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 No damage prior to FRP		Repair and Retrofit Damage prior to FRP	
No Openings	Subset A Retrofit, no openings	40 %	Subset B Repair, no openings	32 %
Openings	Subset C Retrofit, with openings	12 %	Subset D Repair, with openings	16 %

FRP Application Purpose

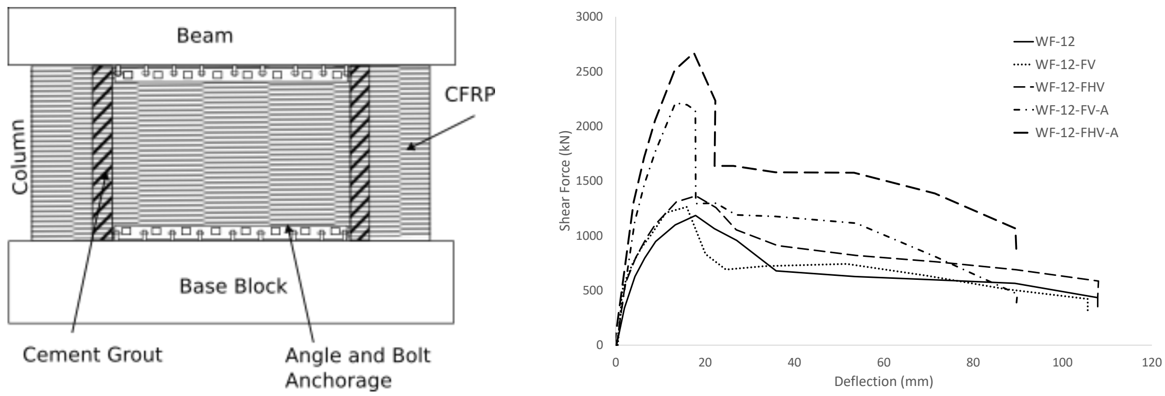
We distinguish walls by the purpose of FRP application during testing. We refer to FRP-retrofitted walls as walls that were tested only once after FRP was applied. This represents the scenario of retrofitting an existing undamaged wall in a building before an event occurs. We refer to FRP-repaired walls 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.

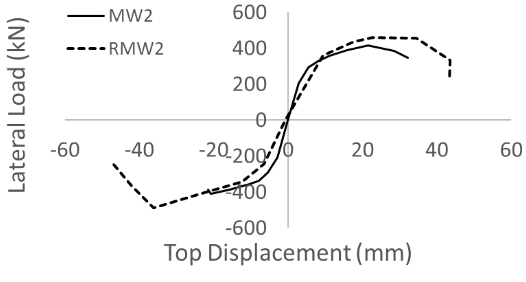


Figure 2: Hysteresis curves of reference wall MW-2 and retrofitted wall RMW-2 (source data from Li and Lim (2010))

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.

