17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020
Paper N° C000444 (Abstract ID)
Registration Code: S- A01918

DEVELOPMENT OF A DATABASE OF EXPERIMENTAL TESTS ON FRP RETROFITTED REINFORCED CONCRETE SHEAR WALLS

J. Dukes[(1)], S. Sattar[(2)]

[(1)] *Research Structural Engineer, National Institute of Standards and Technology, jazalyn.dukes@nist.gov*
[(2)] *Research Structural Engineer, National Institute of Standards and Technology, siamak.sattar@nist.gov*

Abstract

Codes and standards developing organizations, such as American Society of Civil Engineers (ASCE) and American Concrete Institute (ACI), rely on experimental data to develop modeling parameters and acceptance criteria to be used in the performance-based seismic design (PBSD) approach. This data is especially important when developing best practices using materials and techniques that are not covered in current PBSD standards, such as the use of fiber reinforced polymers (FRP) for seismic retrofit. Currently, guidance on the design of a retrofit system for reinforced concrete (RC) shear walls with FRP is missing from standards such as ACI 369.1 and ASCE 41. This paper describes the development of a database of FRP retrofitted shear walls that can assist in filling the information gap in the retrofit design guidance of RC shear walls. The main purpose of this database is to aid in the development of modeling parameters and acceptance criteria that standards developing organizations can adapt in order to provide guidance on the design of FRP retrofitted shear walls. The database includes over 200 experimental tests of shear walls from around the world, which can be filtered into categorized bins, like bins of walls with and without openings, or bins based on the premise of the test (i.e., pre-damaged and repaired vs. undamaged and retrofitted). The database will be available through the DesignSafe-CI platform in the near future, in a format that can be easily accessed and utilized by practicing engineers and researchers. This paper will conclude with recommendations for future experimental tests that would fill in the gaps in the data.

Keywords: retrofit; rehabilitation; fiber reinforced polymer; shear walls; database

1. Introduction

Retrofitting of structural components has become an essential technique for engineers and practitioners to reduce the seismic risk associated with existing buildings. The aging of infrastructure and buildings, as well as changing and improved structural codes has led to the need to retrofit many structures, particularly in the United States (U.S.). Retrofitting of reinforced concrete structures and components is increasingly being performed using fiber reinforced polymer (FRP) composites. Application of externally bonded FRP composites onto structures can help repair deteriorated structural components due to degradation or an excessive loading event. Building components can be retrofitted for increased seismic and gravity loads, or to meet current code requirements. Compared with traditional reinforcement materials, FRP composites are light weight and flexible for ease of application, low profile additions to existing structures, and corrosion-resistant. These unique characteristics make FRP composites a desirable retrofit material for existing buildings.

While the benefits of using externally bonded FRP composites to retrofit a structure are known, there is still uncertainty surrounding the initial and long-term performance of these retrofitted components [1-5]. While the use of FRP in structural applications has increased over the past 20 years, entities such as the National Cooperative Highway Research Program (NCHRP) recommend that guidelines, commentary, and examples be developed for design, construction, and maintenance of FRP composites before the material can fully mature and proliferate [6]. One way that engineers and users understand and come to trust the performance of FRP for retrofit of a structure is through experimental testing. There have been many experimental testing programs of FRP retrofitted structural components in the U.S. beginning in the 1980s, including testing of reinforced concrete columns, beams, and beam-column joints [7, 8, 9]. However, experimental research on FRP retrofitted reinforced concrete (RC) shear walls within the U.S. is limited. This lack of available information is concerning, especially as structural walls are continuing to be retrofitted without an equivalent level of knowledge about performance that is available for other components.

