**Retrofit and Repair of Reinforced Concrete Walls with Fiber-Reinforced Polymers**

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# RETROFIT AND REPAIR OF REINFORCED CONCRETE WALLS WITH FRP: A REVIEW OF EXPERIMENTAL INVESTIGATIONS

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**ABSTRACT**
Retrofit and repair of structures occur under differing circumstances but are both necessary to improve existing building stock and increase resilience of communities against hazards. FRP is an attractive option for both retrofit and repair because of its lightweight properties, corrosion resistant qualities, and ease of application. This paper compiles a literature review on structural behavior of RC shear walls after retrofit or repair with FRP. Details such as the FRP configuration, materials, and wall shape of FRP-retrofitted shear walls are presented. This paper concludes with potential future research topics to gain better understanding on the performance of FRP-retrofitted walls.

**KEYWORDS**
Retrofitted components; repair; experimental studies; database

## INTRODUCTION

Fiber-reinforced polymer (FRP) strengthening of concrete components has become an acceptable and widely used method of retrofit and repair. However, there remain research areas where the performance of these retrofitted systems has not been investigated. Goodwin et al. (2019) states that one of the biggest research needs for FRP-retrofitted structures includes large-scale experiments. While reinforced concrete (RC) components such as columns wrapped in FRP have been studied for over 30 years, components like FRP-retrofitted RC shear walls do not have the benefit of such an extensive interest in experimental research. The goal of this review is to discuss available experimental research on FRP-retrofitted and repaired shear walls, which was gathered as part of the development of a database (Dukes & Sattar, 2021), and to highlight areas where research is needed. The authors distinguish retrofitted walls, which are walls that were untested prior to FRP addition, and repaired walls, which were tested sometimes until failure, repaired, and then applied with an FRP overlay, as the two types of wall tests that often have different goals and outcomes. Across the groups, different characteristics of the walls, including FRP configuration, FRP material type, and wall shapes, will be discussed. Conclusions are summarized in the final section, where additional research needs are highlighted.

## OVERVIEW OF FRP-RETROFITTED WALL DATABASE

This review stems from the information gathered from an experimental database of FRP-retrofitted RC shear walls developed at the National Institute of Standards and Technology (NIST) (Dukes & Sattar, 2021). This database contains over 130 specimens from more than 30 publicly available sources, such as journal articles, reports, and theses. The database is intended to be as comprehensive as possible, providing details such as material properties of the concrete and FRP, geometric properties, and loading and response information. During the development of the database, two major categories were identified for grouping the test programs: whether there were openings in the walls, and whether the walls were damaged prior to FRP application. Table 1 gives general statistics of the types of wall specimens found in the database. The walls discussed in this paper fall under Subset A and B groups, which are walls without openings that were either “retrofitted” or “repaired and retrofitted” with FRP.

Table 1: Summary of types of walls found in FRP-retrofitted shear wall database

| Wall Test and Condition | Retrofit<br>No damage prior to FRP | | Repair and Retrofit<br>Damage prior to FRP | |
|---|---|---|---|---|
| No Openings | Subset A<br>Retrofit, no openings | 40 % | Subset B<br>Repair, no openings | 32 % |
| Openings | Subset C<br>Retrofit, with openings | 12 % | Subset D<br>Repair, with openings | 16 % |

