USE OF FULL-DEPTH POST-TENSIONED GFRP RODS FOR BOND PERFORMANCE UNDER MIXED MODE BENDING CONDITIONS

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Abstract
The feasibility of applying full-depth partially bonded post-tensioned GFRP rods for the purpose of improved bond performance in full-scale hybrid structural members is explored in this paper. Comparative experimental testing using two sets of small-scale mixed-mode bending specimens determined a 160% increase in load resistance, with an associated 273% increase in deflection, due to the addition of the full-depth partially bonded post-tensioned GFRP rods. The utilization of less than 25% of the ultimate capacity in the GFRP rods during experimental testing demonstrate greater potential for bond improvement using this technique. The application of initial post-tensioning force to the GFRP rods, however, did not show significant enhancements in bond performance. Non-prestressed GFRP rods are recommended for implementation in full-scale hybrid structural members.

1. Introduction

The creation of an effective bond mechanism between dissimilar materials is a critical component in the design of hybrid structural members. In the field of hybrid designs consisting of Fibre Reinforced Polymers (FRPs), bond has typically been achieved through epoxy adhesive bonding or discrete friction and mechanical interlock elements, such as shear studs[1-3]. Occasionally, the two techniques are implemented together for enhanced bond performance. To characterize a bond system intended for application in structural elements subjected to flexural loading, such as hybrid beams and bridge decks[4-7], it is important to understand its performance when loaded under a combination of normal and shear forces.

The study presented in this paper discusses the feasibility of using full-depth partially bonded post-tensioned GFRP rods, as an alternative to GFRP shear studs, to enhance bond performance between Glass FRP (GFRP) and Ultra-High Performance Concrete (UHPC). This set of small-scale specimen tests is part of larger research program and the results from this study will be implemented in the design and testing of a full-scale hybrid FRP-UHPC bridge deck system[7].

2. Design of Test Specimens

Small-scale mixed-mode bending (MMB) specimens were chosen to test the bond performance between Glass Fibre Reinforced Polymer (GFRP) pultruded plates and cast-in-place Ultra-High Performance Concrete (UHPC). The overall plan dimension of the MMB specimens was based on the manufactured size of the GFRP plates, which had a width of 130 mm, a length of 460 mm and a thickness of 9.6 mm. In all specimens, prior to casting of the 50 mm thick UHPC material, a layer of epoxy bonded coarse silica sand aggregates was bonded directly to the coarsened surface of the GFRP pultruded plate with a moisture insensitive epoxy[8]. Excluding the control specimen, 5/8" (~16 mm) diameter GFRP threaded rods were cast directly into the specimens, perpendicular to the direction of expected crack propagation; they were first lubricated with a coating of SAE10W30 motor oil in order to achieve a partially bonded fixity with the surrounding material, a technique recommended by the manufacturer [9]. Accompanying GFRP nuts were installed at the top and bottom of the GFRP rods after allowing for curing of the UHPC material. The GFRP nut located at the GFRP plate end was epoxy bonded to the plate as a fixed constraint, allowing free rotation and post-tensioning torque to be applied to the rod end at the UHPC side. The material properties for the different components in the MMB specimens are listed in Table 1.

Material	Tension Properties		Compression Properties	
	Strength [MPa]	**Modulus of Elasticity [MPa]**	**Strength [MPa]**	**Modulus of Elasticity [MPa]**
GFRP pultruded plate [10]	400	25000	–	–
GFRP threaded rod [9]	94	13790	–	–
UHPC [11]	16	50000-60000	150-180	50000-60000

Unit conversion: 1 MPa = 145.037 psi

Table 1. A selection of properties for materials used in hybrid bridge deck system design.

