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Mechanically fastened hybrid composite strips for flexural strengthening of concrete beams

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HIGHLIGHTS

- Novel mechanically-fastened FRP flexural reinforcing developed for reinforced concrete.
- Reinforcing system is easy to install and cost-effective.
- Flexural tests indicate reinforcing provides strength gains of nearly 50%.
- Environmental and fatigue durability were experimentally assessed.

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ABSTRACT

While externally bonded fiber-reinforced polymer reinforcing has become an accepted technology for the flexural strengthening of reinforced concrete members, less information is available on flexural strengthening using mechanically fastened FRP (MF-FRP). This study presents the development of a vacuum-infused, hybrid glass–carbon MF-FRP system for the flexural strengthening of reinforced concrete beams. Two different FRP fabric architectures were considered to assess the impact of fiber orientation on behavior. The resistance of the MF-FRP composite strips to freeze–thaw cycling and saltwater submersion was assessed with single-fastener tension–bearing testing. Test results indicate that the MF-FRP system should display adequate residual capacity in typical cold-climate bridge applications. The flexural strengthening capabilities of MF-FRP composite strips were evaluated using four-point bending tests of MF-FRP-strengthened, steel-reinforced concrete beams and non-strengthened beams. The flexural test results for two glass–carbon MF-FRP reinforcing systems show an average increase in ultimate capacity of nearly 50% with good ductility. Flexural fatigue testing was conducted on four MF-FRP reinforced specimens. The cyclic flexural test results indicate that the strength gains that can be realized with the MF-FRP systems used here may be limited by fatigue performance, and that fatigue is an area that warrants further study.

1. Introduction

The use of externally bonded fiber-reinforced polymer (EB-FRP) reinforcing for the flexural strengthening of reinforced concrete members has become a fairly mature technology over the past few decades. Initial studies focused on experimentally quantifying achievable strength gains and assessing failure modes [1] and analytical investigations into the mechanics of behavior [2]. Other early studies discussed a variety of methods in which FRP materials can be used to enhance the performance of civil infrastructure including flexural strengthening with tensioned and untensioned FRP materials [3–6]. Since this foundational research, numerous additional studies have considered the efficiency of various FRP types, stress concentrations near FRP terminations, and the development of design methods. Both the American Concrete Institute (ACI) and the American Association of State Highway and Transportation Officials (AASHTO) have published guidelines for the design of reinforced concrete beams with EB-FRP flexural reinforcement [7,8].

However, there are drawbacks to the use of EB-FRP plates and strips for the flexural strengthening of reinforced concrete members. Since EB-FRP flexural strengthening is generally performed in-situ on older structures, careful concrete surface preparation is

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required prior to bonding, and adhesive cure times can be significant [9]. Additionally, special care is required near the reinforcement terminations, where peeling (tensile) stresses develop in the FRP–concrete bond line [10]. Recognizing these drawbacks, some researchers have explored the use of mechanically fastened FRP (MF-FRP) flexural reinforcing. Lamanna et al. [11] initially assessed the feasibility of EB-FRP reinforcing, demonstrating flexural strength gains of up to 36% through the testing of 35, 1.22 m-long beams. In a subsequent study, Lamanna et al. [9] performed additional testing using different FRP types and showed flexural strength gains of 20%. Bank and Arora [12] tested four, 7.32 m-long specimens where the MF-FRP strips were attached with powder-actuated fasteners along the majority of their length and expansion anchors at the strip terminations to provide confinement, and observed flexural strength gains ranging from 50% to 71%. Martin and Lamanna [13] used large diameter concrete screws to fasten FRP strips to six concrete beams, and their testing showed a strength gain of 39%. Lee et al. [14] tested 12 reinforced and two control specimens in flexure using the commercially available SafStrip® material [15] fastened with powder-actuated fasteners and threaded fasteners at the FRP termination, and noted a strength gain of 35% relative to unreinforced specimens.

Beyond the experimental work documented above, other studies have focused on the analysis of reinforced concrete beams with EB-FRP. Of particular importance is accurately accounting for imperfect bond, or slip, between the FRP and concrete (see, for example, studies by Bank and Arora [12], Napoli et al. [16] and Nardone et al. [17]). Napoli et al. [18] provide a critical review of modeling and analysis methods developed for MF-FRP flexural strengthening systems.

