Guidance Emerges for FRP Retrofits of Concrete Diaphragms

ACI Foundation-funded research project has filled knowledge gaps in design practices

by Victoria K. Sicaras, on behalf of the ACI Foundation

When it comes to rehabilitating older reinforced concrete buildings, engineers often encounter a lack of consensus around design recommendations for strengthening deficient force-resisting systems. Specifically, the limited data regarding the use of fiber-reinforced polymer (FRP) to strengthen concrete floor diaphragms has created uncertainty about which approaches are appropriate. New research funded by the ACI Foundation fills this critical knowledge gap.

The 2-year research project, "Development of FRP Retrofit Guidelines for Deficient Reinforced Concrete Horizontal Lateral Force Resisting Systems,"[1] developed and tested retrofit techniques for diaphragms using externally bonded FRP. The resulting design recommendations are expected to be included in the next revision of ACI PRC-440.2-23, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures."[2] Currently, FRP retrofits for diaphragms are outside the scope of ACI PRC-440.2 and other FRP-related design documents.

Key findings from the research are being translated into guidance on how to establish the effective FRP design strain and the nominal shear strength contribution of the FRP. The recommendations also address the use of intermediate and end FRP anchors, limitations on the clear spacing between sheets, and other factors pertinent to retrofit design.

"The developed design guidelines will enable the confident reuse and repurposing of existing buildings to meet evolving occupant and societal needs—all while ensuring their structural resilience and safety," said ACI Foundation Executive Director Ann Masek. "The ACI Foundation was pleased to support this research, which promises far-reaching impacts."

The Need for Experimental Testing

Externally bonded FRP as a retrofit technique involves using epoxy to adhere sheets of glass or carbon fabric to the concrete surface. These sheets provide additional tension reinforcement to the structure, which improves strength and performance. Strengthening reinforced concrete diaphragms may be necessary to:

- Enhance seismic performance;
- Address inadequate strength or stiffness;
- Provide missing or incomplete load paths;
- Improve inadequate shear transfer/connection capacity; and
- Accommodate changes in the use and occupancy of the structure.

FRP is a proven construction technology that is widely used for mitigating earthquake vulnerabilities and corrosion-related issues in slabs, moment frames, and shear walls. Yet, there is not enough information on the use of FRP to address horizontal lateral force-resisting system (hLFRS) deficiencies related to inadequate chords, collectors, and in-plane shear capacity to be included in design documents.

"Engineers and manufacturers are doing a fair amount of work retrofitting diaphragms with FRP, but there have been virtually no tests and very little numerical data—or even code provisions—informing them how to best apply externally bonded FRP to diaphragms," explained Eric Jacques, Principal Investigator of the research project.

Consequently, designers must rely on experimental tests of FRP-strengthened shear walls to justify strengthening applications for an hLFRS. "But without documented knowledge on how a concrete floor diaphragm will behave, and its stress state at various sizes and scales, designs end up being very conservative," Jacques said. An overly conservative approach can lead to costly and wasteful overdesigns. On the other hand, a design that is not conservative enough can lead to risk, liability, and the highest cost—loss of life.

"Proven methods with the data to back them up lowers risk and raises confidence in design decisions," Jacques said.

Project Details

Name: Development of FRP Retrofit Guidelines for Deficient Reinforced Concrete Horizontal Lateral Force Resisting Systems.
Principal Investigator*:* Eric Jacques, Assistant Professor of civil and environmental engineering, Virginia Tech.
Co-Principal Investigator: Matthew R. Eatherton, Professor of civil and environmental engineering, Virginia Tech.
Graduate Research Assistants: Pratiksha Dhakal and Hunter G. Hutton.
ACI Technical Committee Endorsement: 440, Fiber-Reinforced Polymer Reinforcement.
Funder: ACI Foundation.
Industry Partners: Simpson Strong-Tie, Structural Technologies, Fyfe, GeoTree Solutions; in-kind funding partner: Banker Steel.
Advisory Panel: Tarek Alkhrdaji, Scott Arnold, Aniket Borwankar, Enrique del Rey Castillo, Kent Harries, John Hepfinger, John Hooper, and Ravi Kanitkar.
Specimen Construction Assistance: Garrett Blankenship, Brett Farmer, and David Mokarem.
Test Assistance: Ray Bodnar, Thomas Bracy, Quinton Moyer, and Grace Whitesell.
About the Research: The objective was to develop design guidelines for strengthening deficient horizontal lateral force-resisting systems (hLFRS) in older reinforced concrete buildings using externally bonded FRP design. To do this, the researchers developed retrofit design approaches that included both conventional and innovative solutions. They conducted a series of large-scale experiments to investigate the behavior, optimal arrangement, and anchorage of FRP in strengthening deficient reinforced concrete diaphragm zones carrying primarily shear.