The design of the MMB specimens was based upon guidelines provided in ASTM Standard D6671-06[12] with modifications made to account for the asymmetric (materials of different heights) and nonhomogeneous (composed of more than one material) nature of the specimens. One control specimen without the presence of a full-depth partially bonded post-tensioned GFRP rod (hereafter referred to as PT GFRP rod) was tested. Five additional specimens were tested with a single PT GFRP rod located 150 mm away from the specimen end. The design of the small-scale MMB specimens allowed for both ends of the specimen to be tested; Side A was tested first, followed by Side B. Details and dimensions of MMB specimens are provided in Figure 1.

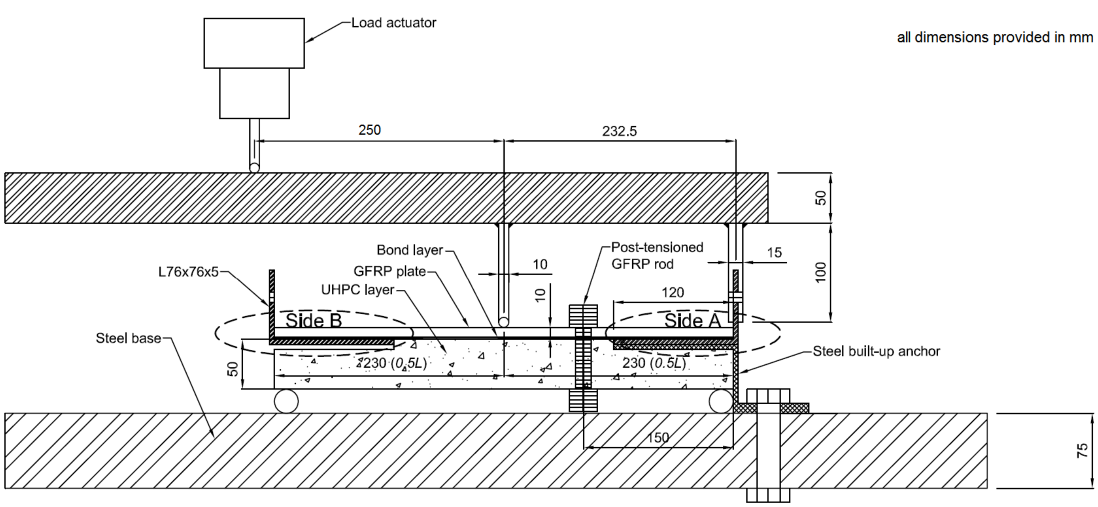

Figure 1. Dimensions of MMB test specimens.

3. Experimental Program

The five specimens with PT GFRP rods installed were subjected to varying levels of post-tensioning force (5, 10, 15, 20 and 25 ft·lbs) prior to loading under MMB conditions; post-tensioning was applied through external torqueing via a GFRP nut. The test matrix for the experimental program is shown in Table 2.

Description	Specimen ID	Post-tensioning force (ft·lbs)
Control MMB specimen	C-A	–
	C-B	
MMB specimens with PT GFRP rod	PT-5-A	5
	PT-5-B	
	PT-10-A	10
	PT-10-B	
	PT-15-A	15
	PT-15-B	
	PT-20-A	20
	PT-20-B	
	PT-25-A	25
	PT-25-B	

Unit conversion: 1 ft·lbs = 1.35582 N·m

Table 2. Experimental program test matrix.

MMB load testing was conducted under displacement-control at a loading rate of 1 mm/min, with an applied moment arm of 250 mm for all specimens. Two internal strain gages were installed on each PT GFRP rod, to record the strain level during post-tensioning as well as during MMB testing.

4. Experimental Test Results

4.1 Initial post-tensioning of PT GFRP rods

The initial tensile strain induced in the PT GFRP rods of each post-tensioned specimen prior to MMB testing is shown in Table 3.

Parameter	Specimen ID									
	PT-5		PT-10		PT-15		PT-20		PT-25	
	A	B	A	B	A	B	A	B	A	B
Tensile strain (με)	205	117	138	325	191	746	534	297	–	660
Average tensile strain (με)	161		232		469		416		660	

Table 3. Initial tensile strain in PT GFRP rods.