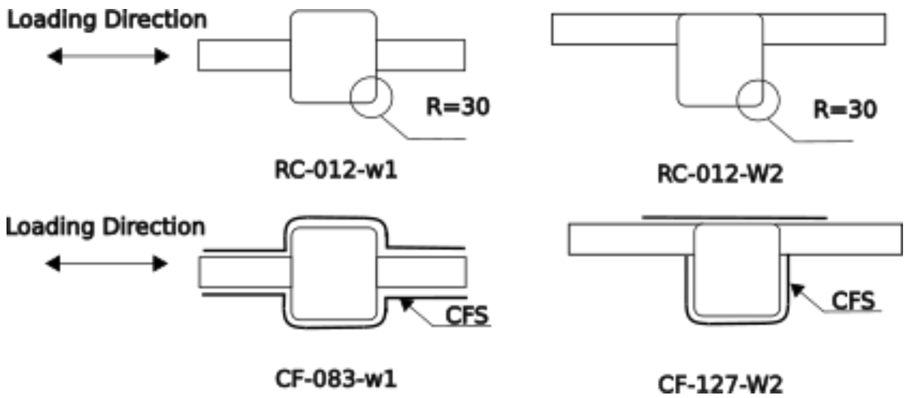
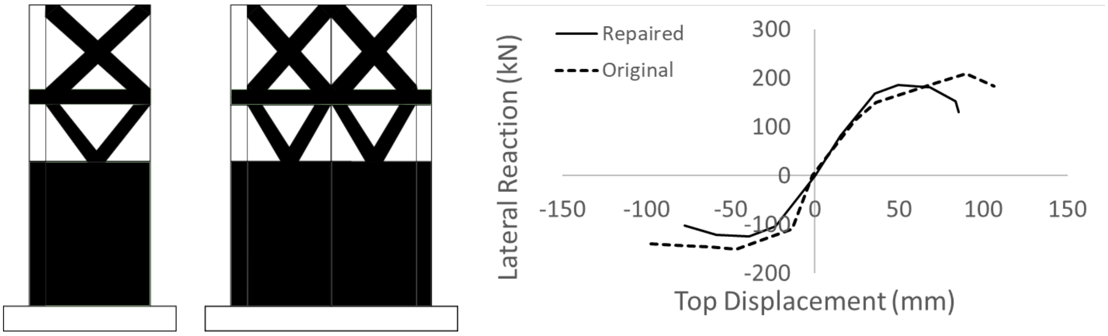


Figure 3: Examples of wing wall specimens tested (adapted from Sonobe et al. (1999))

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.



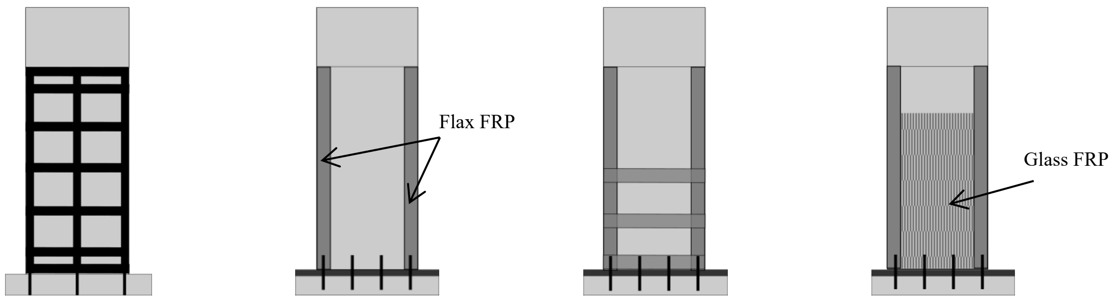
(a) LWR1 FRP repair elevation 1 (b) LWR1 FRP repair elevation 2 (c) Backbone Response Curve

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.



(a) SLR4/SLR6 CFRP retrofitted specimen
(b) FRSL1 flax FRP retrofitted wall
(c) FRSL2 flax FRP retrofitted wall
(c) FRSL3 flax FRP retrofitted wall

Figure 5: Configuration of RC walls retrofitted with composite materials (adapted from Di Luccio et al. (2017))

Table 2: Maximal loads and displacements for each wall specimen (source data from Di Luccio et al. (2017))

			Push Direction			
Specimen	Type FRP	Layers	Max Load (kN)	Percent change	Max Disp. (mm)	Percent change
SL3	None	-	27.75	-	20.56	-
SLR4	Carbon	1	36.01	+ 30	20.52	- 1
SLR6	Carbon	1	47.24	+ 70	14.57	- 30
FRSL1	Flax	3	55.25	+ 99	18.82	- 8
FRSL2	Flax	4	54.00	+ 94	22.92	+ 11
FRSL3	Flax + Glass	2+2	68.5	+ 147	26.86	+ 31

