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The Effects of a Curved Soffit on FRP-Strengthening of Concrete Bridges

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16. Abstract Through testing, coupled with theoretical analysis, a model will be developed which provides designers with a tool to determine the impact of concave curvature on the effectiveness of strengthening using CFRP laminates or sheets			
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The Effects of a curved Sofit on FRP Strengthening of Concrete Bridges

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ABSTRACT

The objective of this experimental program has been to study CFRP strengthening of existing concrete bridges that contain soffit curvature. In the presence of such curvature, the FRP laminates attempt to straighten under tension, leading to direct transverse tensile stress in the adhesive, which may cause premature peeling. This tensile stress could also lead to the cover being ripped off prematurely.

In this research program, six beams, each 6m in length and each having different extents of curvature, were tested under a three-point static load test setup at the University of Missouri – Rolla (UMR). One of the beams containing soffit curvature was anchored using GFRP anchor spikes to prevent the expected premature peeling.

INTRODUCTION

Strengthening of existing structures avoids the need to demolish and replace, enabling the design life of the current structure to be increased. Extensive research on external flexural strengthening of RC sections has been conducted using fiber-reinforced polymer (FRP) materials. The presence of curvature on the soffit of structural elements is common to many strengthening applications, but not much research has been carried out into its effect. Curvature is referred to either as the profile of a structural element or as localized unevenness. The effectiveness of the strengthening scheme in the presence of concave curvature is highly dependent on the bond between the composite and the existing structure (Porter, 2002). Premature peeling and debonding are critical considerations in the design of RC member strengthening in the presence of curvature since this failure mode limits the capacity of the structure to some level less than that which would be expected without curvature. Debonding failure is caused mainly due to the following: flexural cracks, shear cracks, insufficient end anchorage and uneven surface profiles (TR 55, 2002). The current design guidelines recognize this and offer a limitation on the allowable curvature of 5mm over a length of 1m, prior to application of the composite (BD 85, 2001). One way to prevent or delay premature peeling is to anchor the FRP sufficiently. Various anchorage systems for FRP laminate strengthening applications have been investigated. Mechanical anchors by means of steel angles, steel plates and anchor bolts have been used, decreasing stress concentrations in the laminate and increasing the bond strength. This paper presents the use of GFRP anchor spikes as a mechanical anchorage system to prevent premature peeling of CFRP laminates in the presence of curvature.

EXPERIMENTAL PROGRAM

Six beams were tested to compare the effect of curvature against flat-soffited beams. Three beams had a flat soffit, one unstrengthened, one strengthened using three layers of CFRP wet layup (Sikawrap HEX 103C) laminate and the last strengthened with a Sika Carbodur pultruded precured laminate. These three beams were used as control specimens. The rest of the beams contained an identical degree of curvature of 5mm per meter in each case, extending over 5m, almost the entire clear span (global curvature). Because of expected premature peeling, one of the beams containing global curvature was designed to contain GFRP anchor spikes.

Development of GFRP anchor spikes

Each anchor spike consisted of a precured fiber portion and a dry fiber portion, as shown in Figure 1. The anchor spikes were constructed in-house at UMR. Firstly, glass fibers were bundled together and half of the fiber length was covered with plastic and duct tape. Secondly, the uncovered bundled fibers were impregnated and saturated thoroughly with resin. Lastly, the saturated fibers were passed through a circular hole in a steel plate (a die) to obtain the desired diameter of the anchor spikes. In this experimental program the diameter of the anchor spikes used was 10mm (0.375in). The saturated fibers were cured in ambient temperature for 24-48 hours and the plastic sheet was removed from the anchor spike to free the unsaturated dry fibers. These dry fibers were to be used for bonding purposes, suitably trimmed to different lengths according to specific requirements.