It can be immediately noted that, though a linear relationship exists between the applied torque and the resulting tensile strain, there is significant variability in the tensile strain present within the GFRP rods for specimens subjected to the same torque level. A figure illustrating the trend between the externally applied torque and the average tensile strain is provided in Figure 2.

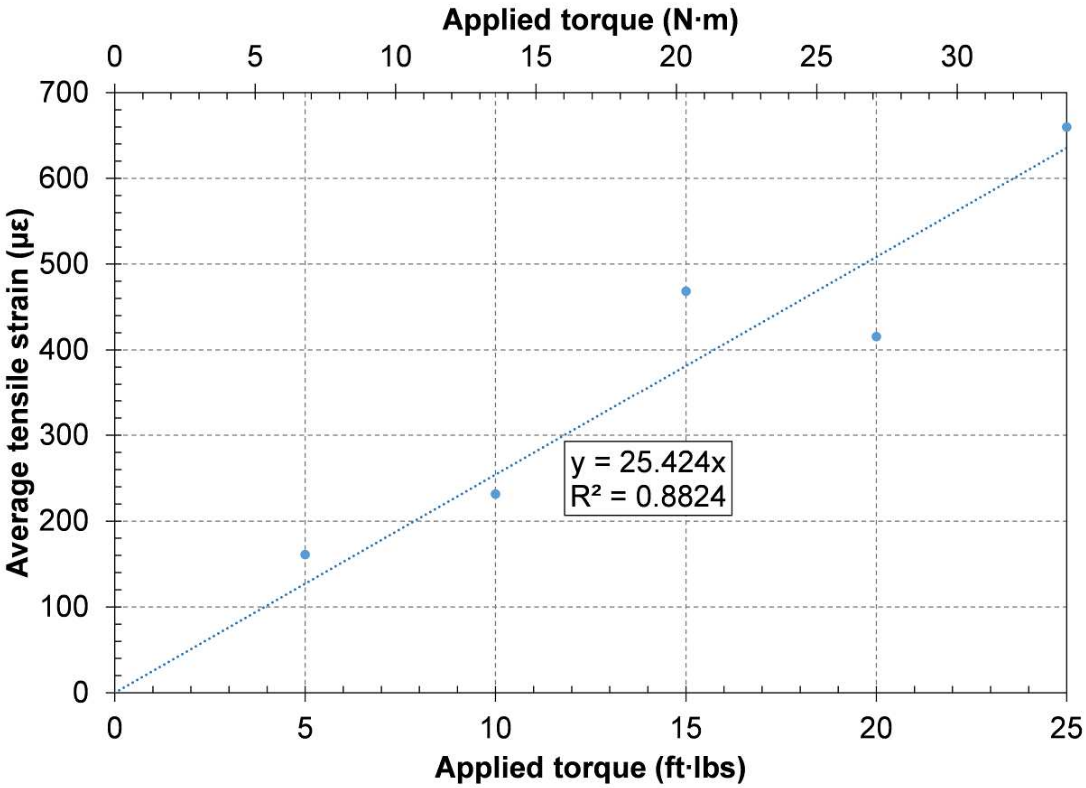

Figure 2. Relationship between externally applied torque and the average tensile strain induced in the PT GFRP rods.

4.2 Testing of small-scale specimens under MMB conditions

Failure in the control specimen occurred due to debonding along the GFRP-UHPC interface. Photographs of the failed specimen, shown in Figure 3 below, confirm fracturing of the epoxy bonded silica sand aggregate as the main cause of the ultimate failure mechanism.

Figure 3. Failure mode of control specimen showing the debonded surfaces on the GFRP pultruded plate (left) and on the UHPC (right).

In the case of the post-tensioned MMB specimens, tensile cracking in the UHPC occurred at ultimate condition, without any indications of debonding at the bond interface. Representative photographs for the failure mode exhibited in the post-tensioned MMB specimens are shown in Figure 4.