Zhou et al. (2013) tested the capabilities of a new type of polymer matrix retrofit, called CarbonFlex, which is a unique polymeric matrix composite system consisting of amino-based time-dependent reacting compounds. Dhiradhamvit et al. (2011) detail the attributes of the material further. This material was investigated because conventional CFRP materials perform in a brittle manner and have low energy dissipation capability, where CarbonFlex was designed to sustain high strengths under large deformations. The matrix has an internal energy dissipation mechanism, which can redirect the damage path in extreme loading conditions. This results in stabilized crack propagation and ductile mechanical failure. The researchers tested the material on a reinforced concrete wall with a rectangular cross section that was cycled laterally until the wall had reached 40 % of the peak strength. It was then repaired and retrofitted with the CarbonFlex material. The retrofit consisted of CarbonFlex cross-bracing strips placed in the diagonal directions on both sides of the wall, vertical strips along the wall edges, horizontal strips along the top and bottom edges of the wall for anchorage, and a full wrap around the wall with horizontal sheets. Comparison of the as-built wall to the repaired and retrofitted wall shows increased confinement, improved strength on the negative side of the backbone curve, improved ductility, and controlled crack propagation. The backbone curves are shown in Figure 6. More tests are needed to show the potential of this material as a viable alternative to typical CFRP applications.

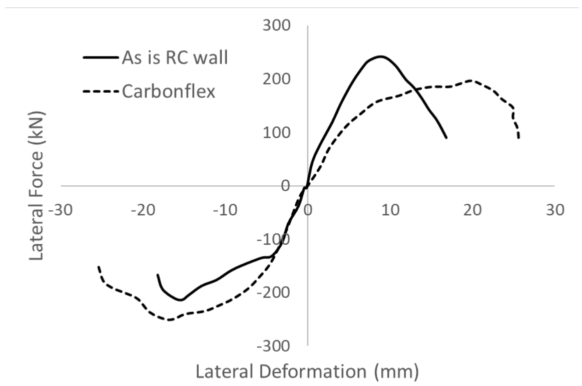
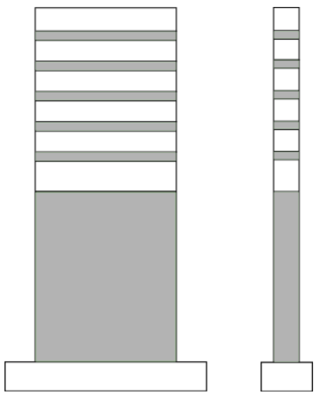


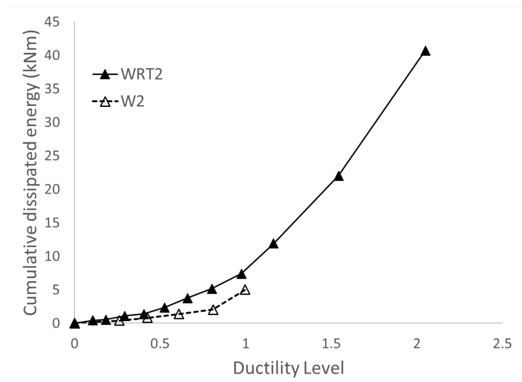
Figure 6: Backbone curve response of as-built wall and a wall retrofitted with CarbonFlex (source data from Zhou et al. (2013))

FRP CONFIGURATION

Fully confined

The majority of the walls in the database were retrofitted on both sides and confined around the corners, either by continuous wrapping, or with C-shaped FRP wraps around the corners. The configuration varied from full coverage on the faces of the walls, to intermittent strips or other type of arrangement of FRP. The most common type of FRP retrofit was the full coverage wrapped around the wall. Antoniades et al. (2003), El-Sokkary and Galal (2013), Ghoborah and Khalil (2004), and Hwang et al. (2004), among others, wrapped the wall specimens covering the entire face with one or more FRP layers. Differences appeared in the number of layers, orientation of the layers, and the use of anchors. Layssi et al. (2012) wrapped wall specimens with one layer of CFRP to cover the plastic hinge zone to prevent premature lap splice failure. Horizontal strips were placed above the plastic hinge zone to the top of the wall, to improve the shear strength. Figure 7 (a) shows the retrofit configuration. The results showed that the addition of the FRP confinement of the lap splice delayed the premature brittle failure of that region. Comparison of the cumulative energy dissipated of the as-built wall and the retrofitted walls (Figure 7 (b)) reveals that the FRP confinement effectively increased the dissipated energy.