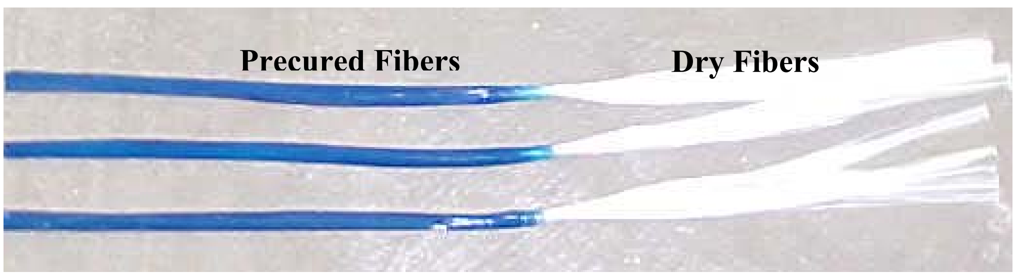


Figure 1. Anchor Spikes

Standard pull out tests were conducted for these anchor spikes. In this particular situation, the glass fibers were *fully* impregnated with saturant along their length to make GFRP bars for these tests. These anchors were embedded in 150mm (6in) concrete cubes over different lengths of 25mm (1in), 51mm (2in), 76mm (3in) and 102mm (4in) to perform the pull out tests.

A 530kN (120kip) Tinus-Olesen machine was used for these pull-out tests. The recorded average pull-out loads at failure were 22kN (5kip), 29kN (6.5kip), 36kN (8kip) and 31kN (7 kip) respectively. Based on these results, it was decided that in the main experimental program on curved-soffit beam tests, the anchor spikes would be embedded 76mm (3in).

Beam details

Three beams had a flat soffit and dimensions 6000×200×400mm (240×8×16in). The remaining three beams, also all of 6m in overall length, contained constant soffit curvature of 5mm per meter over 5m (almost the full clear span) with a cross section of 530×200mm (21.5×8in) near to the supports and a cross section of 400×200mm (16×8in) at midspan. Therefore, the cross section at the midspan was the same for all beams. Assuming the surface profile to be circular, an associated radius of curvature, R, can be obtained. The maximum deviation, Y, from horizontal, over any length, X, was determined based on radius, R as shown in Figure 2. All the beams were fabricated using ready mix concrete and cured under laboratory conditions. Details of the reinforcement are shown in Figure 3.

Two different CFRP strengthening techniques were used. The length of external strengthening was 5m and the width of laminate was 100mm in all beams. Table 1 summarizes the test matrix. The procedures for the installation of each system are described next.