The test results were used to develop design recommendations for shear strengthening existing concrete diaphragms using externally bonded FRP. These recommendations included guidance on how to establish the effective FRP design strain and the nominal shear strength contribution of the FRP. They also address the use of intermediate and end FRP anchors, limitations on the clear spacing between sheets, and other factors pertinent to retrofit design.

The project contributes to increased infrastructure sustainability by:

- Facilitating reuse and reconfiguration of existing buildings to satisfy changing occupant needs.
- Mitigating structural deficiencies to produce resilient behavior during natural hazards.

The study also revealed the need for more accurate design recommendations, as existing ones tended to underestimate the actual behavior observed during experiments.

Getting Funded

Jacques is an Assistant Professor in the Charles E. Via, Jr. Department of Civil and Environmental Engineering at Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, USA. His research activities are focused on the analysis, design, and retrofit of reinforced concrete structures as well as blast protection and energetic materials. Matthew Eatherton, a Professor and faculty Fellow in the same department, serves as the project's co-Principal Investigator.

Through discussions with an FRP supplier at an ACI Concrete Convention, Jacques realized the scarcity of relevant data. He and Eatherton began reaching out to manufacturers, engineering firms, and other industry professionals to gauge interest in supporting a program to develop experimentally validated design methods. They found financial and in-kind funding partners in Simpson Strong-Tie, Structural Technologies, Fyfe Co., GeoTree Solutions, and Banker Steel.

"Our industry partners were more than just a funding source," Jacques said. "They contributed their expertise and technical support, as well. Plus, we had an advisory panel that included academics and engineering consultants. Their feedback and advice were essential to ensuring the relevance and impact of our work in meeting industry needs."

Jacques and Eatherton also found a champion for the project in the ACI Foundation's Concrete Research Council (CRC). The ACI Foundation's mission is to make strategic investments in ideas, research, and people to create the future of the concrete industry. As part of that mission, CRC offers an annual request for proposal (RFP) program that awards funding to several concrete research projects.

The open RFP program allows researchers to submit unsolicited research projects. The funding is awarded based on relevancy and potential impact of the research, overall proposal quality, researcher capability, supplemental support for the project (that is, collaboration with other funders and organizations), and ACI Technical Committee engagement. Jacques and Eatherton's project had commitments from industry partners and an endorsement by ACI Committee 440, Fiber-Reinforced Polymer Reinforcement. Their proposal was selected to receive funding in 2021.

As part of the program, the ACI Foundation strives to award at least two grants annually to projects led by an associate or assistant professor, like Jacques, or other type of early career faculty to support their work and research goals. The grants limit funding of indirect costs to 15% to ensure the funds are directed to the people (in the form of stipends and salaries) and activities involved in a project and not the organization's overhead. This gives graduate students an opportunity to participate in important concrete research to help them develop and apply critical technical and professional development skills. The research opportunity on this project was timely for one of the research graduate students involved: Hunter Hutton, the 2022-2023 ACI Foundation Robert F. Mast Memorial Fellowship awardee (refer to sidebar on p. 60).

Members of the Virginia Tech research team include (from left): Principal Investigator Eric Jacques, Co-Principal Investigator Matthew Eatherton, and Graduate Research Assistants Pratiksha Dhakal and Hunter Hutton

Large-scale tests demonstrated that externally bonded FRP retrofitting significantly improved both the shear strength and stiffness of deficient reinforced concrete diaphragms

"Being awarded the funding and having an ACI Foundation fellowship awardee on the project was a happy coincidence, and Hunter played a huge role in the research. We are grateful to the ACI Foundation and the ACI members who recognized the importance of this project—the need for it—and worked with us to make it a reality," Jacques said.

Laying the Groundwork

"Investigating the behavior of diaphragms, both with and without FRP strengthening, poses significant challenges," Jacques said. "To accurately understand their behavior, they need to be tested at scales approaching their real-world application."

The researchers kicked off the project by conducting a workshop with their industry partners and advisory panel to better understand the state of the practice and the knowledge gaps to address. Throughout the project, the team met regularly with the advisory panel to share updates and receive guidance and recommendations.