(a) Illustration of FRP retrofit scheme



(b) Graph of dissipated energy between the as-built specimen and the retrofitted specimen

Figure 7: FRP retrofit for lap splice confinement of RC wall (source data from Layssi et al. (2012))

Altin et al. (2013) explored the effects of different FRP configuration by varying the arrangement of discrete FRP strips along the full length of the wall. Figure 8 shows the retrofit configuration of each of the tested wall specimens. The purpose of the tests was to understand the influence of shear strengthening for shear deficient wall specimens, under different CFRP configurations. Each retrofit configuration was applied to both sides of the wall, and all strips were anchored using FRP fan anchors at spacings between 270 and 300 mm. Each specimen was cyclically loaded without axial load applied until the specimen lost lateral load carrying capacity. The best performing retrofit scheme was the horizontally placed strips, Specimen 2 in Figure 8 (a) and in the response curve of Figure 9. This specimen reached the highest lateral capacity and the highest lateral drift. The fan anchors also proved to be essential in preventing debonding of the CFRP strips. The researchers concluded that shear strengthening of shear deficient walls using CFRP strips was an effective technique and that FRP configuration is important.

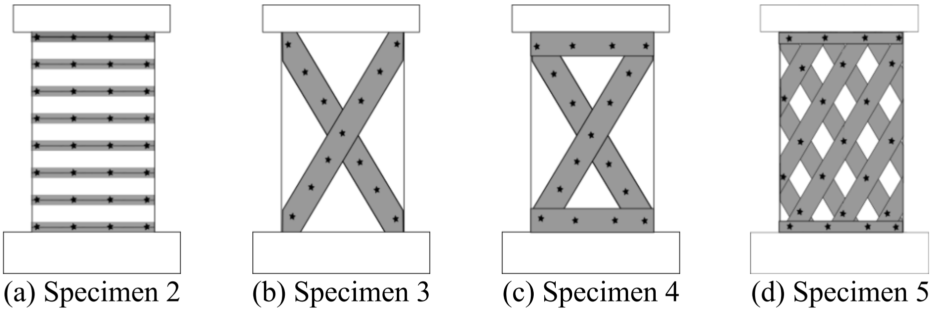


Figure 8: FRP strengthening congifurations of test wall specimens (adapted from Altin et al. (2013))

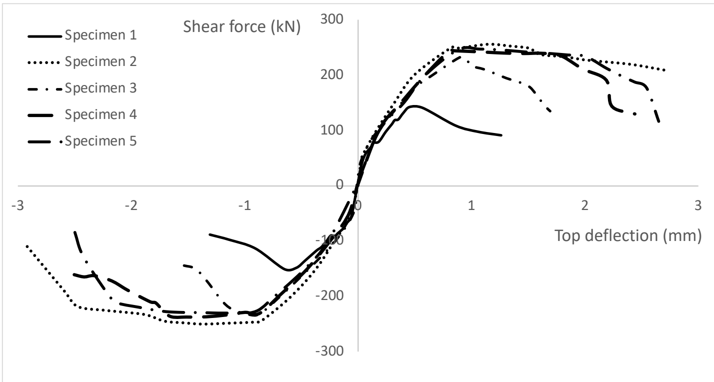


Figure 9: Backbone response envelopes of all specimens (source data from Altin et al. (2013))

Two-sided retrofit

Many of the walls tested were retrofitted on both sides, but without corners confined. Cruz Noguez et al. (2015) retrofitted RC wall specimens on both sides without wrapping the corners to simulate a minimally invasive field application where the edges may not be accessible. They used two types of anchor systems to transfer loads from CFRP to the supporting elements: one system was an off the shelf steel angle and bolt system, while the other system was an innovative mechanical tube system. The tested wall specimens were designed to modern standards as the purpose of the test was to understand the performance of the FRP without influence from insufficient shear strength. Both repaired walls and retrofitted walls were investigated. In comparing the two anchoring system used, it was determined the tube system performed better than the steel angle system, as the tube system maintains structural integrity throughout the loading process. However, both systems helped the FRP retrofit to increase flexural strength of the specimens and regain or increase the stiffness of both repaired and strengthened walls. This is illustrated in Figure 10, which shows the load-deformation response envelope curves of Phase 2 (tube anchor) specimens both repaired and strengthened against the control specimen.

