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Effect of web reinforcement on the behavior of pultruded fiber-reinforced polymer beams subjected to concentrated loads

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HIGHLIGHTS

- Failure mode and ultimate capacity of web-strengthened FRP beams subjected to concentrated loads.
- Eleven beams were tested; three strengthening systems were used.
- Strengthening systems: doubler plates, bearing stiffeners, and junction stiffeners.
- All strengthening system increased ultimate capacity of specimens.
- Only junction stiffeners changed the failure mode of specimens.

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ABSTRACT

This paper describes an experimental program designed and executed to investigate the failure mode and ultimate capacity of web-reinforced pultruded FRP beams subjected to concentrated loads in the plane of the web. Six 203.2 mm × 101.6 mm × 12.7 mm beams and five 203.2 mm × 203.2 mm × 9.5 mm beams manufactured with vinylester resin were strengthened with one of three systems and subjected to concentrated loads applied directly to the top flange. The three systems were (a) full-depth web bearing stiffeners, (b) "doubler" plates attached to the web, or (c) stiffening elements applied to the upper (loaded) web-flange junction of the specimen. Experimental results showed that the junction stiffeners (58.7%), bearing stiffeners (52.8%), and "doubler" plates (31.7%) all increased the ultimate capacity of the beams when compared to unstrengthened control beams. Beams prepared with bearing stiffeners and "doubler" plates failed in the same manner as the control beams (shear "wedge" failure at loaded web-flange junction), while failure in the beams with reinforced loaded web-flange junctions occurred in the bottom flange near the simple supports. Digital image correlation software was used to capture out of plane displacement of the web and confirms the modes of failure.

1. Introduction

The primary objective of the experimental program was to investigate the mode of failure and ultimate capacity of web-reinforced FRP beams subjected to concentrated loads in the plane of the web. The purpose behind the investigation is to not only determine which stiffening system best alleviates the effects of concentrated loads but also to provide initial recommendations for use to designers and construction professionals. Examples of web stiffening can be found in both the steel and FRP composites construction industries. In steel construction, full-depth transverse web stiffeners and "doubler plates" are used to mitigate the effects of concentrated forces [1]. The composites industry primarily utilizes these stiffeners to prevent stability failures of the web [2]. However, researchers investigating the behavior of full-scale pultruded FRP beams under various loading conditions have had to use stiffening mechanisms to prevent premature material failure during testing [3,4]. Standard plans for full-depth web stiffeners [5] were reviewed during the development of trial designs for the experimental program. Stiffening of the web-flange junction via the bonding of a small angle is recommended when trying to increase the local flange buckling capacity of a section [2], but its ability to mitigate the effects of concentrated loads is unknown. In light of these industry practices and procedures, full-depth web stiffeners in the transverse direction, "doubler plates" attached to the web in the vicinity of the concentrated load, and longitudinal stiffeners along the junction of the web and the loaded flange were chosen as the three web-strengthening systems. The experimental objective was be met by applying concentrated loads to strengthened 203.2 mm deep vinylester "W" and "I" shaped

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beams until ultimate failure (eleven specimen total). Load and stroke data was used to examine the overall performance of the section, while digital image correlation software provided full-field out-of-plane displacement data to examine the behavior of the sections.

2. Design of experimental program

The investigation of strengthened beams was limited to 203.2 mm deep shapes pultruded with vinylester resin. This was done for several reasons. First, it limited the amount of variables affecting the test regimen. Second, the 203.2 mm deep section is the most common structural shape used in industry. Third, prior tests of similar beams [6,7] provided sufficient data for comparison. Finally, 203.2 mm × 101.6 mm × 12.7 mm and 203.2 mm × 203.2 mm × 9.5 mm vinylester sections from three pultruders (Bedford, Fibergrate, Strongwell) were available. These three manufacturers were chosen as a sample of the US industry because of their similar production methods and material properties. The nominal properties are the same for all three manufacturers with the flange thickness equalling the web thickness for all specimens.

As with the previous tests [6,7], the span-to-depth ratio was chosen as 4:1 in order to reduce the chance of a global stability failure. This limitation was changed for one specimen to 8:1 to investigate the behavior of a "long span" strengthened beam. There were four specimens strengthened with bearing stiffeners, four specimens strengthened with "doubler" plates, and three specimens with a strengthened web-flange junction. A listing of the specimen name, specimen type, and test purpose is summarized in Table 1. The naming convention for the test specimens is as follows: Manufacturer (BF = Bedford, FG = Fibergrate, SW = Strongwell) – Shape (I8 = "I" section, W8 = Wide-flange section) – Resin (VE = Vinylester, PE = Polyester) – Tracking Name and Number.

