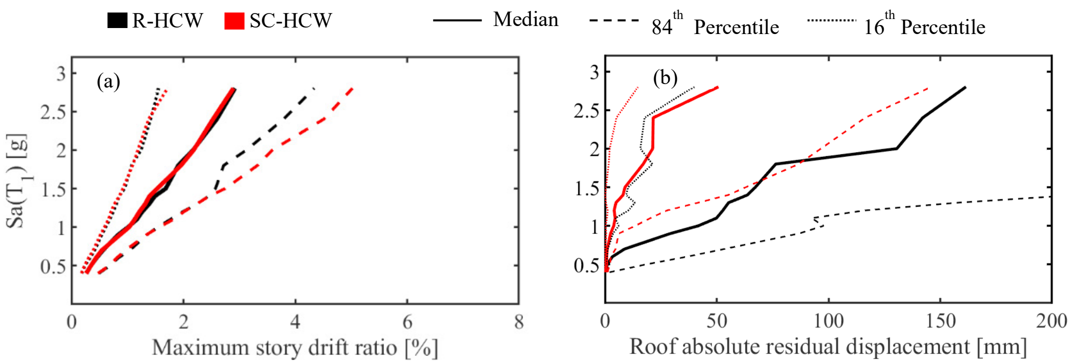

Fig. 3 Median, 16th, and 84th percentiles for (a) Maximum story drift; (b) Roof residual displacement

The same observation is made for the chord rotation of the central links ($\theta_{chord,L}$) defined as the ratio of the relative displacement at both sides of the links to their length. Fig. 4(b) shows that the median of peak $\theta_{chord,L}$ at different levels of SC-HCW is smaller than that of R-HCW at both intensity levels *IM*=0.9*g* (Equivalent to the Design Base Earthquake) and *IM*=1.5*g* due to the higher stiffness of the SC links. The chord rotation of the SC links is fully restored, while the residual rotation of the R-HCW links are considerable (refer to Fig. 4(c)). It is worth mentioning that the mechanical properties and configuration of the SC links can be updated and optimized to reduce further the peak links chord rotations and story drifts (Pieroni et al. 2022); however, this was not the intent of this study, and the improvement of the self-centering configuration to increase its efficiency can be the focus of future studies.

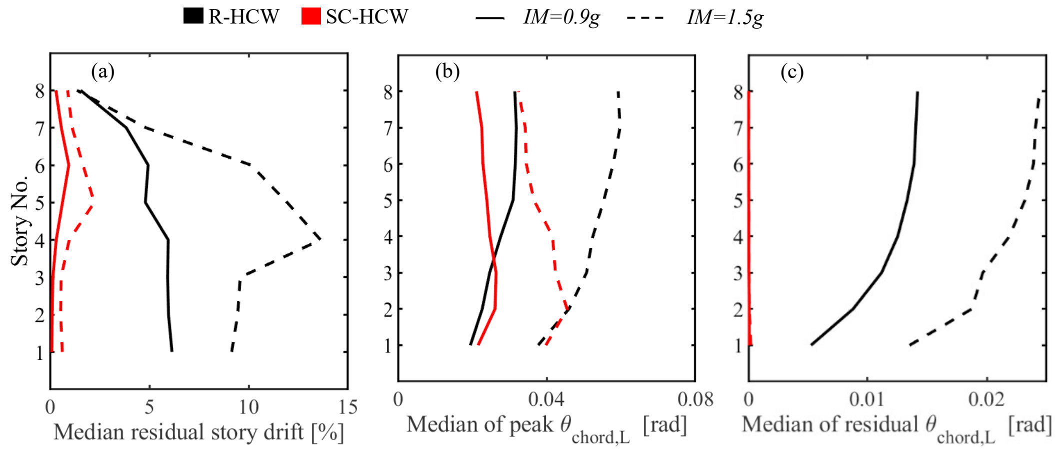

Fig. 4. (a) Median of story residual drifts; (b) Median of the links peak chord rotation; (c) Median of the links residual chord rotation obtained for *IM* = 0.9g (DBE) and *IM* = 1.5g.

Fig. 5 clarifies that the damage to the pier walls of SC-HCW is estimated to be similar to the damage estimated for the pier walls of the R-HCW. Fig. 5 shows the median and percentile values of the cumulative plastic tensile strain as an index of the pier walls damage. This index was calculated for the boundary areas of the pier walls.