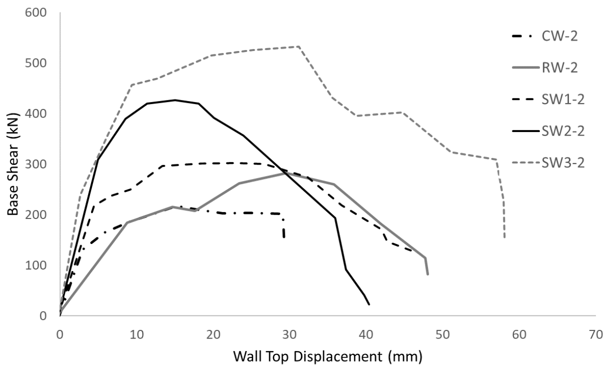


Figure 10: Shear force-deflection response envelope curves for repaired and retrofitted walls (source data from Cruz Noguez et al. (2015))

Another method of strengthening explored by researchers includes retrofitting with strips of FRP instead for full wall coverage. Qazi et al. (2013) investigated the behavior of slender RC walls under-designed in flexure and subsequently retrofitted with FRP. The arrangement of the CFRP included vertical strips along the sides and down the center of each face of the wall and intermittent horizontal strips, as shown in Figure 5 (a). There were FRP fiber anchors embedded in the foundation block to enable load transfer, and anchors embedded in the wall of some specimens to prevent debonding. The variables in the strengthening scheme involved the size of the anchor, including anchors in the wall panel, and the width of the center strip on the wall. The loading protocol for all specimens included lateral cyclic loading, along with constant axial compression loading. Figure 11 shows the backbone curves of the tested specimens. When compared to the reference wall (SL4), the retrofitted specimens displayed improved ultimate load capacity and displacement. SLR3 specimen, which included only anchors at the foundation, displayed the greatest increase in ultimate displacement, while SLR6, which included anchor throughout the wall panel, displayed the greatest increase in ultimate capacity. The researchers noted that the CFRP strips method limited crack propagation but not to the detriment of limiting the ability to dissipate energy effectively.

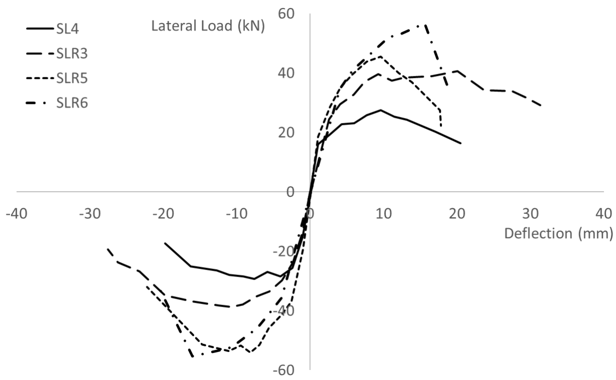
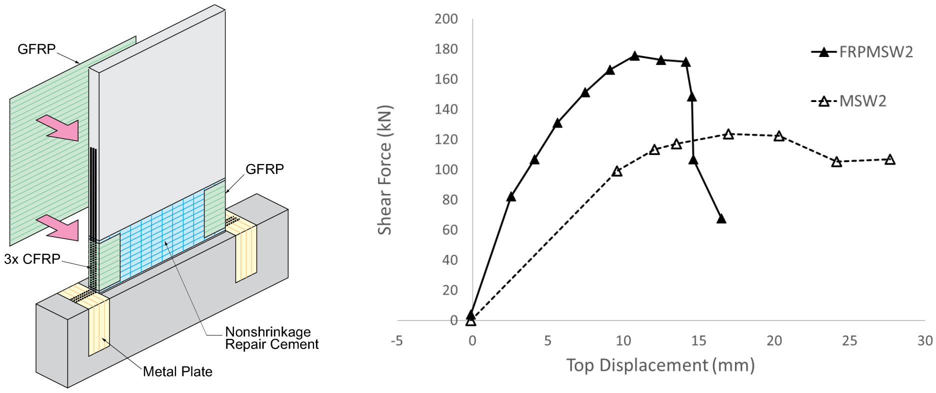