Fortified by insights from the workshop, the team created large-scale specimens and a total of eight tests to investigate the behavior, optimal arrangement, and anchorage of FRP in strengthening deficient reinforced concrete diaphragm zones carrying primarily shear. The tests included a baseline unretrofitted concrete specimen and five retrofitted specimens with different configurations of externally bonded FRP. Each retrofitted specimen was designed to maintain a similar FRP axial stiffness while varying the FRP retrofit parameters.

Jacques credited graduate research students Pratiksha Dhakal and Hunter Hutton for executing the work that was conceived. While Dhakal, a doctoral student, focused on numerical modeling, Hutton performed laboratory testing.

As the lead student on the ACI Foundation-funded project, Hutton conducted a comprehensive literature review, designed and constructed the specimens, and analyzed the results of the retrofitted tests. The test setup featured a unique configuration involving two specimens joined by a reusable steel frame, where one specimen was integrated into the setup for the other. The arrangement allowed for the simultaneous construction and rapid testing of two large-scale specimens, significantly accelerating the pace of the research in an otherwise slow process that relies on placed concrete to harden.

"He really laid the groundwork for how these tests should be conducted," Jacques said.

Meanwhile, Dhakal carried out a finite element analysis of the experimental configuration to validate Hutton's design calculations and predict the shear behavior of the strengthened diaphragms. Both students analyzed the results and applied equations and theory to make sense of it all while diligently documenting their work. They maintained open communication with the Advisory Panel, sharing the team's most recent findings and coordinating upcoming tests.

Project Outcomes

"We demonstrated that FRP retrofits are effective for addressing structural deficiencies in reinforced concrete diaphragms and increasing shear strength," Jacques said. "We also developed an experimental test method to assess various FRP retrofit arrangements and their design variables on the shear behavior of diaphragms."

The team's accomplishments include developing a calculation procedure to predict the shear strength of diaphragms with FRP. The calculations were benchmarked against the experiments to determine their accuracy.

Engineers designing FRP retrofits for diaphragms face uncertainties regarding the proportioning and detailing of strengthening schemes. Another challenge is confidently calculating the strength enhancement offered by these externally bonded composites. The research team found the retrofitted specimens' overall performance was significantly affected by the proportioning and detailing of FRP retrofit schemes. FRP applied parallel to the shear direction enhanced diaphragm strength most effectively, while perpendicular application improved ductility.

The shear strength contribution of externally bonded FRP was also greatly influenced by the extent of retrofit surface coverage, showing that spreading less dense fabric more uniformly over the surface offered better shear crack control than narrow, high-density fabric strips. Moreover, no substantial performance differences were noted between diaphragms strengthened with glass or carbon FRP composites when retrofits were similarly proportioned, indicating either type of composite fabric may be used.

"The test results underscored the importance of adding mechanical anchorage to supplement the epoxy's chemical bond that secures the FRP to the concrete surface," Jacques said. "The major failure mode is debonding of the FRP from the concrete surface. While the anchorage doesn't enhance strength, it plays a crucial role in arresting and delaying the onset of debonding, if it occurs."

Lasting Impacts

The ACI Foundation-funded portion of the research project concluded in July 2023, having produced a wealth of information that can be distilled into design documents and shared at conferences. The team is currently collaborating with ACI Subcommittee 440-F, FRP-Repair-Strengthening, to add diaphragm shear strengthening provisions in the next revision cycle of ACI PRC-440.2. Advisory Panel members are incorporating the recommendations into their work.

The research also attracted attention and funding from the National Science Foundation (NSF). The NSF-funded component explores the use of topology optimization to develop patterns of non-orthogonal FRP diaphragm strengthening.

"While the ACI Foundation was interested in generating design provisions and guidance for the safe, efficient use of these materials, the NSF is interested in understanding the science behind the strengthening technique," Jacques said.

Dhakal is performing the deep-dive theoretical portion. She is exploring how to optimize FRP to strengthen diaphragms, particularly with respect to how it is oriented on the diaphragm. She is also investigating how the retrofit of the

Meet Hunter Hutton

ACI Foundation's 2022-2023 Robert F. Mast Memorial Fellowship recipient

Hunter Hutton

Investing in people is a critical component of the ACI Foundation's mission. When the Foundation staff learned one of their fellowship recipients was also a student lead in a Foundation-funded concrete research project, "we were thrilled," said Ann Masek, ACI Foundation Executive Director.

Hunter Hutton was awarded the Robert F. Mast Memorial Fellowship for 2022-2023. ACI Foundation student fellowships are offered to high-potential students in concrete-related studies who are endorsed by an ACI member. At the time, Hutton was a graduate student at Virginia Tech, where he was studying structural engineering. The cash award that comes with the fellowship aided Hutton in completing his graduate research.