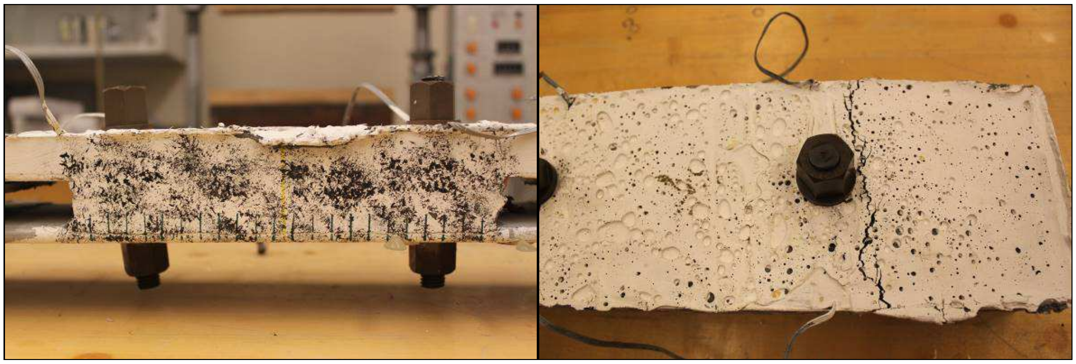

Figure 4. Failure mode of PT specimens showing the tensile cracking of the UHPC with views from the side (left) and from the top (right).

It should be noted that malfunctions in the data collection system occurred during testing of Specimen PT-10; thus, the load-deflection behavior (PT-10-A) as well as the tensile strain data (PT-10-A and PT-10-B) are not presented here. Comparison of the global load-deflection behavior between the different specimens tested, describing the relationship between the applied load and the deflection at the applied load, is provided in Figure 5.

