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.

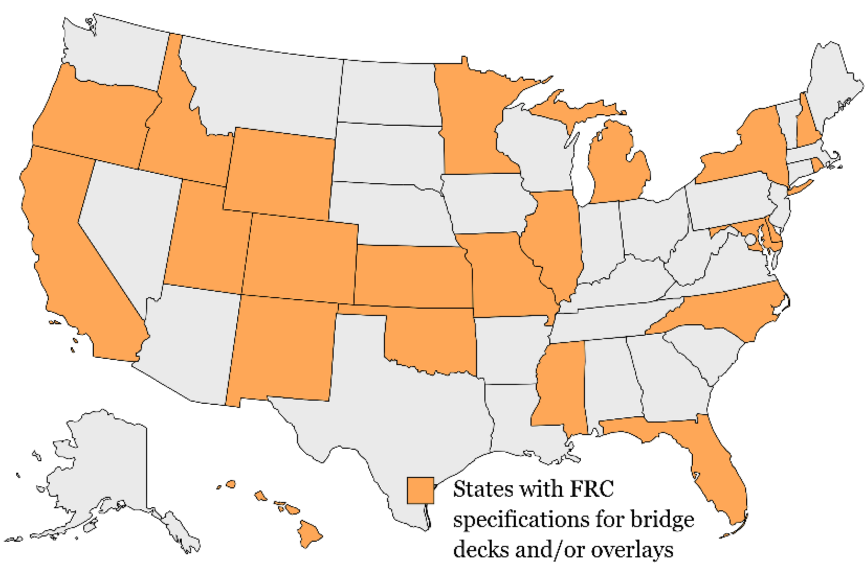

Fig. 1. States with FRC specifications for bridge decks and/or overlays, data from [Amirkhanian and Roesler 2019]

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

Testing is complete, data analysis is ongoing. 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 and deformed bar reinforcement in resisting shear forces and provides valuable data that is needed to build a shear behavior model in Task 3.

Table 1 shows the test matrix for the panel testing program and progress to date. The variables of interest within the experimental campaign include the deformed bar and macro-synthetic fiber reinforcement ratios, expressed as V_f the fiber volume fraction (fiber volume / total volume), and ρ_v the transverse reinforcement ratio (area of deformed bar / thickness of element × bar spacing). Additional details of the testing program including the reinforcement configurations, test setup, construction sequence, and instrumentation can be found in the Dec 2022 Progress Report.

Table 1. Panel test matrix and progress to date

Panel	V_f (%)	ρ_v (%)	Status
PFRC-000-000	0	0	TESTED
PFRC-000-029	0	0.29	TESTED
PFRC-000-058	0	0.58	TESTED
PFRC-000-114	0	1.14	TESTED
PFRC-026-000	0.26	0	TESTED
PFRC-026-029	0.26	0.29	TESTED
PFRC-026-058	0.26	0.58	TESTED
PFRC-026-114	0.26	1.14	TESTED
PFRC-052-000	0.52	0	TESTED
PFRC-052-029	0.52	0.29	TESTED
PFRC-052-058	0.52	0.58	TESTED
PFRC-052-114	0.52	1.14	TESTED

To accompany the panel elements, 4×8 cylinders and ASTM C1609 [ASTM 2020c] beams were cast at the same time as the panel elements. These companion specimens were used to determine strength and toughness parameters needed to develop the shear behavior model in Task 3. Table 2 gives a summary of the measured material properties on testing day for the tested panels.

Table 2 Test day mechanical properties of companion cylinders and flexure beams

Panel	Specimen name	Compressive strength (psi)	Elastic modulus (ksi)	Flexure, 4×4 beams		Flexure, 6×6 beams	
				Peak, f_1 (psi)	Residual, f_{150} (psi)	Peak, f_1 (psi)	Residual, f_{150} (psi)
P1	PFRC-000-000	6400	4700	750			
P2	PFRC-000-029	5500	4100	850		790	
P3	PFRC-000-058	4500	4300	440			
P4	PFRC-000-114	6100	4700	770		650	
P5	PFRC-026-000	4700	3800	710	70	860	100
P6	PFRC-026-029	5500	4400	730	150	630	140
P7	PFRC-026-058	5000	3900	780	60	700	90
P8	PFRC-026-114	6300	4600	710	60	560	100
P9	PFRC-052-000	4300	*	590	140	530	170
P10	PFRC-052-029	6500	4300	790	180	630	200
P11	PFRC-052-058	5100	4700	560	120	630	110
P12	PFRC-052-114	5200	4100	660	180	500	190

* Not available due to an instrument malfunction during testing

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 equations will be based on a rational shear behavior model developed for PFRC and will add to, or modify, the steel contribution of the elements shear strength based on the interactions measured during the experimental testing program (Task 2).

The measured response of the specimens were compared to predictions obtained using the Vector2 and Membrane2000 finite element softwares [Wong et al. 2013, Bentz 2000]. Both softwares utilize 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 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 Membrane2000 predictions and the measured response of a reinforced specimen without fibers (PFRC-000-058). The results suggest that reasonably accurate predictions can be expected for RC panels without fibers. However, modifications to the current constitutive relationships may be necessary for the PFRC panels since the crack width–stress relationship found in the test may be different for RC and PFRC. The modeling task is ongoing and further information will be presented in future progress reports.

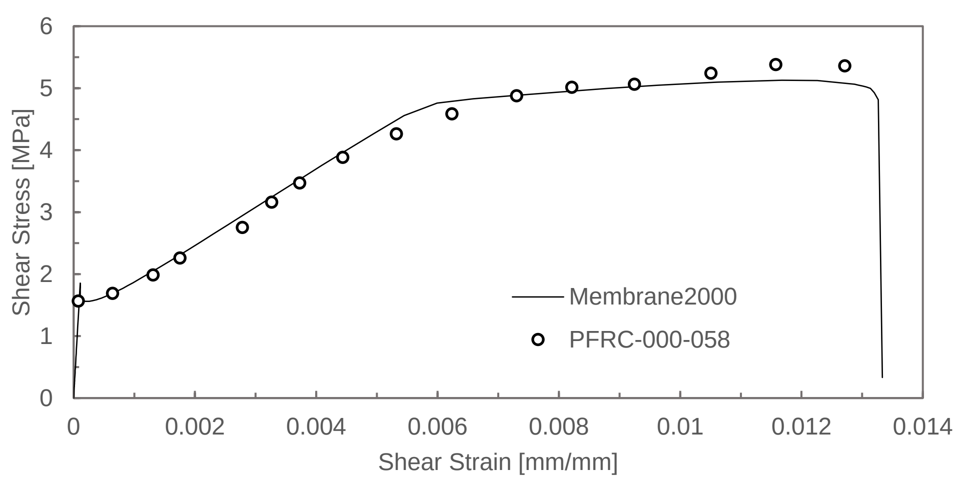

Fig. 2. Measured shear stress-shear strain behavior of PFRC-000-058 and Membrane2000 estimate

In addition to the PFRC shear behavior model developed as part of this study, numerous equations for the fiber contribution to shear strength have been proposed in the literature. Although these relationships were developed using databases of SFRC beams without stirrups and are therefore likely unsuitable for elements that contain both deformed bar and distributed macro-synthetic fiber reinforcement, both the newly developed code-oriented equations and the empirical relationships from the literature will be evaluated against the test data available for beams containing both fibers and deformed bar reinforcement gathered during Task 1 and Task 2.

The design recommendations will be established in cooperation with the advisory panel and industry professionals to develop language suitable for submission to AASHTO T10 Committee for adoption.

Task 5 – 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	60%

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

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