This paper describes a database that was developed to fill in the gap of knowledge about available experimental tests that have been performed on FRP-retrofitted reinforced concrete shear walls. There is no other published database that focuses exclusively on FRP-retrofitted reinforced concrete shear walls, to the knowledge of the authors. The database described in this paper details available published research on retrofitted shear walls and compiles them into one location. The database includes over 200 experimental tests of shear walls from around the world, which can be filtered into categorized bins, like bins of walls with and without openings, or bins based on the premise of the test (i.e., pre-damaged and repaired vs. undamaged and retrofitted). This paper details the format and structure of the database, characteristics of the walls studied in the paper, and key research gaps in the database. The intent is to make this database available through the DesignSafe-CI platform [10] in the near future for researchers to use in order to 1) further the understanding of the performance of FRP-retrofitted shear walls, and 2) determine research gaps in the data and develop research programs. Research programs should address gaps in the data that represent the typical walls in existing buildings that are in need of retrofit. Throughout the paper, research gaps and future research needs are noted.

2. Motivation

Several factors motivated the development of this database. First, a workshop held at the National Institute of Standards and Technology (NIST) in 2018 identified the need to understand the extent of experimental testing of FRP-retrofitted structures and components. NIST Special Publication 1244 [11] details the results of the workshop that invited experts and practitioners who use and manufacture FRP materials for design and construction. One of the main concerns identified at the workshop is the lack of large-scale experimental testing of FRP-retrofitted components, and the corresponding lack of understanding of the performance of those structures. From the workshop, as well as a literature review of current research, the idea to focus on

FRP-retrofitted walls was concluded. There is currently no known database that contains all of the information regarding experimental tests performed on FRP-retrofitted walls, so the authors decided to develop the database for future study and for the benefit of the wider community.

Another motivating factor for creating the database is to gather the data needed to enhance current building codes and standards since there are currently no provisions in U.S. design standards such as ACI 369 and ASCE 41 for the design of FRP-retrofitted components. If a designer were designing an FRP-retrofitted wall, for example, there would be no modeling parameters or acceptance criteria that directly relate to that component. The designer may use the backbone curve of an unretrofitted, code-compliant concrete shear wall, but that may not accurately capture the performance of a retrofitted wall. The proposed database will be used to develop modeling parameters and acceptance criteria for inclusion in future iterations of buildings codes and standards. The inclusion of modeling parameters specific to retrofitted components will improve the accuracy of the assessment of the retrofit, and subsequently increase the confidence of the designer in their design of retrofitted components.

3. Database Development

The proposed database contains over 200 reinforced concrete wall tests collected from almost 40 research programs reported in the literature. In the database, each specimen is given a unique specimen identification number (ID) and also retains the specimen name given in the research paper. The digital object identifier (DOI) number that links to the publication from which details about the experimental testing were retrieved is noted in the database, when available. A citation of the paper is also included.

Fig. 1 illustrates the countries of origin of the research programs that are included in the database. Canada has contributed the largest number of research programs of any country to this database. European countries, such as France and Greece, contribute about 30 % of the research programs. Asian countries, such as Singapore and Japan, contribute about 35 % of the research programs. In this database, only 3 of the research programs originate out of institutions based in the U.S. This information suggests that most of the research on the performance on FRP-retrofitted shear walls were on specimens that may not have been designed to the U.S. standards and codes or designed with similar material properties. This is a research gap that should be addressed: to increase the number of experimental tests on FRP-retrofitted shear walls that are designed to prior editions of U.S. codes in order to represent typical shear wall construction in existing structures within the U.S.