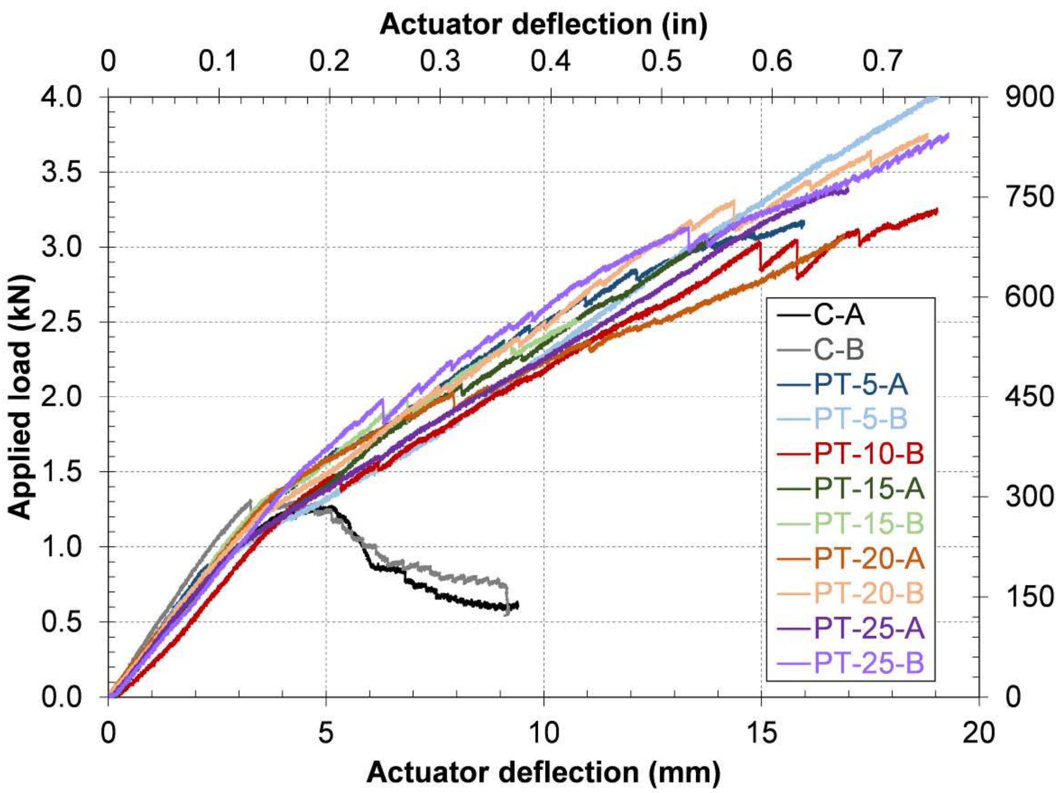

Figure 5. Comparison of global load-deflection behavior between control specimen and specimens with PT GFRP rods.

From the relationships shown in Figure 5, it is clear that the addition of PT GFRP rods significantly enhances the performance of MMB specimens, regardless of the initial applied post-tensioning force. The load-deflection behavior of all specimens (control and post-tensioned) were the same up until the peak load of the control specimens. Past this point, the load resistance of the post-tensioned specimens continued to increase while the load carrying capacity of the control specimens decreased to less than 50% of the peak load reached. It should be noted, however, that failure in the post-tensioned MMB specimen occurred due to tensile cracking of the UHPC and not debonding; therefore, a higher peak load is expected if premature UHPC tensile cracking had not occurred.

Close examination of the tensile strain experienced during MMB loading of the five post-tensioned specimens is presented in Figure 6.

