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Seismic Retrofit of RC Shear Walls Using Selective Weakening and Self-Centering

S. Sharma¹, S. Basereh², S. Aaleti³ and P. Okumus⁴

ABSTRACT

Traditional retrofit methods typically focus on increasing strength/stiffness of the structure. This may increase seismic demand on the structure and could lead to excessive damage during a seismic event. This paper presents an alternative retrofit method which integrates concepts from selective weakening and self-centering (rocking) to achieve low seismic damage for sub-standard reinforced concrete shear walls. The proposed method involves converting traditional cast-in-place built shear walls into rocking walls, which softens the structure, while allowing re-centering. Laboratory tests were performed to validate the retrofit concept on a benchmark wall specimen designed to pre-1970s standards. Observations from the test showed minimized damage and excellent recentering in the retrofitted wall. Additional testing was carried out to verify a novel anchorage scheme for post-tensioning elements, required to implement the proposed retrofit. Ultra-High-Performance Concrete (UHPC) was judiciously used to minimize damage and optimize the retrofit process.

Introduction

Most of the reinforced concrete (RC) buildings built prior to implementation of the 1976 Uniform Building Code are non-ductile and are under risk to suffer irreparable damage or even collapse during a major earthquake. The major deficiencies in shear walls of such non-ductile RC buildings are inadequate shear strength and improper detailing of the boundary elements (BE). Traditional retrofit measures like concrete, steel or fiber reinforced polymer composites jacketing focus on increasing strength/stiffness of structural walls [1]. These retrofit approaches may lead to increased demand in structure or result in excessive damage. Stakeholders are increasingly interested in retrofit solutions that minimize damage, lower downtime, and allow immediate occupancy [2]. Recent tests of unbonded post-tensioned rocking concrete walls have shown these walls to have excellent recentering ability and minimal damage under large drift levels compared to traditional monolithic walls [3] [4]. The study presented in this paper investigates an alternative retrofit solution where RC shear walls are converted into rocking walls by integrating selective weakening and self-

¹ PhD Candidate, Dept. of Civil, Const. & Env. Engineering, University of Alabama, 2024 SERC Building, Tuscaloosa, AL 35401 (email: ssharma11@crimson.ua.edu)

² Structural Designer, Mar Structural Design, 2332 Fifth St., Suite D, Berkeley, CA 94710 (email: sina.basereh@marstructuraldesign.com)

³ Associate Professor, Dept. of Civil, Const. & Env. Engineering, University of Alabama, 2037 C SERC Building, Tuscaloosa, AL 35401 (email: saaleti@ua.edu)

⁴ Associate Professor, Dept. of Civil, Structural and Env. Engineering, University at Buffalo, 222 Ketter Hall, Buffalo, NY 14260 (email: pinaroku@buffalo.edu)

centering techniques. This paper presents results from large-scale laboratory testing of a benchmark and retrofitted slender RC wall and a post-tension (PT) anchorage system proposed as part of the retrofit scheme.

Retrofit Scheme

The basic steps involved in the proposed retrofit method are shown in Fig. 1. First, cold joints are created at the wall-foundation interface to soften the structure (selective weakening). Selected vertical bars are left uncut to provide energy dissipation (ED). Unbonded post-tensioning (PT) elements are attached to the wall to achieve self-centering and to partially restore the strength lost by cutting of vertical bars. Past laboratory testing has shown damage at the rocking corners of walls at higher drift levels [3] [4]. Thus, local retrofit of inadequately confined BE is necessary. In this study, normal concrete in the critical rocking corners of the wall is replaced with UHPC. UHPC is a special class of concrete material with compressive strengths ranging from 22 to 26 ksi, and sustained tensile strengths ranging from 1.2 to 1.7 ksi. Use of UHPC in the BE of the retrofitted wall is intended to provide additional confinement and minimize damage in rocking corners of the wall. As part of the experimental program, a retrofitted wall was designed and tested to overcome deficiencies of a pre-1970s standard shear wall tested at University of Buffalo (UB). Additional testing was performed to verify a novel PT anchorage concept.