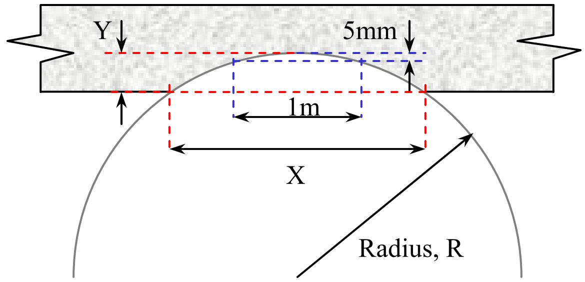


Figure 2. Curvature Design

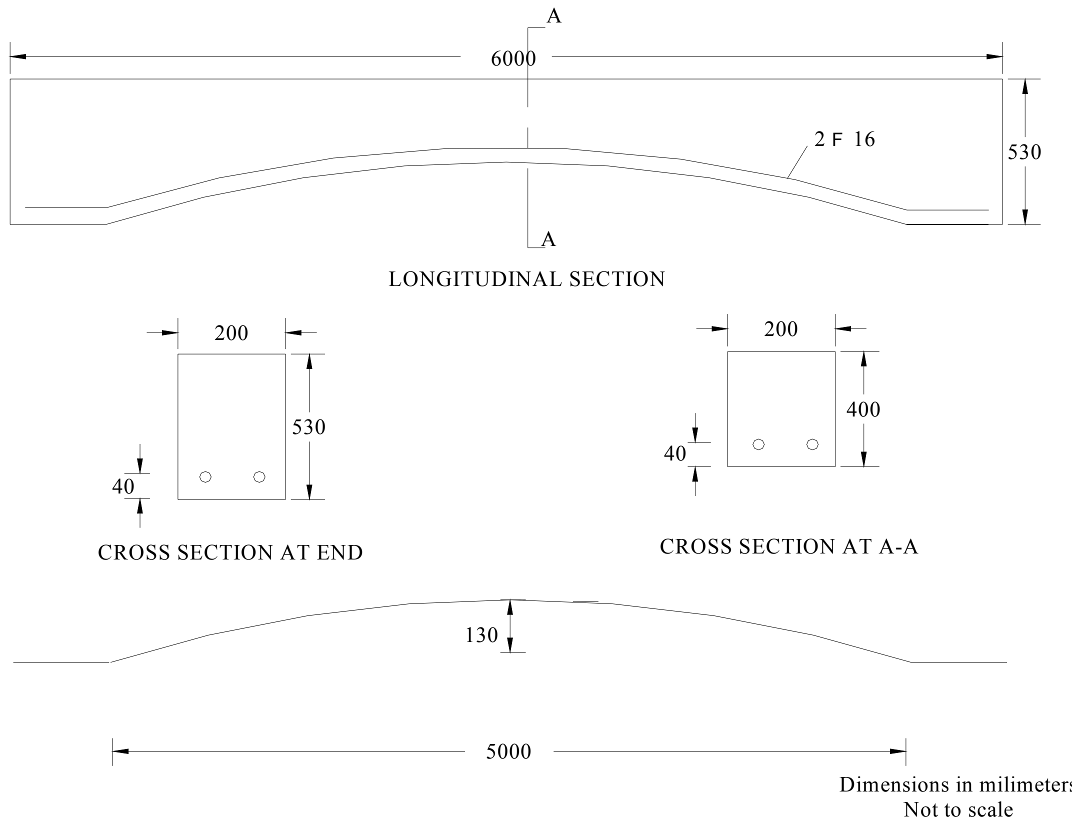


Figure 3. Typical Beam Dimensions

Table 1: Test Matrix

Beam	*Strengthening Technique*	*Type of Soffit*
1	*N/A*	*Flat*
2	*1 Laminate plate*	*Flat*
3	*3 layers of manual wet layup sheet*	*Flat*
4	*1 Laminate plate*	*Curvature over 5m*
5	*3 layers of manual wet layup sheet*	*Curvature over 5m*
6	*3 layers of manual wet layup sheet and strengthened with anchor spikes*	*Curvature over 5m*

Material properties

a) Concrete. The compressive strengths for each beam are presented in Table 2.

b) Steel Reinforcement. An average yield stress of 414MPa (60ksi) and Young's Modulus of 200GPa (29000ksi) were obtained from tensile tests.

c) CFRP Systems. Table 3 shows the mechanical properties of the CFRP systems provided by the manufacturer.

d) Adhesive. The epoxy and saturant were both two-part systems. The epoxy had a paste-like semi-solid form while the saturant had a liquid form after mixing. Table 4 shows the adhesive properties provided by the manufacturer.

Table 2: Compressive Strength of Concrete

Beam	*Concrete Compressive Cylinder Strength, MPa (psi)*
1	*41.3 (6000)*
2	*41.3 (6000)*
3	*41.3 (6000)*
4	*35.8 (5200)*
5	*35.8 (5200)*
6	*35.8 (5200)*

Table 3: Material Properties of CFRP Systems

CFRP System	*E_f kN/mm^2 (Msi)*	*Tensile Strength f_{fu} N/mm^2 (ksi)*	*E_{fu} Ultimate Strain, %*
*Fiber Laminate Sheet**	*34 (234.5)*	*3800 (550)*	*1.5*
Pultruded Laminate Plate	*165 (23.9)*	*2800 (406)*	*1.69*

* Based on dry fiber cross section area

Table 4: Adhesive Properties

Adhesive	*Tensile Strength N/mm^2 (ksi) (7 day)*	*Compression Strength N/mm^2(ksi)*	*Bond Strength N/mm^2(ksi)*	*Elongation at 77^{0}F, %*
Epoxy gel	*24.8 (3.6)*	*53.7 (7.8)*	*18.6 (2.7)*	*1*
Saturant	*72 (10.5)*	*-*	*-*	*4.8*

INSTALLATION PROCEDURES

All the concrete surfaces were sand blasted and cleaned to ensure good bonding before strengthening shown in Figure 4(a). The adhesive was mixed in a specified ratio until uniform.

Cold cured adhesive (laminate plate)

Beams 2 and 4 were strengthened with cold cured adhesive bonded laminate plate. The epoxy gel was spread uniformly using a spatula over the area where the CFRP plate was to be placed. The CFRP precured laminates were cut to the desired length of 5m (198in) and pressed to the wet epoxy gel using a hard roller. Air trapped within the epoxy gel was rolled out before curing. The thickness of the epoxy gel was approximately 1.5mm (0.0625in), uniform thickness being achieved through the use of metal strips and a spatula. Figures 4(b) and 4(d) show the beams after the application of laminate plate.