The MF-FRP flexural strengthening of existing, cast-in-place concrete bridges has also been documented in the literature. Bank et al. [19] report on the use of MF-FRP to strengthen a concrete slab bridge in Wisconsin, USA, which was then loaded to failure, and concluded that a 29% increase in flexural capacity was achieved cost-effectively. Similarly, Rizzo et al. [20] later used MF-FRP to strengthen a T-beam bridge in Missouri, USA. Live load testing results agreed well with finite-element analysis predictions and justified an increase in the assessed structural capacity. More recently, Whittemore and Durfee [21] reported on the use of SafStrip® MF-FRP strips to cost-effectively strengthen a concrete slab bridge in New Hampshire, USA.

A significant portion of past research into MF-FRP strengthening systems has focused on increasing the flexural strength of concrete bridges, for which fatigue is a design consideration. Despite this, the fatigue performance of MF-FRP flexural strengthening systems has seen relatively little investigation. In addition to monotonic strength testing, Quattlebaum et al. [22] tested MF-FRP reinforced beams in fatigue, concluding that their fatigue performance exceeded that of EB-FRP reinforced beams. However, Quattlebaum et al. [22] raised concerns about the long-term durability of the powder-actuated fasteners used in their study to attach the FRP strips. In addition to conducting monotonic flexural strength tests, Ekenel et al. [23] tested one MF-FRP beam reinforced with SafStrip® material in flexural fatigue, concluding that MF-FRP systems are a viable alternative to EB-FRP reinforcing.

Taken as a whole, these prior studies indicate that MF-FRP strips are seeing increased interest from researchers and practitioners, and can significantly increase the flexural strength of conventionally reinforced concrete members. However, additional research is warranted not only to increase confidence in strength gains that can be reliably achieved, but also to better assess fatigue performance and durability for bridge applications. This study seeks to increase the engineering community's knowledge of the performance of MF-FRP flexural strengthening technologies and enhance the database of experimental results in this growing field.

Rectangular concrete beams were tested in four-point bending both with and without MF-FRP reinforcing to assess bending strength gains. The FRP strips used in this study differed from those used by prior researchers in that they were cut from uniform, vacuum-infused FRP plates that were produced specifically for this application. The test beams were designed to mimic reinforced concrete slab bridges, a structure type of particular interest to the Maine State Department of Transportation [24]. In addition to flexural testing, tension–shear tests were conducted on single fastener specimens to assess FRP–concrete connector strength. FRP–concrete connector strength was also determined following freeze–thaw cycling and exposure to de-icing chemicals, as these are both important for long-term durability in harsh climates. Finally, flexural fatigue tests were conducted to quantify the performance of the MF-FRP strengthened beams under the repeated application of load.

2. Development and characterization of MF-FRP reinforcement

2.1. Development of the FRP reinforcement

The MF-FRP reinforcement system used in this study was designed to be easily fabricated with a minimum of specialized equipment and labor. It is essential that the FRP has sufficient fastener bearing strength. The values of width, end distance, and laminate thickness required for a system to achieve full bearing strength are dependent on the FRP layup [25,26]. Collins [27] found that balance about the mid-plane of an FRP section is necessary for achieving higher bearing capacity due to the interlaminar shear stresses generated in less homogeneous stacking sequences. The commercially available MF-FRP system SafStrip®, produced by Strongwell Corporation, incorporates off-axis fibers, but is produced with a continuous pultrusion process that requires a significant capital equipment investment. For the present study, we chose to use vacuum-infusion to produce uniform cured FRP sheets that could be easily ripped into strips of any width for application to a beam.

This paper reports results achieved using two different composite layups fabricated as shown in Fig. 1. The layup of the FRP sheets used in this study was initially established in consultation with engineering personnel at Kenway Corporation, a local composites manufacturer in Augusta, ME, USA who ultimately produced the sheets using readily available of-the-shelf materials. Both layups

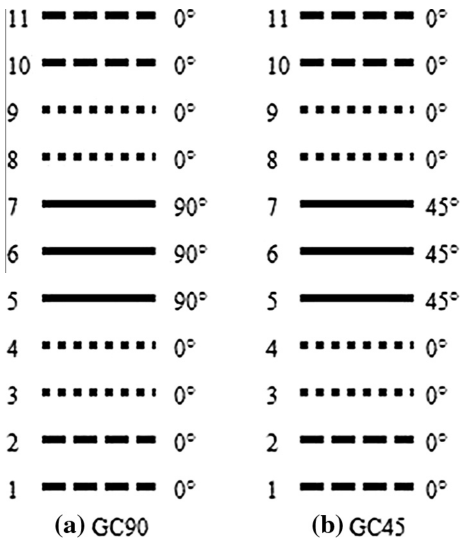

Fig. 1. Glass–carbon hybrid FRP layups.