EXPLORING THE COMBINED USE OF DISTRIBUTED FIBER AND DEFORMED BAR REINFORCEMENT TO RESIST SHEAR FORCES

Quarterly Progress Report
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1. Background and Introduction

Macro-synthetic fibers are often added to concrete mixtures as secondary reinforcement, designed to control shrinkage and temperature cracks and improve the durability of bridge superstructures. The addition of fibers to concrete improves the tensile behavior of the material, which leads to more durable concrete elements with increased ductility and better crack control. In addition to these desirable effects, the tensile strength of the fibers also contributes to the strength of the member, however this benefit is not included in current bridge design specifications [e.g., AASHTO 2020]. The lack of provisions regarding the use of macro-synthetic fibers as supplemental reinforcement is of detriment to the bridge construction industry because the use of fibers in PBEs and cast-in-place connections would result in a reduction of bar reinforcement and congestion, lighter members, smaller crack sizes, better distribution of localized stresses, and increased confinement and performance of member ends.

Developments in PFRCs are applicable to accelerated bridge construction (ABC) in two ways. The use of PFRC would permit thinner prefabricated bridge element (PBE) sections, enabling lighter members for transportation and erection. The great majority of ABC is conducted using PBEs, so any activity that benefits PBEs will encourage the use of them, and by direct implication, ABC. For prestressed girders, the use of PFRC could ameliorate the impacts of thinner girder webs by providing additional web-shear cracking strength, by arresting flexural cracks prior to their development into flexure-shear cracks, and by preventing splitting that would be exacerbated by the reduction in web width, as demonstrated in previous test series of girder end regions [e.g., Haroon et al. 2006]. The improved serviceability and durability of prestressed girders made from FRC would also create an additional incentive for owners to choose ABC techniques over other alternatives. Finally, the use of field-cast PFRC in ABC projects in connection regions would be beneficial by expediting on-site activities, alleviating congestion in connection regions and reducing the required deformed bar reinforcement.

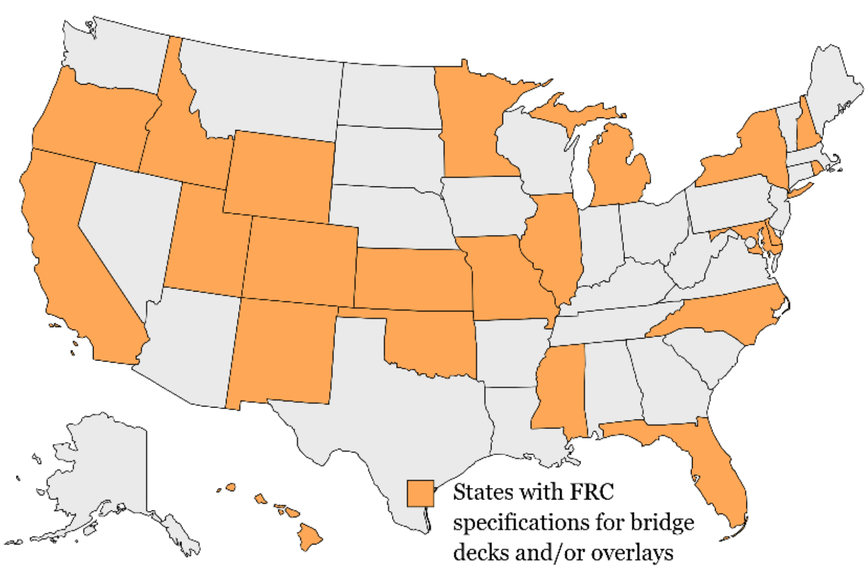


Fig. 1. States with FRC specifications for bridge decks and/or overlays, data from [Amirkhanian and Roesler 2019]

2. Problem Statement

Fiber-reinforced concrete already enjoys widespread use in practice, as shown in Fig. 1, and is required in several states (e.g., California, Oregon, and Delaware) for bridge decks [Amirkhanian and Roesler 2019]. The remaining bridge elements (e.g., prestressed girders) could similarly benefit from the improved strength and durability that FRC provides. To realize the full benefits of PFRC in practice, rational design equations are needed to predict the strength of members containing both macro-synthetic fibers and deformed bar reinforcement, particularly in shear. This research project will result in design guidelines for the combined use of distributed fiber and deformed bar reinforcement to resist shear forces, implementable in future bridge specifications.