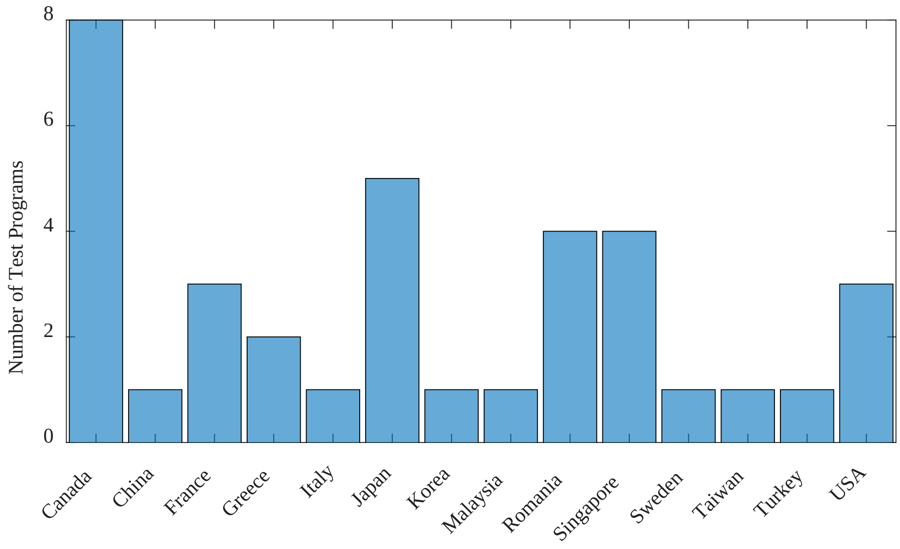

Fig. 1 – Country of origin of all research programs in the database

Experimental research on FRP-retrofitted shear walls began in the late 1990s, according to the research programs included in the database. Approximately ten percent of the papers in the database were published before 2000. About 30 % of papers were published between 2000 and 2009. Almost 60 % of the papers were published in the last decade. This could suggest that interest in determining the performance of FRP-retrofitted walls has been increasing in recent years, and that there may be areas of research yet to be explored.

Wall specimens are categorized in several ways in the database. Two distinctions among the wall specimens were quickly apparent after collecting the information: the presence of openings, and the type of retrofit application. The wall specimens tested in the database either had openings that were built into the wall or created after the solid wall was built, or no openings. The presence of openings in the walls is denoted by a "Y or N" entry, "Y" meaning openings are present, "N" meaning the specimen is a solid wall. The other distinction is related to the presence of damage and repair before the application of the FRP retrofit. For example, many programs built plain (unretrofitted) RC walls, tested them under cyclic loads, repaired then applied FRP and retested the specimen again under a cyclic loading protocol. These specimens are denoted as "Repair" specimens in the database. The other RC walls which were built in the lab and immediately treated with an FRP retrofit without prior testing are denoted as "Retrofit" specimens. The walls that acted as control walls without any FRP retrofit are denoted as "Control". By noting these important distinctions, users of the database can filter out the specimens based on their research needs. Table 1 shows subsets of walls from the database based on these two distinctions. Details about Subsets A and B will be referred to later in this paper, and will also be referred to as Retrofit and Repair subsets, respectively. Subsets A and B represent about half of the total number of specimens in the database and are discussed in more detail in this paper. Details about Subsets C and D are not discussed in this paper.

Table 1 – Subsets of database based on presence of openings and prior damage

Wall Test and Condition	Retrofit No damage prior to FRP		Repair and Retrofit Damage prior to FRP	
No Openings	Subset A Retrofit, no openings	62 specimens	Subset B Repair, no openings	54 specimens
Openings	Subset C Retrofit, with openings	55 Specimens	Subset D Repair, with openings	33 Specimens

4. Characteristics of the walls

4.1 Wall parameters

The data and details stored in the database describe the types of walls that have been tested in the literature. These details include wall parameters such as geometric and material properties, FRP design and material properties, the loading types and testing protocols, and the results from the test including maximum drift ratio and maximum lateral force and the backbone curves. Table 2 shows the ranges of the following wall parameters for the Retrofit and Repair subsets: concrete compressive strength (f'_c), wall aspect ratio (a/l_w), yield strength of the longitudinal steel reinforcement (f_y), horizontal steel reinforcement ratio (ρ_t), longitudinal steel reinforcement ratio (ρ_l), and axial load ratio ($P/A_g{*}f'_c$). Figs. 2 and 3 show four wall characteristics in the form of histograms for Subsets A and B of the database. By viewing the data in this way, gaps in representation of wall or test conditions become apparent, and wall characteristics which have been tested more than others or have not been tested at all can be identified. For example, most of the tested walls in the database were tested without any axial load (i.e., axial load ratio equals zero), and the highest axial load ratio was less than 10 % for most of the tests in Subsets A and B. Knowing this limitation in available data can direct future research programs, as testing FRP-retrofitted walls under higher load ratios could be of interest for researchers or designers. The same analysis can be performed for the wall aspect ratio, longitudinal steel reinforcement ratio, and horizontal steel reinforcement ratio.