**FRP Application Purpose**

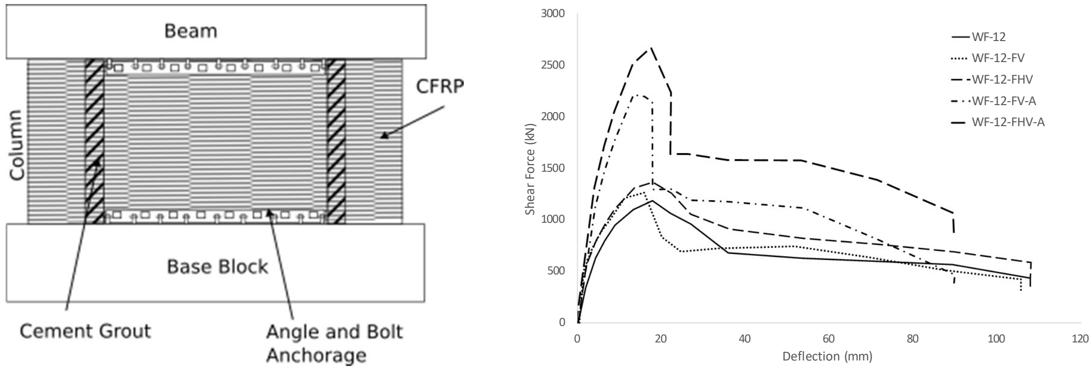
We distinguish walls by the purpose of FRP application during testing. We refer to FRP-retrofitted walls as walls that were tested only once after FRP was applied. This represents the scenario of retrofitting an existing undamaged wall in a building before an event occurs. We refer to FRP-repaired walls as walls that were tested or cycled as plain RC walls, then repaired with FRP. FRP-repaired walls represent the scenario where an existing wall is damaged or degraded to the point of needing repair. Over 40 % of the walls in the database were tested as retrofitted walls, and 30 % are repaired and strengthened. Throughout the paper, the specimens discussed will be referred to in these terms: retrofitted or repaired.

## WALL SHAPE

Rectangular wall shapes are the dominant shape found in the database. These walls are planar walls without barbells or pronounced boundary elements. As these wall types are easier to build and test in the lab it is understandable why many research programs focused on this shape. However, this wall shape does not represent all wall conditions found in existing buildings, which indicates a research gap that should be explored. This section describes research studies that focused on non-rectangular wall shapes.

**Barbell walls**

Hwang et al. (2004) looked at the effectiveness of enhancing shear strength of seismically insufficient RC partition walls with external carbon FRP (CFRP) materials. The research plan included experimental and analytical studies of the specimens. The tests included six large scale specimens with sizeable boundary elements or columns at each end, making the cross section of the wall a barbell shape. The researchers tested the conditions of a retrofitted wall web without end anchors (walls WF-12-FV and WF-12-FHV) and with end anchors (walls WF-12-FV-A and WF-12-FHV-A) of the CFRP laminates. The identification of each specimen included the orientation of the laminates (FV meaning vertical laminates, FHV meaning vertical and horizontal laminates) and presence of anchors (with "-A" appended). The anchor system consisted of structural steel angles bolted to the wall base and reaction beam. This allowed the CFRP reinforcement to be able to transfer the load to the supports. The backbone envelope curves of the resulting cyclic testing in Figure 1 reveals that anchorage improves the response of the retrofitted walls, while the retrofitted walls without anchors showed almost no difference to the unretrofitted wall. The retrofitted walls with anchors WF-12-FV-A and WF-12-FHV-A showed an increase of 88 % and 126 % in shear strength compared to the as-built wall. The retrofitted walls without anchorage, WF-12-FV and WF-12-FHV, performed similarly to the as-built wall, showing that the FRP retrofit in this case had little effect on the performance.




(a) Illustration of retrofitted wall specimen

(b) Backbone response curves

Figure 1: Envelope curves of the load-deflection response for all wall specimens in (source data from Hwang et al. (2004))

Li and Lim (2010) tested axially loaded RC walls with boundary elements to determine the effectiveness of FRP as a repair method. The goal of the study was to investigate the seismic performance of RC walls with limited transverse reinforcement, representing walls found in buildings located in regions with low or moderate seismicity. Two sizes of walls, with aspect ratios of 1.125 (low-rise walls) and 1.625 (medium-rise walls), were subject to axial loading and cyclic loading to simulate seismic loads until failure, then repaired with FRP materials and testing again. The original specimens all failed in a similar mode, which was predominantly flexural failure. The FRP repair configuration was based on the engineering judgement of the researchers. FRP sheets, consisting of either all glass or a combination of glass and carbon fibers, were bonded in the horizontal and vertical directions on both sides of the walls. The wall was confined by the addition of U-wraps around the boundary elements, secured by grinding and rounding the corners of the wall. The FRP sheets were also secured with glass FRP (GFRP) anchors located at various places along the length of the sheets. In the case of wall specimen MW2, a medium-rise wall was tested until failure, then repaired by replacing concrete with mortar and injecting epoxy into cracks. The specimen was then strengthened with a layer of vertical carbon FRP on both sides and along the edges of the wall, and a layer of horizontal glass FRP along the web of the wall. The repaired wall was tested under the amended ID RMW2. After the tests, the results showed that strength and ductility could be restored or improved with the addition of FRP as a repair technique, as shown in Figure 2 for specimen MW2. The use of CFRP showed an advantage in recovering strength over GFRP, which was used exclusively for the other medium-rise wall specimen. The U-wraps used at the ends of the walls assisted in preventing debonding of the jackets. However, there was debonding of L-shaped strips at the base of the walls, which shows the potential difficulty of effectively anchoring critical regions, such as the base of walls.