3. Objectives and Research Approach

The objective of the proposed research is the development of simple, rational design equations for the contribution of macro-synthetic fibers to the shear strength of reinforced concrete members containing at least the minimum shear reinforcement required by the *AASHTO LRFD Bridge Design Specifications* [AASHTO 2020]. The design equations will be based on a rational shear behavior model that will be developed as part of this work using the response of PFRC panel elements, subjected to in-plane loads (e.g., shear and axial tension or compression). The PI's are uniquely positioned to develop a shear behavior model for PFRC members due to the experimental capabilities available at the University of Washington's (UW) Large-Scale Structural Engineering Testing Laboratory (SETL) and the ability to generate uniform shear stress states using the UW SETL Panel Element Tester. A similar experimental apparatus was used to develop the Modified Compression Field Theory [Vecchio and Collins 1986], which is the basis for the current shear provisions in the *AASHTO LRFD Bridge Design Specifications*. Thus, the experimental data collected will be uniquely suitable for developing the proposed design equations.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature Review

This task is complete. The objective of this task is to establish a database to be used to evaluate the design expression developed in Task 3. An extensive review of past experimental research involving polyolefin fiber-reinforced concrete was completed, focusing on specimens that utilized both deformed bar and fiber reinforcement to resist shear forces. The collected data was summarized in the Dec 2022 Progress Report.

Task 2 – Panel testing program

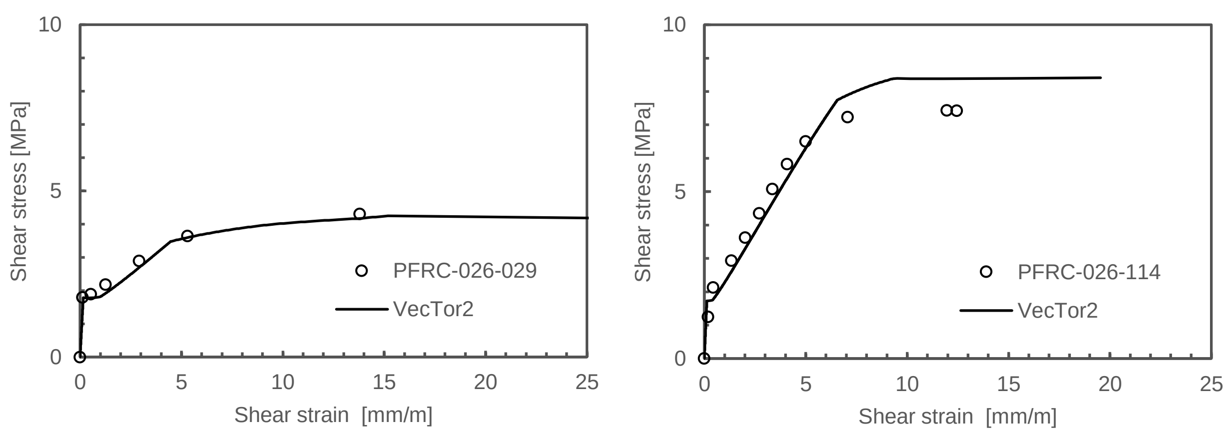
This task is complete. The objective of this task is to elucidate the contributions and benefits of the separate and combined used of deformed bar and macro-synthetic fiber reinforcement. Previous tests of PFRC members did not include deformed bar reinforcement or included only a single deformed bar reinforcement configuration ($\rho_v \approx 0.15\%$ for both test series). This is one of the first experimental programs to specifically investigate the interaction between macro-synthetic fibers (STRUX 90/40) and deformed bar reinforcement in resisting shear forces and provides valuable data that is needed to build a shear behavior model in Task 3. The results of the experimental tests was summarized in the Jun 2023 Progress Report.

Task 3 – Development of design recommendations

This task is ongoing. The results of the panel tests in Task 2, will be used to develop design recommendations that capture the potential beneficial interaction between deformed bar and distributed fiber reinforcement. These recommendations will be based on a rational shear behavior model developed for PFRC based on the interactions measured during the experimental testing program (Task 2).

The measured response of the panel and beam specimens collected from Task 1 and Task 2 were compared to predictions obtained using the Vector2 finite element software [Wong et al. 2013]. VecTor2 utilizes the Modified Compression Field Theory (MCFT) [Vecchio and Collins 1986], which was specifically formulated to simulate cracked reinforced concrete elements subjected to in-plane loads and is the basis for the current shear provisions in the *AASHTO LRFD Bridge Design Specifications* [AASHTO 2020]. Each element consists of cracked concrete and smeared in-plane steel reinforcement and is governed by compatibility and equilibrium equations derived from first principles and constitutive models derived from a series of reinforced concrete panel element tests [Vecchio and Collins 1986] similar to those performed in this study.