Table 2 – Summary of wall parameters for Subsets A and B

Subset	f'_c (MPa)		a/l_w		f_y (MPa)		ρ_t, %		ρ_l, %		$P/(A_g*f'_c)$	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Retrofit (A)	14	45	0.44	3.12	235	500	0.09	0.57	0.16	1.83	0	0.09
Repair (B)	16.6	42	0.85	2.5	320	585	0.25	0.57	0.28	3.0	0	0.2

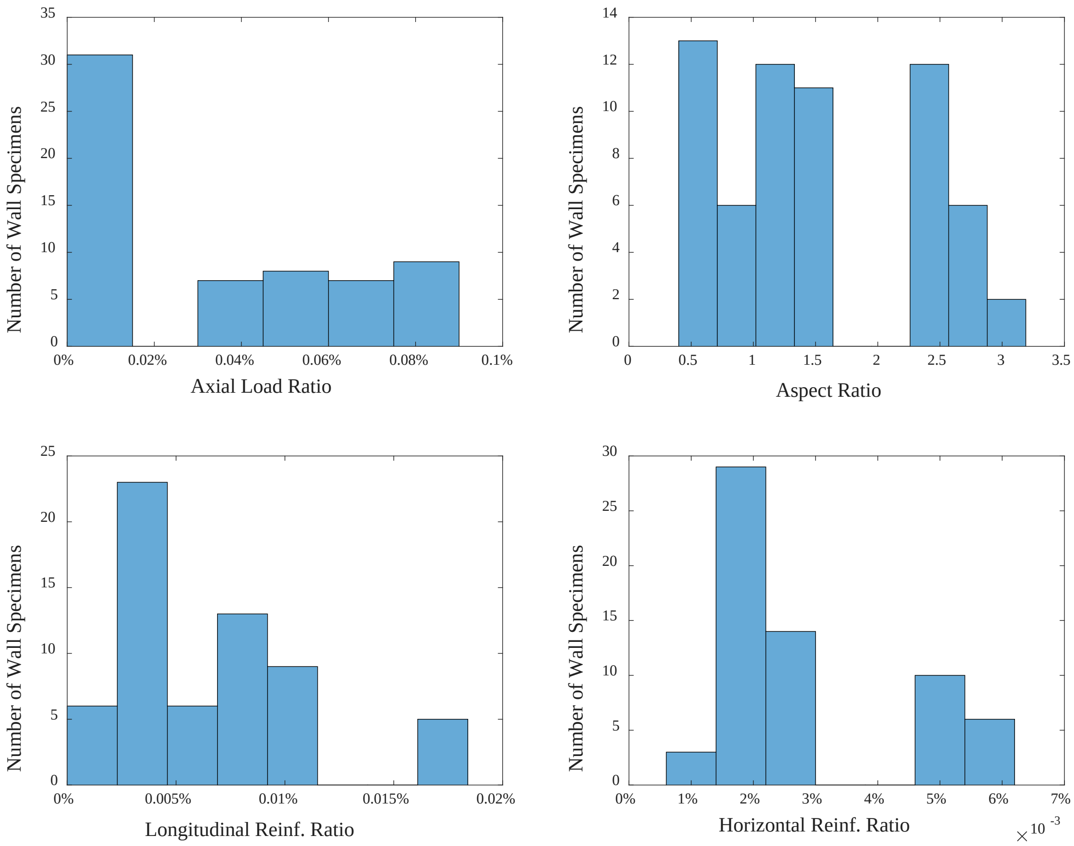

Figure 2 – Histograms of wall parameters of Subset A (Retrofit)