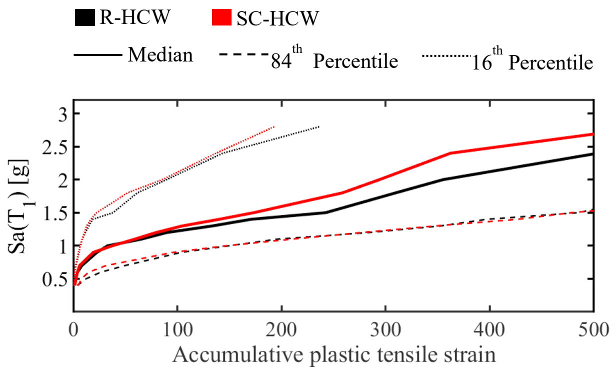

Fig. 5. Median and percentile values of the cumulative plastic strain calculated for the boundary areas of the pier walls

5. Conclusions

This study assessed the effects of applying self-centering coupling beams on the seismic performance of Hybrid Coupled Wall (HCW) systems. The efficiency of the applied self-centering mechanism in decreasing earthquake induced damages was proved by comparing the seismic performance of the case study HCW with self-centering (SC) links and that of the reference conventional HCW. It is worth mentioning that the significant reduction in residual deformations was achieved by using the self-centering links without aggravating the damage to the pier walls. Hence, the proposed HCW system with SC links allows the easy repair of the damaged links and fast re-occupation after severe earthquakes, and it can be implemented in practice as a high-seismic-performance system capable of sustaining a design-level earthquake with limited socio-economical losses.

It should be noted that the mechanical properties of SC links (activation force) were chosen similar to those of the counterpart conventional steel links in this study. However, further investigation is required to assess the optimum mechanical properties for the SC links and to develop the most efficient self-centering configuration.

References

ACI. 2019. *Building code requirements for structural concrete* (American Concrete Institute).

AISC. 2016. *Seismic provisions for structural steel buildings* (AISC: Chicago).

El-Tawil, S., Harries, K. A., Fortney, P. J., Shahrooz, B. M., and Kurama, Y. 2010. 'Seismic Design of Hybrid Coupled Wall Systems: State of the Art', *Journal of Structural Engineering*, 136: 755-69.

Elettore, E., Lettieri, A., Freddi, F., Latour, M., and Rizzano, G. 2021. 'Performance-based assessment of seismic-resilient steel moment resisting frames equipped with innovative column base connections', *Structures*, 32: 1646-64.

EN1998-1. 2004. *Eurocode 8: Design of structures for earthquake resistance* (Brussels).

Huang, X., and Wang, Y. 2021. 'Development and modelling of new friction damped self-centring link for coupled wall systems', *Engineering Structures*, 239: 112365.

Ji, X., Liu, D., Sun, Y., and Molina Hutt, C. 2017. 'Seismic performance assessment of a hybrid coupled wall system with replaceable steel coupling beams versus traditional RC coupling beams', *Earthquake Engineering & Structural Dynamics*, 46: 517-35.

Ji, X., and Molina Hutt, C. 2020. 'Seismic design and application of hybrid coupled walls with replaceable steel coupling beams in high-rise buildings', *The Structural Design of Tall and Special Buildings*, 29: e1727.

Kolozvari, K., Orakcal, K., and Wallace John, W. 2015. 'Modeling of Cyclic Shear-Flexure Interaction in Reinforced Concrete Structural Walls. I: Theory', *Journal of Structural Engineering*, 141: 04014135.

Kolozvari, K., Terzic, V., Miller, R., and Saldana, D. 2018. 'Assessment of dynamic behavior and seismic performance of a high-rise rc coupled wall building', *Engineering Structures*, 176: 606-20.

McKenna, F., GL, G. F., Scott, M., and Jeremic, B. 2000. "Open System for Earthquake Engineering Simulation (OpenSees)." In. C Berkeley (CA): Pacific Earthquake Engineering Research Center.

Okazaki, T., Arce, G., Ryu, H.-C., and Engelhardt Michael, D. 2005. 'Experimental Study of Local Buckling, Overstrength, and Fracture of Links in Eccentrically Braced Frames', *Journal of Structural Engineering*, 131: 1526-35.

Pieroni, L., Freddi, F., and Latour, M. 2022. 'Effective placement of self-centering damage-free connections for seismic-resilient steel moment resisting frames', *Earthquake Engineering & Structural Dynamics*, 51: 1292-316.

Shahrooz, B. M., Fortney, P. J., and Harries, K. A. 2018. 'Steel Coupling Beams with a Replaceable Fuse', *Journal of Structural Engineering*, 144: 04017210.

Wang, B., Nishiyama, M., Zhu, S., Tani, M., and Jiang, H. 2021. 'Development of novel self-centering steel coupling beams without beam elongation for earthquake resilience', *Engineering Structures*, 232: 111827.

Zareian, M. S., Esfahani, M. R., and Hosseini, A. 2020. 'Experimental evaluation of self-centering hybrid coupled wall subassemblies with friction dampers', *Engineering Structures*, 214: 110644.

Zona, A., Degée, H., Leoni, G., and Dall'Asta, A. 2016. 'Ductile design of innovative steel and concrete hybrid coupled walls', *Journal of Constructional Steel Research*, 117: 204-13.