Fig. 2 shows comparisons between the calibrated VecTor2 predictions and the measured response of four of the panel specimens from Task 2. The Task 2 specimens were used to calibrate constitutive models for the concrete and steel reinforcement and determine the most appropriate modeling assumptions (e.g., neglecting crack slip). This modeling approach will be used to conduct a larger parametric investigation that will explore levels of the study parameters (fiber volume and transverse reinforcement ratio) that were not tested experimentally. The results of the parametric study will be used to assess current empirical relationships for the shear strength of PFRC members and develop new expressions, or modifications, as necessary. The modeling task is ongoing and further information will be presented in future progress reports.



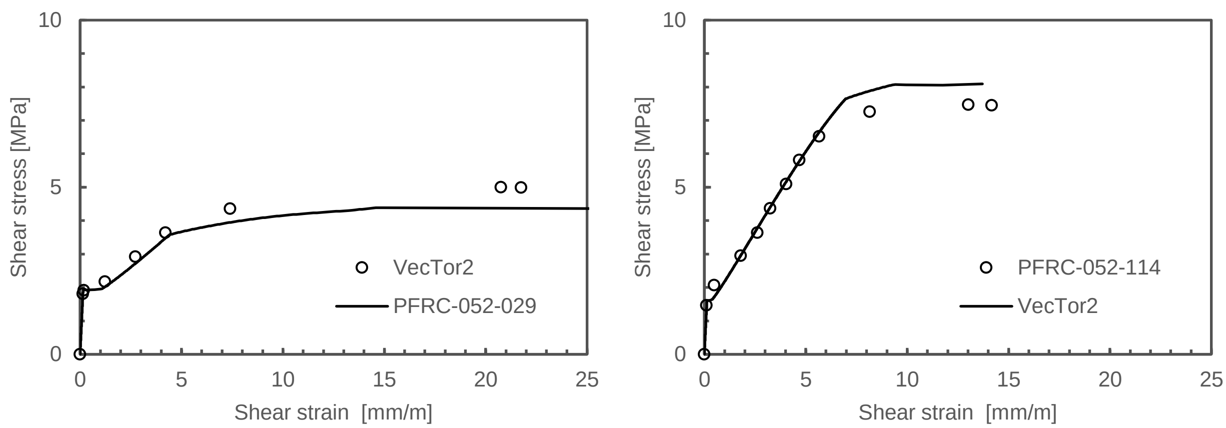


Fig. 2. Measured shear stress-shear strain response and calibrated VecTor2 estimates

Task 4 – Interim and Final Reporting

This task in ongoing. The research team will submit timely quarterly reports, present annually at the Research Days meeting, and complete a final report summarizing findings reached during the project.

5. Expected Results and Specific Deliverables

The successful completion of the research project will directly impact the design/construction industry, by providing guidelines for the combined use of distributed fibers and deformed bars to resist shear in field-cast and precast reinforced concrete bridge elements and connections, quantifying the potentially beneficial interaction between the two types of reinforcement.

The expected products resulting from this research will include:

- Database of structural tests of fiber reinforced concrete elements that also contained deformed bars for shear reinforcement,
- Recommended guidelines for the sectional shear strength of PFRC elements with at least the minimum deformed bar shear reinforcement, and
- Design example that demonstrates new design equations.

In addition, the results of the project will be summarized in a 5-min demonstration video and a journal publication.

6. Schedule

Progress on tasks in this project is shown in the tables below.

Item	% Completed
Percentage of Completion of this project to Date	85%

Research Tasks	2022							2023												2024		
	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Task 1 – Literature Review																						
Task 2 – Panel Testing Program																						
Task 3 – Development of Design Recommendations																						
Task 4 – Interim and Final Reporting																						

7. References

AASHTO (2020) *AASHTO LRFD Bridge Design Specifications (9th Edition)*. American Association of State Highway and Transportation Officials (AASHTO), Washington, DC.

Amirkhanian, A. and Roesler, J. (2019) "Overview of Fiber-Reinforced Concrete Bridge Decks." InTrans Report 15-532, Iowa State University, Ames, IA

Vecchio, F.J. and Collins, M.P. (1986) "The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear." ACI J, 83 (2): 219–231.

Wong, P.S., Vecchio, F.J., and Trommels, H. (2013) "VecTor2 & FormWorks User's Manual (2nd Ed.)." VecTor Analysis Group, Toronto, ON.