Manual wet layup (laminate sheet)

Beams 3 and 5 were strengthened with wet layup laminate sheets. An adequate layer of saturant was spread uniformly on the prepared surface of the concrete before applying the first layer of laminate sheet. The length and width of the CFRP laminate sheet was similar to that of the precured laminate plate. Three layers of CFRP sheet were used for the strengthening. After applying the first layer of sheet, it was pressed down with a “bubble roller” to eliminate trapped air and to impregnate the laminate sheet with saturant. The second and third layers of sheet were applied in a similar manner. A final layer of saturant was applied to complete impregnation prior to curing. Figures 4(b) and 4(d) show the application after curing.

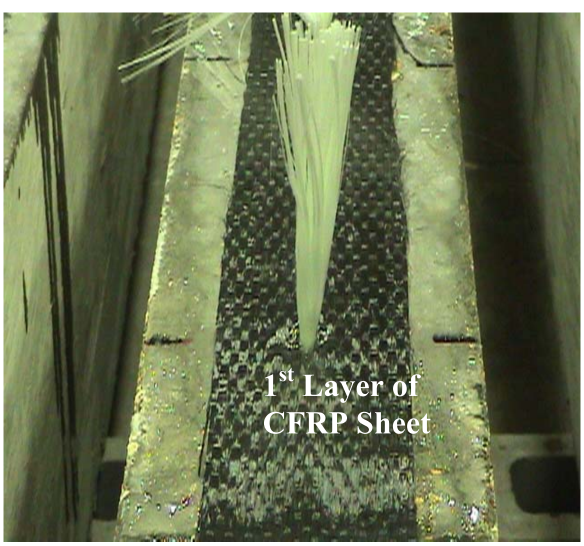
<u>GFRP anchor spikes with manual layup laminate sheets</u>

To avoid expected premature peeling, Beam 6 was strengthened with manual wet layup laminate sheets, anchored using GFRP spikes. After the surface preparation had been completed, eleven holes of 13mm (0.5in) diameter and 76mm (3in) depth were drilled into the concrete soffit at a center to center distance of 500mm (20in) prior to the strengthening. A layer of saturant was spread uniformly on the prepared surface areas and the holes were half filled with saturant.

After applying the first layer of CFRP sheet, the precured portions of the anchor spikes were inserted into the holes. The dry fibers were spread around the first layer of sheet in circular fashion and a layer of saturant was applied, as shown in Figure 4(c). Second and third layers of CFRP sheet were applied over the first layer containing the splayed fibers. Finally, a layer of saturant was applied to complete the impregnation prior to curing. Figure 5 shows the location of the anchor spikes.

(a) Surface preparation before strengthening

(b) Application of CFRP System



(c) GFRP Anchor Spike

(d) Beams after strengthening

Figure 4. Test Specimens

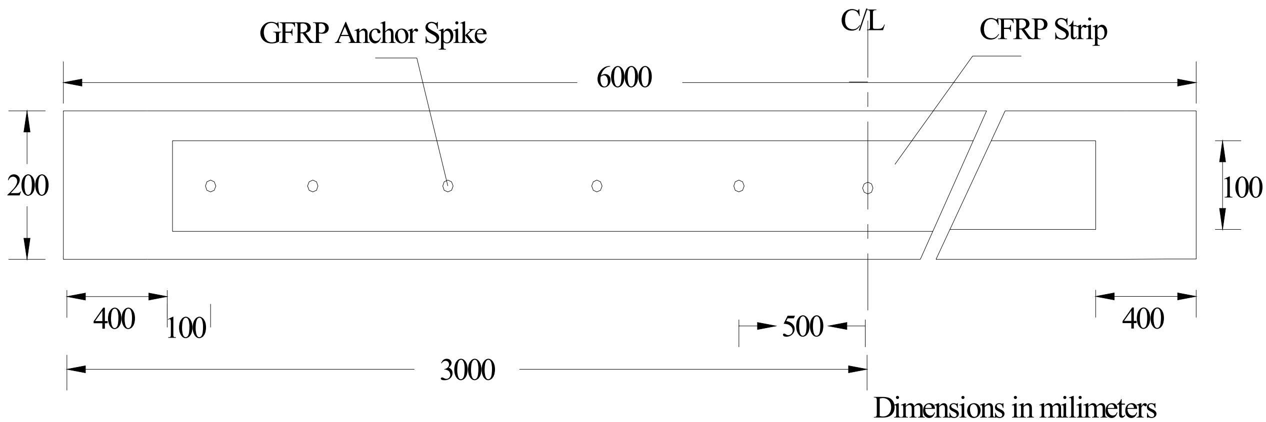


Figure 5. Location of Anchor Spikes (Plan View)