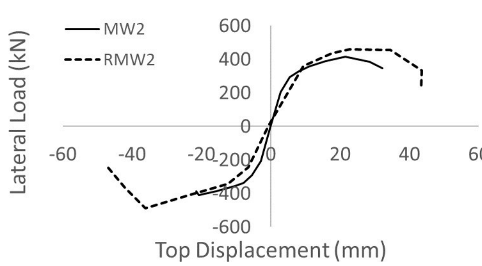



Figure 2: Hysteresis curves of reference wall MW-2 and retrofitted wall RMW-2 (source data from Li and Lim (2010))

**Other non-rectangular shapes**

Sonobe et al. (1999) tested columns with wing walls. These shapes have a symmetrical or asymmetrical column in the center of two attached wing walls, as illustrated in Figure 3. This experimental program consisted of 16 wall specimens that used both carbon and aramid fiber sheets and included one repaired wall along with retrofitted walls. The wall design was based on a pre-1971 design code to represent old existing building stock. The testing variables included position of wing walls to the column, width of wing walls, and the type and amount of FRP shear reinforcement. During testing, axial load was applied to each wall as well as reversed cyclic lateral loading. After testing, nearly all of the specimens exhibited shear failures. It was concluded that both carbon and aramid fibers enhanced the seismic behavior of these specimens, and that more fiber reinforcement resulted in higher ultimate shear strengths, up to a limit. For specimens with three and four layers of FRP, the researchers found similar ultimate shear strengths, which they attribute to there being a limitation of retrofit effects with increasing layers of FRP. The authors proposed an equation to evaluate the ultimate shear strength of columns with wing walls. As these test specimens are unlike others in the database, which are mostly rectangular, it is unclear how these results would translate to more typical retrofitted walls.

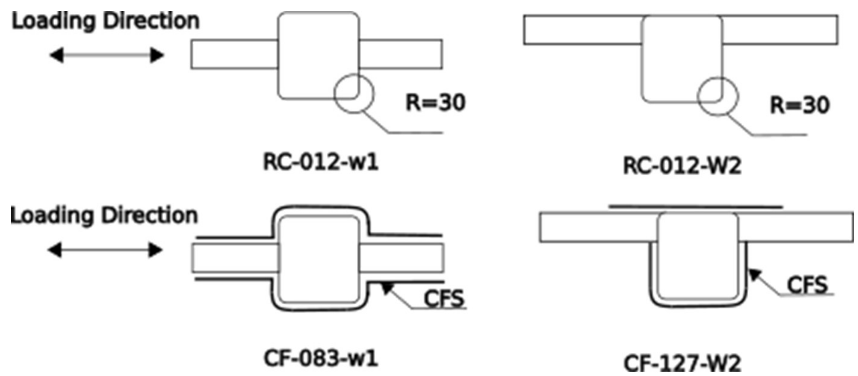
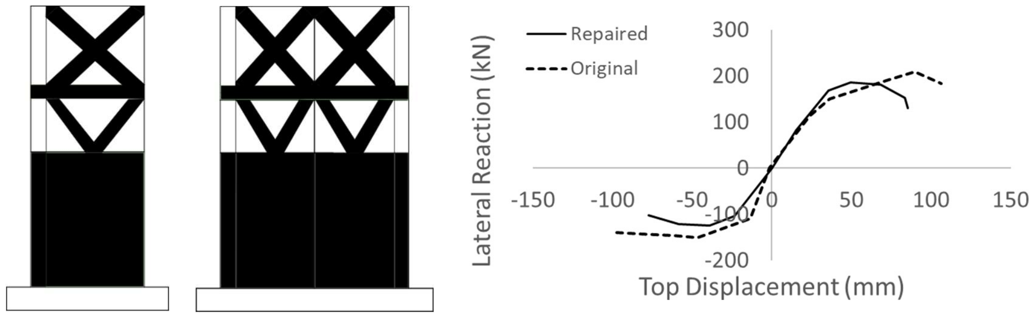