Figure 11: Hysteresis backbone envelope curves for the tested specimens (source data from Qazi et al. (2013))

One-sided retrofit

Of the many wall specimens included in the portion of the database with solid seismically tested FRP repaired walls, only one study included a wall specimen with a one-sided retrofit. Antoniades et al. (2005) tested five specimens with 2-sided application, and only one specimen with a single sided application of FRP. An illustration of the one-sided FRP retrofit is shown in Figure 12 (a). This study researched code-compliant walls tested to failure, repaired conventionally with high strength mortar and lap welding of fractured reinforcement, then wrapped with FRP jackets. The focus of this study was to determine the performance of FRP retrofit on code-complaint walls and the use of a novel type of anchorage for the FRP strips. GFRP was used for the wrapped and one-sided applications, while CFRP was used on the wall edges to increase flexural strength. For this study, the results from the tests of repaired walls were all similar, as the researchers noted that the single sided retrofitted wall and the fully wrapped wall seem to have the same response and failure mode due to the walls failing in flexure rather than shear. They concluded that while shear strength and stiffness could be improved with an FRP-repaired wall, hysteretic behavior and dissipated energy was significantly lower than the original specimens, as shown in Figure 12 (b). They also noted anchorage in critical regions such as the base of the wall is difficult and concluded that the addition of plates or angles can assist in preventing early peeling off of FRP anchorage.



(a) Illustration of FRP retrofit

(b) Backbone curves

Figure 12: Load-displacement curves for the original wall specimen and repaired and strengthened with one-sided FRP (adapted from Antoniades et al. (2005))

CONCLUSIONS

This literature review highlights the experimental studies that have been performed on FRP-retrofitted reinforced concrete shear walls. The research is varied in terms of wall shape, FRP configuration, FRP material, among other variables. However, there remains many areas of interest that may be covered in future research studies, that would be beneficial for researchers and practitioners. Below are observations of research gaps found in studying the database developed on these components, in no particular order of importance.

1. The types of wall shapes present in the database are limited to mainly rectangular and barbell shaped walls. Very few nonrectangular walls (such as L-shaped, C-shaped, and T-shaped walls) retrofitted with FRP have been structurally tested in the lab. Research on more nonrectangular walls would be helpful, if current practice in the field suggests FRP is used to retrofit these types of walls.
2. Very few wall specimens were retrofitted on only one side of the wall, as the majority of walls were retrofitted on both sides of the wall, either with full sheets or strips. This is a major research gap as, often in the field, only one side of the wall is accessible. Research on one-sided wall would greatly increase understanding of the performance of these components.
3. The main material types that were present in the studies are carbon and glass FRP. Very few alternative material types were investigated. Also, glass FRP was usually in combination with carbon FRP when used in experiments. It may be of interest to perform experiments on walls retrofitted with glass only, or with alternative materials to advance the knowledge of performance of new materials.
4. Most of the walls tested included anchors. However, anchor placement and types of anchorage is still a topic of research that needs exploration. Many studies used steel angles at foundations of walls, but there may be a need to investigate more fiber anchors or alternative anchor types for the base and throughout wall panels.
5. None of the walls in the database included weathering or degraded materials. This is important to consider the long-term performance of retrofitted components. In some cases, retrofitted walls are exposed to environmental conditions, so research studying the effects of

weathering or degradation on the retrofitted component (as opposed to just the FRP material) would be useful to understand how these components perform over time.

CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest associated with the work presented in this paper.

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DATA AVAILABILITY
Data on which this paper is based is available from the authors upon reasonable request.

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