"It was an honor to receive the fellowship," Hutton said. "It helped lift financial burdens from my shoulders while also providing incredible networking opportunities where I received guidance from fellow concrete enthusiasts and structural engineers. I aim to inspire future engineers by designing innovative structural solutions in practice and translating my knowledge to the classroom as an adjunct professor later in life."

Hutton completed his master's research under the direction of Assistant Professor Eric Jacques. When Jacques became principal investigator for the research project, "Development of FRP Retrofit Guidelines for Deficient Reinforced Concrete Lateral Force Resisting Systems," Hutton earned a spot as one of the project's first two graduate research assistants. Graduate students participating in such roles enhance their experience while pursuing a degree.

"I was very fortunate to have the opportunity to work as a graduate research assistant while at Virginia Tech and lead an ACI and industry co-funded project focused on retrofitting shear deficient reinforced concrete diaphragms with FRP laminates," Hutton said. "This position allowed me to pursue my master's degree, in which I vastly expanded my knowledge of structural engineering."

Hutton now works as a structural engineer at McSweeney Engineers in South Carolina, USA. Since he graduated from Virginia Tech, other graduate students have joined the research project.

"Having excellent students like Hunter involved is instrumental to the project's success and continued momentum," Jacques said.

The purpose of ACI Foundation's Student Fellowship Program is to identify, attract, and develop outstanding professionals for productive careers in the concrete field. All donations made to the ACI Foundation go directly to students, research, and innovation. Learn more at **www.acifoundation.org/scholarships.aspx**.

floor impacts the global structural response.

As for practical testing, more tests are being conducted based on requests from the industry. For example, because there are currently no code requirements for the FRP retrofits, building officials typically require a test report with in-depth analysis to demonstrate the design will work.

"Companies approach us to test unique aspects of their diaphragm shear retrofit designs and provide a test report along with calculations and analysis," Jacques said. "Lately, they're coming to us with scenarios we hadn't considered, like retrofits that employ more FRP than what code normally allows or diaphragms made with subpar materials or lightweight concrete. We've conducted 10 such tests so far, and our lab is scheduled to continue these tests for the next year and a half."

Supporting the Future of the Concrete Industry

The FRP retrofit for diaphragm guidelines project highlights the importance of funding initiatives like those provided by the ACI Foundation's CRC. Such projects not only support early-career researchers and graduate students but also drive advancements in technology, materials, and building methods to ultimately shape a more sustainable future for the concrete industry. Through collaborative research efforts and funding support, the concrete construction industry can continue to innovate and adapt to meet evolving needs while upholding the highest standards of safety and sustainability.

"Ultimately, the public stands to gain the most from this research," Jacques added. "As engineers, we have a duty to ensure the safety of the public, communities, and the environment. As good stewards of the built environment, we aim to enhance its safety and resilience while reducing construction waste sent to landfills by avoiding unnecessary demolitions and rebuilds."

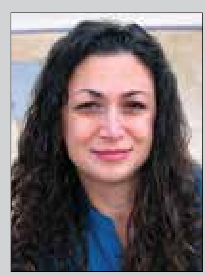
The ACI Foundation continues to fund the people, research, and innovations that provide needed solutions. Organizations can aid the Foundation's efforts and support concrete-related research and technology advancements by contributing their expertise, experience, and donations. For more information, visit **www.acifoundation.org/giving**.

References

1. Hutton, H.G.; Dhakal, P.; Eatherton, M.R.; and Jacques, E., "Development of FRP Retrofit Guidelines for Deficient Reinforced Concrete Horizontal Lateral Force Resisting Systems," Virginia Tech Research Report No. CE/VPI-ST-23/07, Blacksburg, VA, July 2023, 200 pp., https://www.acifoundation.org/Portals/12/xBlog/uploads/2023/8/24/VirginiaTechCE-VPI-ST-23-07FRPRetrofitofDeficientReinforcedConcreteHorizontalLateralForceResistingSystems.pdf.

2. ACI Committee 440, "Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide (ACI PRC-440.2-23)," American Concrete Institute, Farmington Hills, MI, 2023, 109 pp.

Selected for reader interest by the editors.



Victoria (Vikki) K. Sicaras is an Account Manager with Advancing Organizational Excellence (AOE), an ACI subsidiary that provides marketing and association management consulting services. She has more than 20 years of experience writing and editing for leading construction industry publishers, with a focus on concrete construction.