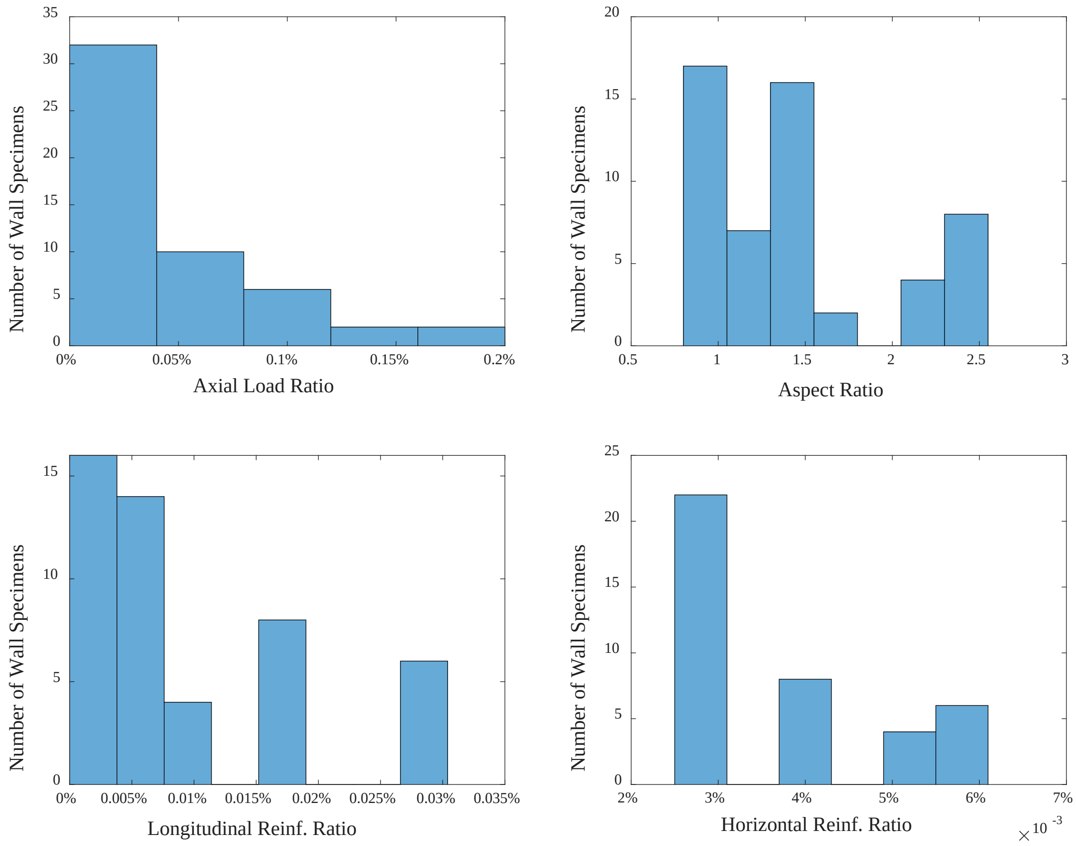

Figure 3 – Histograms of wall parameters of Subset B (Repair)

All of the walls have rectangular cross sections (no L, C or T shaped sections). Most of the walls in the Retrofit subset were loaded with cyclic lateral loading, while a few (~ 12 % of walls) were tested under monotonic lateral loading. All walls in the Repair subset were tested under cyclic lateral loads except for one experimental program that tested walls on a shake table. Less than ten percent of the walls in Subsets A and B were tested to the point of loss of axial load-carrying capacity or significant loss of lateral strength. However, there is value in testing structural components to significant strength loss to observe the behavior of the component as the strength degrades. This information is useful for developing nonlinear models capable of capturing the response of the components in post-peak range of the response. The testing of FRP-retrofitted walls to a state of significant strength loss is an area of research that should be explored. Another area of research to explore is various shapes of walls, including L, C, or T shapes, since these shapes present challenges related to FRP retrofit application as well as a difference in behavior from rectangular walls. This may be a consideration for researchers in the future when creating testing programs.