TEST SETUP AND TEST PROCEDURE

Two pin rollers were used to support the beam on a span of 5.5m (20ft). These pin rollers provided near-frictionless rotational action during the test. A single point load was applied at the center of the beam. A total of 5 linear variable differential transducers (LVDT's) and string transducers were placed as shown in Figure 6 for displacement monitoring. Strain gages were used to measure strains on the CFRP wet layup sheet, precured laminate and steel. A 445kN (100kip) capacity load cell was used to measure the applied load. Load was applied by means of a 30 ton hydraulic jack. The data from the electronic devices were recorded by a data acquisition system at a frequency of 1 Hz.

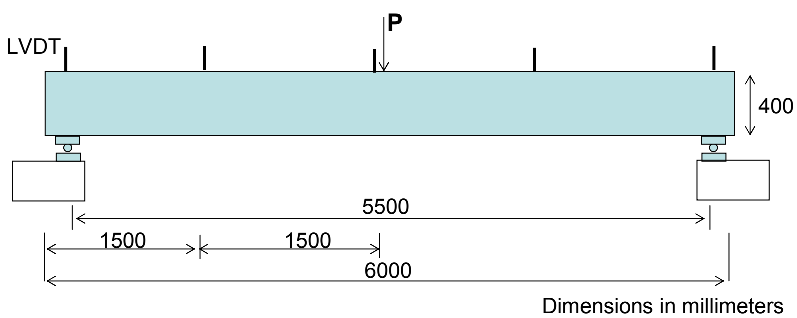


Figure 6. Test Setup

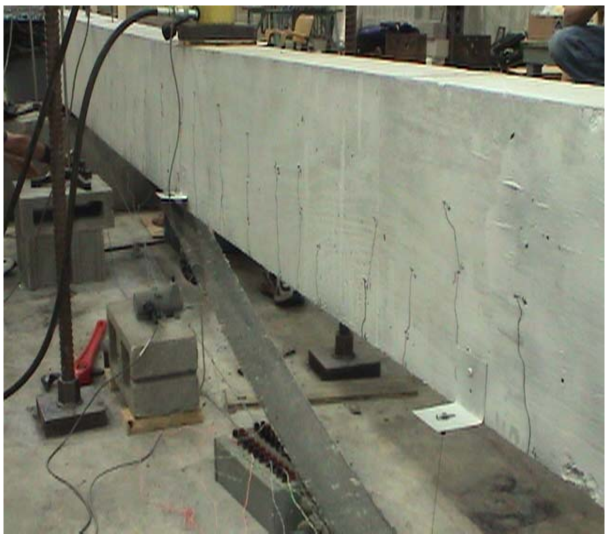
TEST RESULTS

Mode of failure

Table 5 summarizes the experimental results and Figure 7 illustrates the specimens after failure. Beam 1, which was a control specimen, exhibited a typical under-reinforced flexural failure. The test was stopped after the steel yielded and before the concrete crushed at a load of 45.4 kN (10.2 kip) due to large cracks in the tension zone at midspan. The cracks that developed in Beams 2 and 3 were fewer and finer compared with those of Beam 1. Complete delamination of the CFRP plate was observed in Beam 2 at a load of 81.4kN (18.3kip). Similar failure was observed in the wet layup sheet in Beam 3 at 70.8kN (15.9kip). Delamination of FRP from the concrete surface started from the midspan and propagated to the support in both beams. In fact, this mode of failure occurred in Beams 4 and 5 as well.