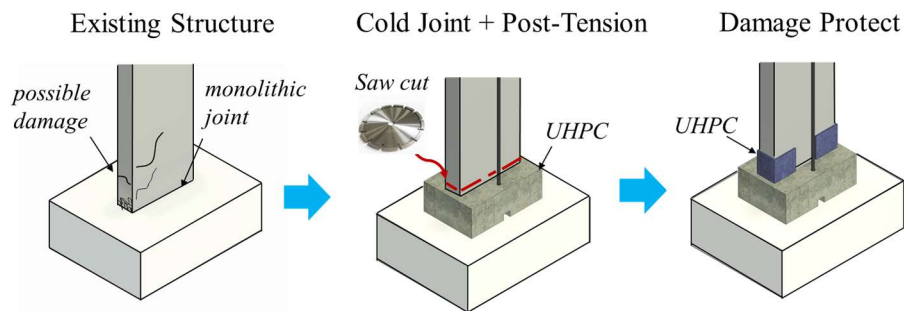


Figure 1. Schematic of the proposed retrofit scheme

Benchmark Shear Wall (BW)

A brief discussion of design and experimental findings of the BW tested at UB is presented in this section. Additional details of design, experimental findings and pre-test numerical investigation can be found in [5] [6]. The test specimen was 1/3rd scale of a prototype wall designed using the equivalent lateral force method of ASCE 7-16 [7]. Shear demand to capacity ratio was kept high to have a significant contribution from shear to the failure mode. The pre-retrofit wall was not compliant with the ACI 318-19 [8] in terms of spacing of transverse web reinforcement, spacing of confinement hoops, and extension of BE into the foundation. The dimension and reinforcement details of the wall is shown in Fig. 2 (a). The measured compressive strength of concrete was 3.8 ksi and grade 60 ASTM A615 mild steel reinforcement was used in the wall.

The specimen was tested under quasi static cyclic loading protocol. An axial load of 95 kips was applied to represent gravity load. In plane lateral load was applied at a height of 130 in. above the base of wall. Flexural cracks initiated in the boundary elements at 0.15% drift. At 0.23% and 0.35% drift, additional flexural cracks formed in the boundary elements, extended into the web of the wall, and became inclined. After 0.50% drift, existing cracks widened, and new diagonal cracks formed in the web of the wall. Concrete cover spalling was observed at 1.00% drift ratio. At 1.54% drift, core concrete crushing in the BE was observed and progressed further in later load cycles. The first vertical bar fracture was observed at 1.54% drift ratio. Peak applied force of 81 kips was observed at 1.77% drift. At drift of 2.5%, eight of the outermost reinforcement bars fractured. A 36% drop from the peak load occurred at 2.5 % drift. The residual drift after the 2.5% load cycle was 1.1%. The measured force displacement response and the observed damage in the wall panel is shown in Fig. 3a and Fig. 3c respectively.