4.2 Wall design and test objective

The initial wall design of the test specimens in the database varied based on two main objectives found in the test programs featured in the database: shear strengthening or flexural strengthening of the wall. Fig. 4 illustrates the difference in the objective of strengthening that is applied to shear walls. Because FRP is being used as a retrofit technique, it is appropriate that most of the walls were designed to have deficiencies. Several research programs describe their walls to have been designed to older design codes that are now known to have produced walls that perform poorly under seismic loads. Other walls were designed to be shear deficient, or under-reinforced in order to fail in shear. Walls that were designed with built-in deficiencies in shear were then retrofitted with FRP to improve shear strength and ductility of the walls and to determine the effectiveness of the retrofit system. Another group of wall specimens were designed to measure the effectiveness of FRP to enhance the flexural strength of a shear wall. These walls were designed to behave in a ductile manner before the expected shear strength was reached. Still other wall specimens were designed for the FRP to improve both shear and flexural strengthening. This information is important to researchers in determining the past research as well as areas of research that have not been explored in terms of wall design and test objectives.

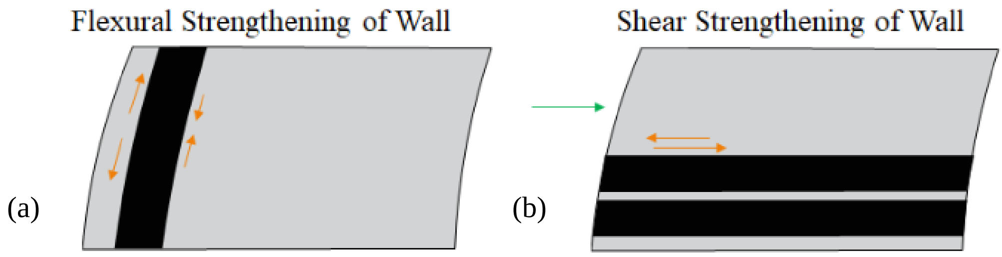

Fig. 4 – Types of FRP strengthening for walls (a) flexural strengthening, and (b) shear strengthening

4.3 FRP retrofit design details

The design of the FRP retrofit varied between test programs, and even between specimens within a test program. No two FRP retrofit designs were the same. Some of the differences between designs include FRP material, number of layers, thickness of the layers, use and spacing of horizontal and vertical laminates, and use of anchors. Fig. 5 shows the types of FRP material used in the walls of subset A and B. Carbon FRP (CFRP) is the most common type of material used, followed by glass FRP (GFRP). Some walls included two or more types of FRP material in the design (designated as "combo"). The focus on CFRP and GFRP in the testing programs are appropriate since these FRP materials are the most common materials used in the U.S. However, if one wanted to determine the performance of a wall retrofitted with FRP material other than carbon or glass, this database does not contain many examples of the performance of alternative materials. This may be a consideration for researchers in the future when creating testing programs.