Table 5. Test Results

Beam	*Max external applied load kN (kip)*	*Increment/Decrement %*
1	*45.4 (10.2)*	*-*
2	*81.4 (18.3)*	*80*
3	*70.8 (15.9)*	*56*
4	*57.4 (12.9)*	*27*
5	*58.7 (13.2)*	*30*
6	*78.8 (17.7)*	*74*



(a)Beam 3 after failure

(b) Premature peeling in Beam 4

(c) Beam 4 after failure

(d) Beam 5 after failure

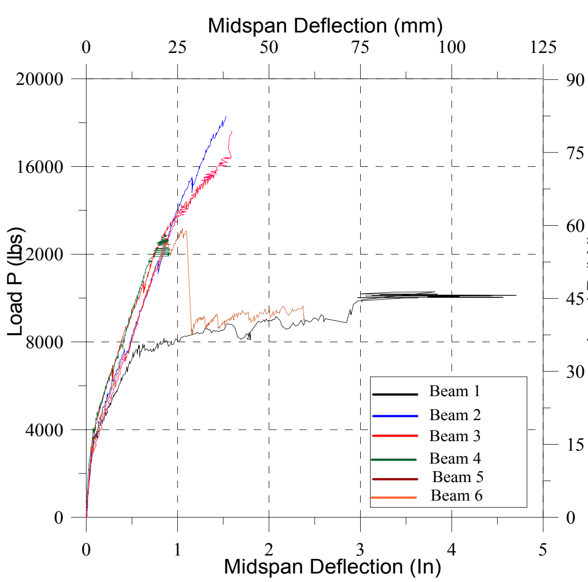
(e) Beam 6 after failure at the anchor spike

(f) Beam 6 after failure

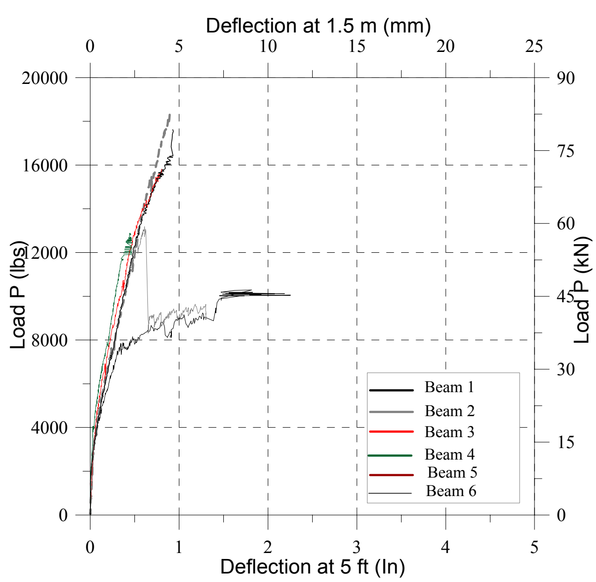
Figure 7. Beams after failure

Due to premature peeling, a 30% reduction in strength was observed in Beam 4 (pre-cured laminate) and a 20% reduction was observed in Beam 5 (wet layup sheets). Inclusion of the anchor spikes with the wet layup system led to the strength being increased by 35% compared with Beam 5. In fact, the strength of the curved-soffit beam containing the anchor spikes was higher than that of the flat soffit beam strengthened with wet layup sheets (Beam 3), indicating that the anchors decreased stress concentration and increased bond strength. This result is very exciting, proving that these GFRP anchor spikes have potential for use.

Figures 8(a) and 8(b) show the load vs deflection curves at mid span and at quarter span for all the specimens. The steel reinforcement in Beam 1 started to yield at a load of 36.5kN (8.2kips) and continued to deform afterwards. Beams 2 and 3 failed suddenly, exhibited low ductility and recorded lower mid span deflections than Beam 1. Because of premature peeling, Beams 4 and 5 recorded even lower deflections. Beam 6 exhibited a different failure mode in the presence of anchor spikes, as shown in Figure 7(f).



(a) Deflection at Midspan



(b) Deflection at quarter span

Figure 8. Load vs Deflection Curves

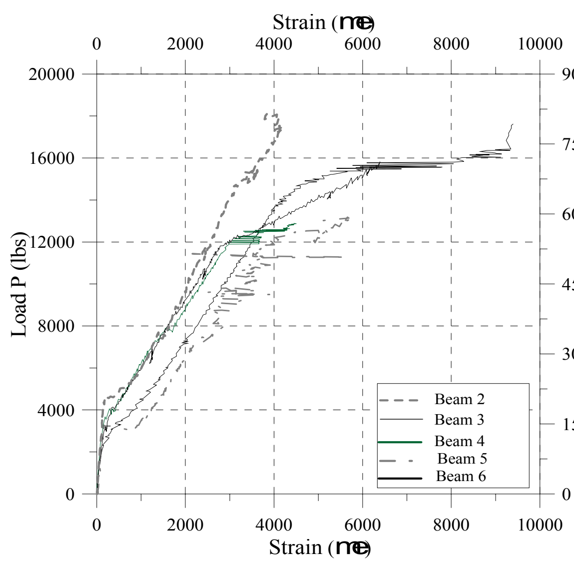
Strain profiles registered at midspan for all specimens are shown in Figure 9(a). The following were observed:

a) CFRP precured laminate in Beam 2 delaminated from the substrate when the strain at midspan reached $4.5^{o}/_{oo.}$

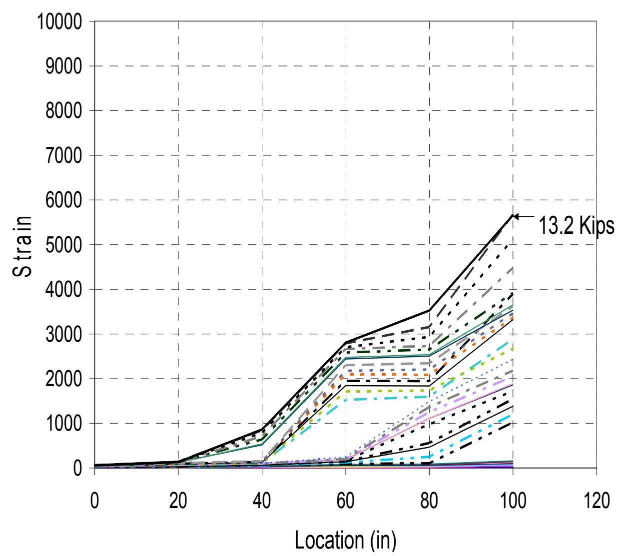
b) Beam 6 recorded a maximum strain of $9.2^{o}/_{oo}$ because of the presence of anchor spikes.

c) Minimum strain was recorded in Beam 5 due to premature peeling.

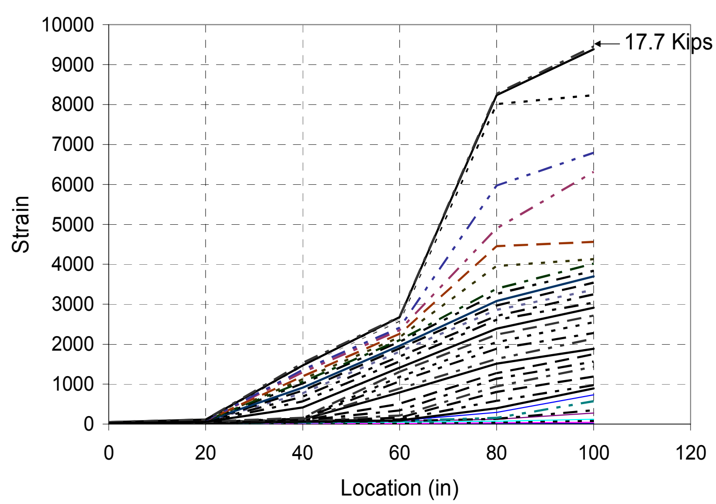
Figures 9(b) and 9(c) show the strain profiles of Beams 5 and 6 recorded in the CFRP sheets as a function of applied load and strain gage location. Strains increased significantly towards midspan. When compared with other research results without anchor spikes (ACI 440, 2001), the stress concentration decreases near the ends of the laminates. These plots show the GFRP anchor spikes are effective in helping to prevent debonding and premature peeling of the CFRP wet layup sheets.



(a) Strain in CFRP at Midspan



(b) Load vs Strain Location in Beam 5



(c) Load v/s Strain Location in Beam 6

Figure 9. Load vs Strain Curves

CONCLUSIONS

Based on the experimental results obtained from this research program, the following conclusions may be drawn:

1) For FRP strengthening schemes involving curved concrete soffits, it has been found that the documented allowable limit of curvature of 5mm per meter is unconservative.

2) Premature peeling was found to occur, leading to the conclusion that such curvature must be considered during the design of such strengthening schemes.

3) The use of GFRP anchor spikes eradicates the problem of premature peeling by resisting the transverse tensile stress that would otherwise lead to premature peeling.

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