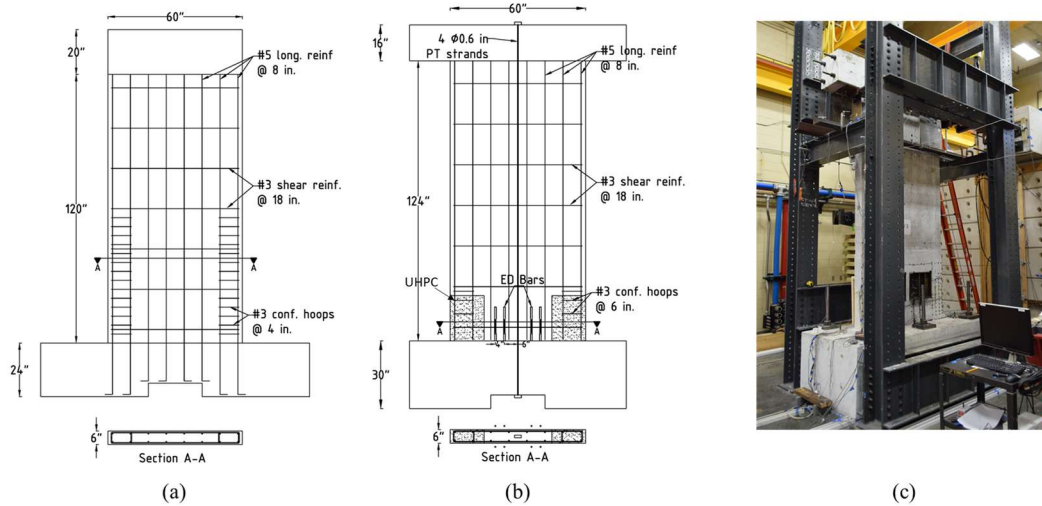


Figure 2. Typical dimensions and reinforcement details of (a) BW (b) RW; (c) Load setup used for RW

Retrofitted Shear Wall (RW)

The RW was tested at University of Alabama, Tuscaloosa and was built as a new wall replicating the details of the BW. A straight cut at the wall foundation interface including all the longitudinal wall reinforcements is proposed in the RW. A simplified analysis method [9] was used to design the amount of ED and PT reinforcement in the RW. The designed area of ED reinforcement was 2.48 in^2 . In this study, ED bars were installed externally, as it is more practical to produce a clean cut at the wall-foundation interface rather than leaving selected wall reinforcements uncut to serve as ED. The ED reinforcements were anchored to the wall using channel sections bolted to the wall panels. The other end of the ED reinforcements was anchored using coupler installed in the foundation block. The designed unbonded length of the ED bars was 12 in. Four 0.6 in. dia. PT strands with initial stress of $0.6f_{pu}$ ($f_{pu}=270 \text{ ksi}$) was designed to apply PT load. The unbonded length of PT strands were 188 in. At the rocking corners, a portion of 15 in. long and 20 in. high normal concrete is replaced with UHPC (see Fig. 2b). The dimensions of the UHPC pockets were chosen to be greater than twice the predicted neutral axis depth and plastic hinge length. To simplify the construction process, the wall corner pockets to be replaced with UHPC were blocked off during casting of the specimen. UHPC was poured later after the normal concrete portion of the wall had cured. To investigate use of UHPC in cases where the concrete confinement ratio could be lower because of inadequate knowledge of mechanical properties of reinforcement or improper reinforcement detailing, the confinement hoops were spaced 1.5 times wider (6 in.) compared to the BW and were terminated soon after the UHPC pocket (see Fig. 2b). Slight changes in specimen height and loading height were made to accommodate lab constraints. Measured compressive strength of NC was 4.2 ksi and UHPC was 20.0 ksi.

The specimen was tested using a similar load protocol to that of the BW. Slight cracking was observed around the channel section used to anchor the ED bars to the wall at 0.5% drift. Surface cracks along the length of wall was formed at locations of shear reinforcements starting at 0.75% drift. This was attributed to low thickness of concrete cover around the shear reinforcements. The ED bars started to buckle in compression around 1.0% drift. At the first cycle of 2.5% drift in the negative direction, one of the PT strands ruptured unexpectedly before yielding (avg. strand stress of 225 ksi) after which the test was stopped. A peak load of 70.6 kips was observed at -1.9% drift. The measured residual drift during testing was less than 0.1%. No major damage was observed in the rocking corners during testing (see fig. 3d).

The retrofit scheme reduced the damages in the wall panel by limiting flexure-shear cracking, crushing of core concrete, rupture of flexural reinforcements, yielding of confinement hoops and enhanced recentering when compared to the BW. There was a 13% drop in peak lateral force compared to the BW.