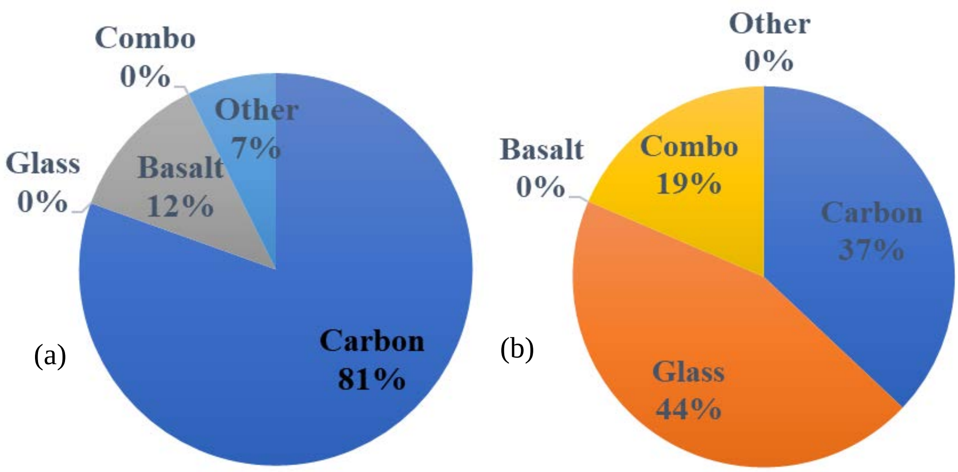

Fig. 5 – Pie chart of FRP material types for (a) Subset A (Retrofit), and (b) Subset B (Repair).

The number of layers and the orientation of FRP layers also varies widely among the tested walls. Walls were either reinforced on one side or both sides. While reinforcing a wall on both sides may provide better confinement and better performance, sometimes it is only practical to retrofit one side of a wall in the field due to limited access to both sides of the wall. Many of the walls included FRP anchors to prevent premature debonding of the FRP from the concrete substrate during testing. FRP anchors are an important part of an FRP retrofit design and are becoming more prominent in the field. However, there are currently no provisions in U.S. design standards on how to design the FRP anchors. Tests that include FRP anchors in the design are helpful for the researchers and practitioners that develop codes and standards to create guidelines related to the FRP anchor design. Fig. 6 illustrates the portion of wall specimens that had FRP anchors and the type of anchors for Subsets A and B.

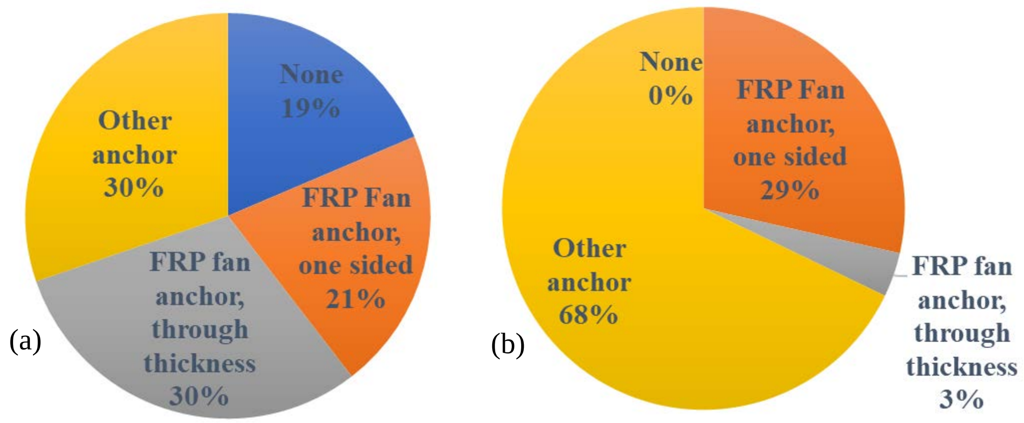

Fig. 6 – Pie chart of FRP anchor types for (a) Subset A (Retrofit), and (b) Subset B (Repair).

5. Conclusion

This study develops a database of experimental tests that have been performed on FRP-retrofitted reinforced concrete shear walls. This database includes all experimental research on FRP-retrofitted walls known to the authors at the point of publication. This database will be published on the DesignSafe-CI platform for future use by researchers to further the understanding of the performance of FRP-retrofitted RC walls. It will also be available for review by researchers who have experimental data to contribute, who can submit their data to the authors for future iterations of the database. In this way, the database will have the most up-to-date collection of experimental data on FRP-retrofitted walls.