3. Specimen preparation

The specimens were either 203.2 mm × 203.2 mm × 9.5 mm wide-flange beams or 203.2 mm × 101.6 mm × 12.7 mm I-shaped beams. Ten of the eleven strengthened beams had a span-to-depth ratio of 4:1 (span = 812.8 mm). The eleventh beam, FG-I8-VE-PLATE 3, had a span-to-depth ratio of 8:1 and a corresponding span of 1625.6 mm. Each specimen had a minimum of 75 additional millimeters on both ends to accommodate the rotational restraints on the simple supports. Once the specimens were cut to size, each type of specimen was assembled in a unique manner. This section details the processes by which the three types of strengthened specimens were prepared.

3.1. Beams with transverse bearing stiffeners

Two separate bearing stiffener patterns were chosen as part of the investigation. The first concept had the bolt pattern aligned directly under the load and the stiffeners alternating on opposite sides of the web. This alternating pattern is shown in Fig. 1a and was applied to beams FG-W8-VE-STIFF 1 and BF-I8-VE-STIFF 2. The second option had the bolt pattern offset of the load such that the legs of the stiffeners were directly under the load on both sides of the web. This aligned pattern is shown in Fig. 1b and was applied to beams SW-I8-VE-STIFF 3 and SW-W8-VE-STIFF 4. Fig. 1a and b show the stiffeners prior to application. In practice, the web of the test specimens sits between the two leg angles as shown in Figs 2 and 3.

The stiffeners for the 9.5 mm-thick members were equal leg angles from Strongwell with dimensions of 76.2 mm × 76.2 mm × 9.5 mm. Strongwell equal leg angles with dimensions of 101.6 mm × 101.6 mm × 12.7 mm were used to strengthen the 12.7 mm thick specimens. All the bearing stiffeners were cut with a diamond-bladed circular saw such that they fit as tightly as possible against both the web and the upper and lower flanges (the presence of the fillet radii at the upper and lower web-flange junction did not allow for an exact fit). As such, the approximate height of the 12.7 mm angles was 178 mm, and the approximate height of the 9.5 mm angles was 184 mm. Once the stiffeners were cut to size, two holes were drilled in the leg that would rest against the web of the test specimen. These holes were drilled with a 14.3 mm drill bit in a drill press and located 50.8 mm down the top edge of the stiffener. This edge distance would ensure a tight fit against the web and minimize the possibility of damage to the web-flange junction.

The holes in the web were drilled with the same 14.3 mm drill bit and drill press, and the bearing stiffeners were worked into position. Once the holes in the web and the stiffeners were aligned, 12.7 mm diameter bolts were placed through the holes. 12.7 mm steel fender washers were used between the head of the bolt and the web on one side and between the 12.7 mm nut and the web on the other side to distribute the force and prevent damage to the composite material. Fig. 2 shows a completed specimen with bearing stiffeners bolted in place.

In accordance with manufacturers' guidance for connections utilizing steel bolts, each nut was tightened to finger-tight plus one half turn [8,9]. Fig. 3 shows the alternating pattern applied

Table 1
Summary of experimental program for strengthened beams.

Specimen	Specimen type	Purpose
FG-W8-VE-STIFF 1	Vinylester beam w/alternating bearing stiffeners at load point and supports	Determine ultimate capacity of VE beam w/bearing stiffeners
BF-I8-VE-STIFF 2	Vinylester beam w/alternating bearing stiffeners at load point and supports	Determine ultimate capacity of VE beam w/bearing stiffeners
SW-I8-VE-STIFF 3	Vinylester beam w/aligned bearing stiffeners at load point and supports	Determine ultimate capacity of VE beam w/bearing stiffeners
SW-W8-VE-STIFF 4	Vinylester beam w/aligned bearing stiffeners at load point and supports	Determine ultimate capacity of VE beam w/bearing stiffeners
BF-W8-VE-PLATE 1	Vinylester beam w/plates bolted to both sides of web	Determine ultimate capacity of VE beam w/doubler plates
BF-I8-VE-PLATE 2	Vinylester beam w/plates bonded and bolted to both sides of web	Determine ultimate capacity of VE beam w/doubler plates
FG-I8-VE-PLATE 3	Long-span vinylester beam w/plates bonded and bolted to both sides of web	Determine ultimate capacity of long-span VE beam w/doubler plates
SW-W8-VE-PLATE 4	Vinylester beam w/plates bonded and bolted to both sides of web	Determine ultimate capacity of VE beam w/doubler plates
BF-I8-VE-JUNCTION 1	Vinylester beam w/angles bonded to both sides of upper web-flange junction	Determine ultimate capacity of VE beam w/strengthened web-flange junction
SW-I8-VE-JUNCTION 2	Vinylester beam w/angles bonded to both sides of upper web-flange junction	Determine ultimate capacity of VE beam w/strengthened web-flange junction
BF-W8-VE-JUNCTION 3	Vinylester beam w/angles bonded and bolted to both sides of upper web-flange junction	Determine ultimate capacity of VE beam w/strengthened web-flange junction