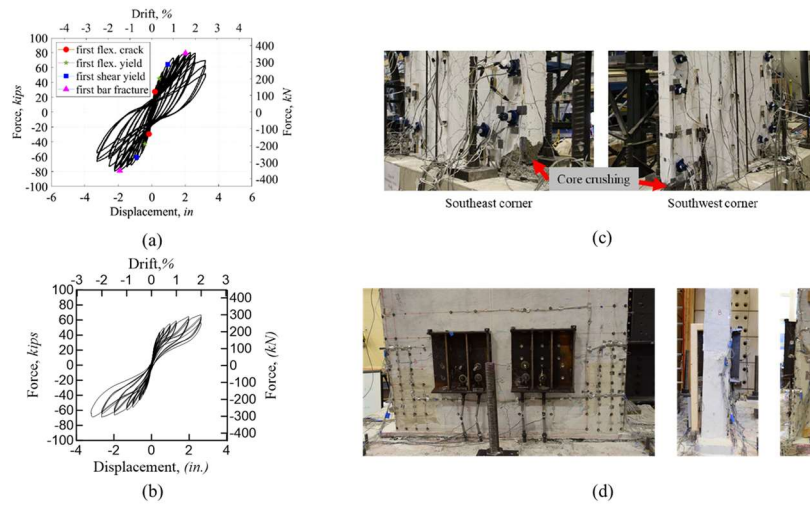


Figure 3. Force-displacement response of (a) BW (b) RW; (c) BW damage after 1.54% drift cycle; (d) RW damage after 2.4% drift cycle

Foundation Retrofit for Anchorage of PT Elements

In the proposed method for anchoring PT elements to the foundation, first vertical dowel bars are embedded into the foundation and transverse interface reinforcement are embedded into the wall panel. UHPC is then poured around the base of the wall. PT elements are anchored in the UHPC block. In this setup, the wall can be cut at a height above the UHPC block to enable rocking. The test specimen was designed at 2/5th scale of the retrofitted shear wall specimen. The dimensions and reinforcement detail of the test specimen is provided in Fig. 4. To simplify the fabrication process, vertical dowel bars (#7) and horizontal interface bars (#3) were installed before casting of NC portion of the specimen. The wall-UHPC block interface was intentionally roughened to achieve roughness depth of 0.2 in.

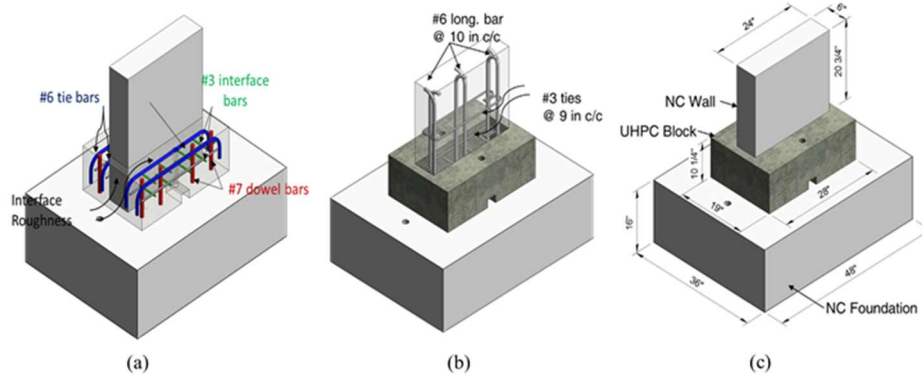


Figure 4. Typical dimensions and reinforcement details of the foundation retrofit specimen

The setup used in testing of the specimen is shown in Fig. 5a. The specimen was loaded using high strength 5/8 in. dia. bars, one end of which was anchored at the UHPC block and the other end anchored to a loading beam. Two 400 kip hydraulic loading jacks were used to load the double channel (loading) beam. The load cycle consisted of monotonic loading upto 110 kips. The damage observed during testing is shown in Fig. 5b. Fine cracks in UHPC initiated around 40 kips of applied load and was observed primarily above the anchorage location and along the locations of vertical dowel bars. Progression of existing cracks and additional cracks was observed with increased loading. The wall longitudinal bars closer to the anchorage zone (W_C) registered higher strain than bars closer to the edge of the wall (W_E) (see Fig. 5c). In case of vertical dowel bars, uniform distribution of strain was observed for the bars located near to the center (D_C) and near to the edge of the specimen (D_E) (see Fig. 5d). The results from the experiment validate the anchorage concept and thus can be used in anchoring PT elements to existing foundations while performing retrofit of walls.