Figure 3: Examples of wing wall specimens tested (adapted from Sonobe et al. (1999))

Zhang et al. (2015) tested four nonrectangular repaired RC wall specimens. The tests included two L-shaped walls, one specimen loaded parallel to one of the segments of the wall, and the other loaded in the symmetrical axis; and two T-shaped walls that were loaded along the symmetrical axis but with 0.10 and 0.20 axial load ratios. The FRP repair was done on previously tested and damaged specimens. Three of the specimens used a combination of glass and carbon fibers for the repair, applying the carbon FRP to the plane of the wall parallel to the loading, and glass to the plane perpendicular to the loading. Specimen LWR1, shown in Figure 4 (a) and (b) and was tested on the symmetrical axis, was strengthened with only CFRP. The scheme of the FRP strengthening is shown in Figure 4 (a) and (b). Fiber anchors were also placed at the intersections of the wall elements to prevent premature debonding of the FRP sheets. The results showed that all of the repaired walls were able to recover most of the lateral strength of the original specimen, where the repaired walls were within ± 20 % of the original peak lateral strength. The results showed that most of the repaired walls maintained or gained ductility through the cyclic tests. The exception was specimen LWR1, the L-shaped wall tested in the symmetrical axis, which lost lateral load capacity at an earlier cycle than the original specimen. Figure 4 (c) shows the final hysteretic loops of the original and repaired test for specimen LWR1.




(a) LWR1 FRP repair elevation 1 (b) LWR1 FRP repair elevation 2 (c) Backbone Response Curve

Figure 4: Backbone response curve of Specimen LWR1 before and after repair (source data from Zhang et al. (2015))

**FRP MATERIAL**

Carbon and glass FRP are the most commonly used FRP materials in construction. Both carbon and glass have been shown to improve strength and ductility in structures, and they perform well in certain environmental conditions (Zaman et al., 2013; Dukes et al., 2022). Carbon FRP is usually preferred because of the high modulus and strength, however glass is used as well, where lower costs are desired and reduced strength is acceptable (Goodwin et al., 2019). Over 70 % of the specimens in the database use carbon FRP, and around 15 % used glass FRP. For researchers or practitioners looking for the performance of FRP materials other than carbon or glass on RC walls, the available research is scarce. However, there were some examples of alternative FRP or composite use for retrofitting RC shear walls.

Some studies have shown the potential for natural fibers in FRP retrofits, as natural fibers can offer similar performance to carbon or glass, with the added benefit of being sustainable, lower cost, and more environmentally friendly. Di Luccio et al. (2017) tested retrofitted RC shear walls with the natural fiber of flax. Among natural fibers, flax has potential for use in composite materials due to its high tensile strength properties, but the characteristics can vary due to the type of species, location of cultivation and even the position along the stem from which the fiber is taken. The researchers compared RC wall performance of flax FRP retrofitted walls against walls retrofitted with carbon FRP. The CFRP retrofitted walls were tested and reported by Qazi et al. (2013), which is described later in this paper. The material properties of the CFRP include a Young's modulus of 105 GPa, and an ultimate strength of 820 MPa, while the FFRP had a Young's modulus of 14 GPa and ultimate strength of 120 MPa. The specimens were loaded under constant 90 kN vertical load, and cyclic lateral load that grew 1 mm in amplitude every three cycles until failure. The configuration of each specimen is illustrated in Figure 5. SLR4 CFRP-retrofitted specimen had one layer of bidirectional CFRP, SLR6 specimen had one layer of unidirectional CFRP, and FRSL1-3 flax retrofitted specimens had the number of layers indicated in Table 2. As is shown in Table 2, the FRSL1 specimen, tested with three layers of flax-FRP, showed an increase in strength but not in ultimate displacement compared to the control specimen SL3. The other flax FRP-retrofitted walls (FRSL2 and FRSL3) showed an improvement in both strength and ultimate displacement over the control. Compared to specimens SLR4 and SLR6, ductility was also improved more substantially. These results, detailed in Table 2, shows that flax-FRP may be to be a viable alternative with more studies and advanced knowledge of the materials, including under different environmental conditions.

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