This database also helps identify gaps in the existing research, which may lead to future experimental testing programs. One gap that was apparent was the lack of tests that had an axial load ratio above ten percent. About a third of the tested specimens had no axial load applied during testing. Another gap in the database is the lack of tests that tested the specimen to significant lateral strength loss. There is a lot of information to be learned from testing components to collapse or significant lateral strength loss, especially for those interested in capturing the response all the way to reaching the residual strength. It is important to understand the post peak range of the response of FRP retrofitted walls as the wall can potentially experience a brittle mode of failure, i.e., abrupt loss of capacity, when the failure is initiated. Finally, research that investigates the effect of FRP anchors on the performance of the wall specimen is important to practitioners in the field in order to effectively design an FRP retrofit system with anchors. The current standards currently do not provide guidance on the use of anchors for designing the FRP retrofit system for walls. Practitioners need guidance on how to design these anchors, including the spacing, shape, and angle of the anchors in order to achieve the desired performance of retrofitted walls and prevent premature failure/debonding of the FRP retrofit system. A structured research program that systematically varies these parameters on shear walls would be useful in the development of design guidance of FRP anchors.

6. Disclaimer

Commercial software may have been used in the preparation of information contributing to this paper. Identification in this paper is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that such software is necessarily the best available for the purpose. No formal investigation of uncertainty or error is included in this study.

7. References

[1] ACI Committee 440 (2015): 440.9R-15 Guide to accelerated conditioning protocols for durability assessment of internal and external fiber-reinforced polymer FRP reinforcement. *American Concrete Institute*, Farmington Hills, MI.

[2] ACI Committee 440 (2017): 440.2R-17 Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. *American Concrete Institute*, Farmington Hills, MI.

[3] AC125 ICC-ES (2007): Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems. *International Code Council (ICC)-Evaluation Service*, Whittier, CA.

[4] AC434 ICC-ES (2016): Proposed acceptance criteria for masonry and concrete strengthening using fiber-reinforced cementitious matrix (FRCM) composite systems. *International Code Council (ICC)-Evaluation Service*, Whittier, CA.

[5] AASHTO (2012): Guide specifications for design of bonded FRP systems for repair and strengthening of concrete bridge elements. *AASHTO*, Washington, DC, 1st Ed.

[6] O'Connor, J.S. and Frankhauser, W. (2016): Advances in Fiber-Reinforced Polymer Composites in Transportation Infrastructure. *Transportation Research Record: Journal of the Transportation Research Board* (2592):56-64.

[7] Saadatmanesh, H., Ehsani, M.R., and Li, M.-W. (1994): Strength and ductility of concrete columns externally reinforced with fiber composite straps. *ACI Structural Journal* 91(4):434-447.

[8] Pendhari, S.S., Kant, T., and Desai, Y.M. (2008): Application of polymer composites in civil construction: A general review. *Composite Structures* 84(2):114-124.

[9] Alvarez, J.C., Brena, S.F., and Arwade, S.R. (2018): Nonlinear Backbone Modeling of Concrete Columns Retrofitted with Fiber-Reinforced Polymer or Steel Jackets. *ACI Structural Journal*, V. 115, No. 1, January 2018.

[10] Rathje, E., Dawson, C. Padgett, J.E., Pinelli, J.-P., Stanzione, D., Adair, A., Arduino, P., Brandenberg, S.J., Cockerill, T., Dey, C., Esteva, M., Haan, Jr., F.L., Hanlon, M., Kareem, A., Lowes, L., Mock, S., and Mosqueda, G. (2017): DesignSafe: A New Cyberinfrastructure for Natural Hazards Engineering. *ASCE Natural Hazards Review*, doi:10.1061/(ASCE)NH.1527-6996.0000246. https://www.designsafe-ci.org/

[11] Goodwin, D., Sattar, S., Dukes, J., Kim, J.K., Ferraris, C., and Sung, L. (2019): Research Needs Concerning the Performance of Fiber Reinforced (FR) Composite Retrofit Systems for Buildings and Infrastructure. *NIST Special Publication 1244*, December, 2019.