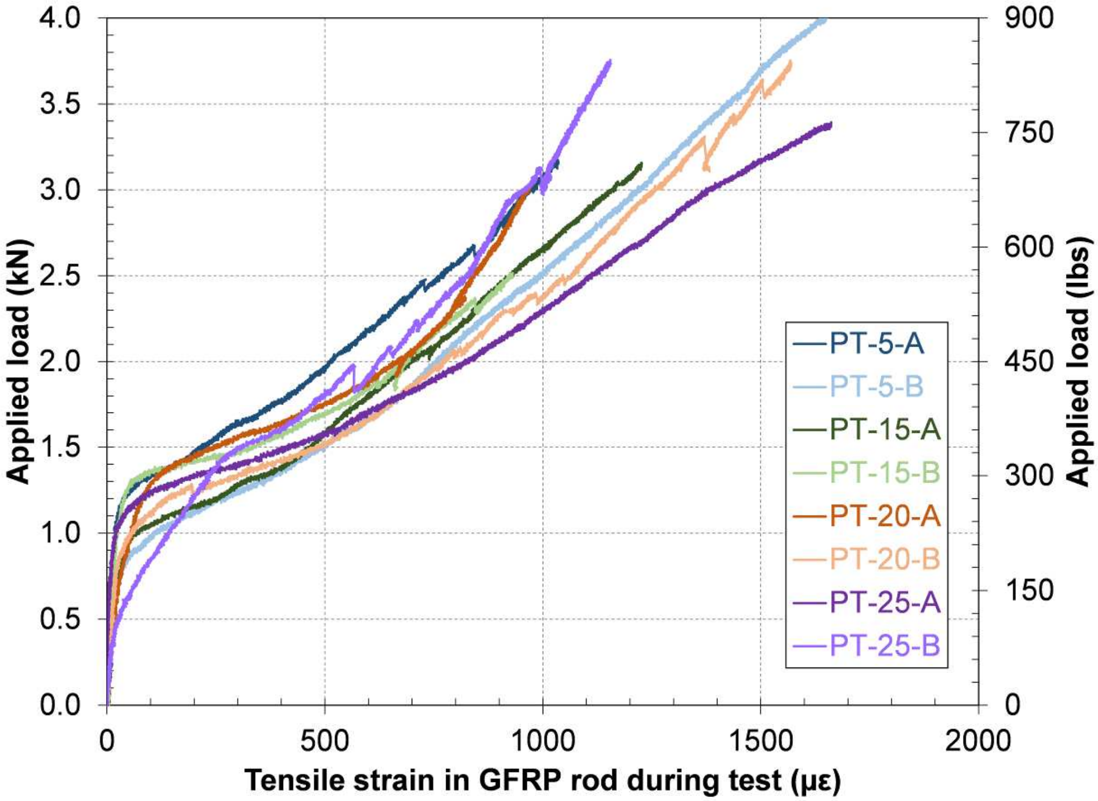

Figure 6. Comparison of tensile strain induced in PT GFRP rods during MMB testing of small-scale specimens.

The results show that the tensile strain induced in the PT GFRP rods followed the same general trend for all specimen configurations, irrespective of the initial torque level applied. In all specimens, the tensile strain experienced in the PT GFRP rods increased minimally during the first portion of testing, until the crack front reached the location of the rod. After that point, the PT GFRP rods began actively resisting further debonding, with significant increases in tensile strain induced with greater load applied.

5. Analysis and Discussion of Results

Overall, there is significant enhancement in the bond performance at the GFRP-UHPC material interface when a single PT GFRP rod is located of the crack front. Compared with the control specimen, both the peak load as well as the maximum deflection reached by the five MMB specimens with PT GFRP rods installed were substantially greater; the percent increase in the peak load and deflection attained during experimental testing is 160% and 273%, respectively. It is clear that the enhancement to bond performance would have been even greater had premature tensile cracking failure not occurred in the specimen designed with PT GFRP rods.

A comparison between the ultimate tensile strain capacity of the GFRP rod (7000 με), the peak tensile strain induced during MMB testing (1600 με) and the tensile strain induced during initial post-tensioning (200 – 800 με) shows the small percentage of the ultimate strain utilized by the initial post-tensioning step. Global load-deflection and local tensile strain behavior comparisons between the five MMB specimens with PT GFRP rods post-tensioned to five different torque levels did not show any discernible differences in performance. Therefore, it can be stated that though the PT GFRP rods provided significant improvements in performance, there was no influence from the application of varying levels of post-tensioning force. Additionally, the tensile strain induced in the PT GFRP rods also showed high variability in the results obtained from the two specimens subjected to the same level of external torque. Due to the low degree of repeatability of consistent tensile strain obtained, for future applications, the use of non-prestressed GFRP rods are recommended for improved bond performance between GFRP and UHPC.

6. Conclusions

Small-scale testing of MMB specimens with and without the presence of PT GFRP rods perpendicular to the direction of crack growth produced consistent and reliable results, demonstrating the significant improvement in bond performance obtained at the GFRP-UHCP material interface when PT GFRP rods are used. Specific conclusions include:

1. The addition of a single PT GFRP rod ahead of the crack front resulted in 160% and 273% increase in the load resistance and deflection, respectively, experienced at peak condition;
2. Due to premature tensile cracking in the UHPC and based upon the tensile strain levels reached in the PT GFRP rod during experimental testing, the ultimate load resistance and deflection is expected to be significantly higher than the peak values obtained experimentally in this study;
3. No decrease in load resistance was observed when PT GFRP rods were used, due to the active participation in bond resistance by the PT GFRP rod past the peak load of the control specimens;
4. The application of initial post-tensioning force in the PT GFRP rod had negligible effect on the overall bond performance, with less than 10% of the ultimate strain utilized at the higher post-tensioning level; and,
5. Large variability in the tensile strain was observed in the partially bonded GFRP rods when subjected to same levels of externally applied torque.

From the results obtained in this investigation, for future applications in full-scale hybrid FRP-UHPC bridge deck system, full-depth partially bonded GFRP rods, without post-tensioning, is recommended for use at the GFRP-UHPC interface in conjunction with the epoxy bonded coarse silica sand layer.

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