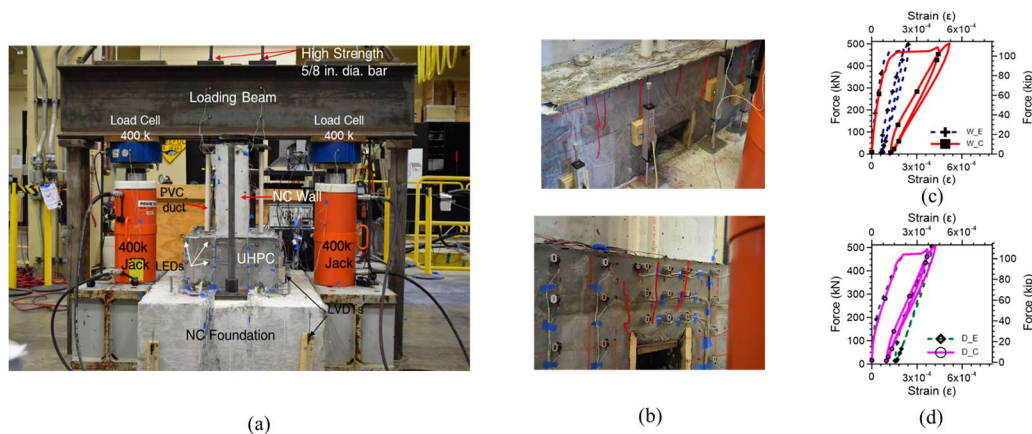


Figure 5. (a) Test setup of foundation retrofit specimen (b) Damages in UHPC block at peak load; Force vs strain in (c) Wall longitudinal reinforcements. (d) Vertical dowel reinforcements

Conclusion

The experimental results show that the shear wall retrofitted using selective weakening and self-centering exhibit minimized damage and low residual drift. UHPC was found to be effective in minimizing damage and providing additional confinement in the rocking corners. A novel anchorage scheme for PT elements proposed as part of the retrofit scheme was also validated through testing. Use of UHPC in the anchorage zone helped optimize the size of the anchorage block. Further research is required to understand the impact of the proposed retrofit on surrounding structural elements like beam-column joints and gravity columns.

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References

1. Moehle J. State of Research on Seismic Retrofit of Concrete Building Structures in the US. US-Japan Symposium and Workshop on Seismic Retrofit of Concrete Structures-State of Research and Practice, Tokyo, 2000.
2. Calvi G.M., Sullivan T.J., Welch D.P. A Seismic Performance Classification Framework to Provide Increased Seismic Resilience. In: Ansal A. (eds.) *Perspectives on European Earthquake Eng. and Seismology, Geotechnical, Geological and Earthquake Engineering* 34: 361-400. Springer: Cham, 2014.
3. Sritharan S., Aaleti S., Henry R.S., Liu K-Y, Tsai K-C. Precast Concrete Wall with End Columns (PreWEC) for Earthquake Resistant Design. *Earthquake Engineering and Structural Dynamics* 2015, 44(12), 2075-2092.
4. Smith B. J., Kurama Y. C., & McGinnis M. J. Behavior of Precast Concrete Shear Walls for Seismic Regions: Comparison of Hybrid and Emulative Specimens. *Journal of Structural Engineering* 2013, 139(11)
5. Basereh S., Seismic Retrofit of Reinforced Concrete Shear Walls Using Selective Weakening and Self Centering Techniques. *PhD Thesis*. State University of New York at Buffalo, 2021
6. Basereh, S., Okumus, P., Aaleti, S., "Reinforced Concrete Shear Walls Retrofitted Using Weakening and Self-Centering: Numerical Modeling." *ASCE Journal of Structural Engineering*, 2020, 146(7), [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0002669](https://doi.org/10.1061/(ASCE)ST.1943-541X.0002669).
7. ASCE 7-16. Minimum Design Loads and Associated Criteria for Buildings and Other Structures (7-16). *American Society of Civil Engineering*, Reston, Virginia, 2017
8. ACI 318-19. Building Code Requirements for Structural Concrete and Commentary. *American Concrete Institute*, Farmington Hills, MI, 2019
9. Aaleti S., Sritharan S. A simplified analysis method for characterizing unbonded post-tensioned precast wall systems. *Engineering Structures*, 2009, 31(12), 2966-2975