Influence of CFRP Strengthening on the Behavior of Concavely-Curved Soffit Concrete Bridge Girders

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Abstract. Over the last few decades, fiber reinforced polymer (FRP) has been increasingly used in strengthening different structural concrete members. The main objective of this research is to study the influence of curvature on the performance of curved soffit reinforced concrete (RC) bridge girders that have been strengthened with carbon fiber reinforced polymers (CFRP). This experimental program was designed to evaluate the effect of concavity and soffit curvature on the CFRP laminate utilization and load capacity, compared to flat soffit RC beams strengthened with the same CFRP system. Accordingly, five beams, 2.7 m in length and having the same degree of soffit curvature (20 mm per 1 meter) extending over 2 meters of the span length, were tested under three-point monotonic static loading up to failure. CFRP pre-cured laminates were used for external strengthening in flexure. It was observed that 20 mm/m degree of curvature reduced the load-carrying capacity of strengthened concavely curved RC beams by 15.9 – 17.8%.

1. Introduction and previous studies
A large number of reinforced concrete (RC) bridge structures around the world have been built with a specific life span. However, increased traffic capacity, change in applied loads and serious damage to specific structural members can weaken bridges and lead to a loss of the bridge’s structural integrity before the end of its intended life span. For example, according to the American Road Transportation Builders Association [1], there are over 50000 structurally deficient bridges in need of repair in the United States. The bridges in Australia have a deficiency rate of ‘poor’ as specified in the Engineers Australia Report Card [2], there are also major deficiencies in state and local bridges that will be exacerbated by increasing traffic loads.

External strengthening of deteriorated reinforced concrete (RC) bridges has been accomplished using various innovative materials and techniques. There are conventional methods of strengthening, such as replacing the degraded element, attaching external steel plates, external post-tensioning and using steel jacks where applicable. These methods are time-consuming, may have some concerns for corrosion resistance, add more loads to the members, and need heavy mechanical lifting during the application process.

Over the last few decades, strengthening of structures using fiber reinforced polymers (FRP) is a technique that has become popular, due to its high strength to weight ratio, ease of installation, corrosion resistance and minimal maintenance requirements [3]. A considerable number of studies have been carried out on reinforced concrete structural elements strengthened with FRP [4, 5, 6, and 7]. These studies have shown that the effectiveness of FRP as a strengthening material is highly dependent on the strength of the bond between the concrete and FRP. CFRP plated RC girders usually fail due to plate delamination from the concrete substrate. The performance of the available adhesives has proved to be of high quality and sufficient for stress transfer between FRP and concrete. However, cracks in high shear regions due to concrete’s low tensile strength are the main reason for de-bonding. De-bonding has been investigated widely and by many researchers. A significant number of experiments have been conducted and many theoretical models have been developed to understand...
and control the de-bonding process. A significant amount of research has been carried out on the failure mechanism of flat soffit RC girders strengthened with FRP. However, quite surprisingly, the failure behavior of curved soffit RC members strengthened with FRP has been given very limited attention and is not fully understood, despite the fact that curved soffit girders are often used. The curvature of the member’s soffit induces direct transverse tensile stresses on the interface between the concrete substrate and the adhesive. Once these tensile stresses exceed the concrete tensile strength, premature intermediate CFRP de-bonding is initiated at the tip of flexural or flexural-shear cracks. De-bonding propagates towards the ends of the CFRP, causing full delamination at strains much lower than the rupture strain of the CFRP, leading to low utilization of the CFRP.

It is worth noting that the existing studies and the available data for strengthening curved soffit reinforced concrete girders with FRP are very limited. Only thirteen tests have been found from the existing literature [8, 9, and 10]. Table 1 shows details and test results of these thirteen beams.

The performance of wet layup and pre-cured CFRP flexural strengthening system for RC beams with local and global curvature was investigated and compared to the performance of flat soffit beams strengthened with CFRP [8]. It was concluded that a maximum allowable degree of curvature of 5 mm per 1 meter can only be tolerated over a chord length up to 1 meter.

Elsewhere, the performance of CFRP laminate flexural strengthening system for RC beams with globally curved soffit over varying curvature was investigated [9]. It is recommended that a 5 mm/m degree of curvature will result in a reduction in the utilization level of strengthening provided by the CFRP laminate compared with flat soffit beam strengthened with similar CFRP system [9]. The degree of curvature means that if a 1-meter long straight line is held against a curved surface, then the maximum normal distance between the straight line and the curved surface is 5 mm.

Moreover, the interface performance of concavely-curved soffit on a concrete joints level strengthened with CFRP sheet was analyzed and a theoretical model was developed to predict the strain distributions along the CFRP at service stage [10]. The test results presented by Aiello et al [10] showed that the presence of curvature leads to a reduction of the ultimate capacity and resulting in de-bonding of the CFRP sheet from concrete substrate.

**Table 1.** Experimental studies on curved soffit RC beams strengthened in flexure with CFRP

| Researcher | Beam ID | $t_{rise}$ (mm) | $b_{chord}$ (mm) | $t_{degree curvature}$ (mm/m) | CFRP form | No. of layers | $t_f$ (mm) | $b_f$ (mm) | Failure load (kN) | Failure mode |
|------------|---------|-----------------|------------------|-----------------------------|-----------|-------------|-----------|-----------|------------------|--------------|
| Eshwar et al. [8] | B-1 | 0 | 0 | 0 | None | 0 | - | - | 45.4 | Flexure |
| | B-2 | 0 | 0 | 0 | Laminate | 1 | 1.20 | 100 | 81.4 | IC de-bonding |
| | B-3 | 0 | 0 | 0 | Sheet | 3 | 0.75 | 100 | 70.8 | IC de-bonding |
| | B-4 | 5 | 1000 | 5 | Laminate | 1 | 1.20 | 100 | 82.3 | IC de-bonding |
| | B-5 | 5 | 1000 | 5 | Sheet | 3 | 0.75 | 100 | 70.8 | IC de-bonding |
| | B-6 | 45 | 3000 | 5 | Laminate | 1 | 1.20 | 100 | 73.8 | IC de-bonding |
| | B-7 | 45 | 3000 | 5 | Sheet | 3 | 0.75 | 100 | 67.2 | IC de-bonding |
| | B-8 | 125 | 5000 | 5 | Laminate | 1 | 1.20 | 100 | 57.4 | IC de-bonding |
| | B-9 | 125 | 5000 | 5 | Sheet | 3 | 0.75 | 100 | 58.7 | IC de-bonding |
| | B-10 | 125 | 5000 | 5 | Sheet | 3 | 0.75 | 100 | 78.8 | IC de-bonding |
| | 1 | 0 | 0 | 0 | Laminate | 1 | 1.40 | 40 | 36.1 | IC de-bonding |
| | 2 | 36 | 2700 | 5 | Laminate | 1 | 1.40 | 40 | 31.7 | IC de-bonding |
| | 3 | 110 | 2700 | 15 | Laminate | 1 | 1.40 | 40 | 32.0 | IC de-bonding |

Notes:
1 See the sketch shown in Figure 1.
2 Sheet with spikes anchors.
3 $t_f$ and $b_f$ – Thickness and width of CFRP sheet or laminate, respectively.
2. Experimental program

The general aim of this research is to understand the behavior of curved soffit RC beams strengthened with FRP using the pre-cured laminate system. Five beams were tested in this experimental program. Two were flat soffit beams; one was un-strengthened (F-1) and one was strengthened with CFRP laminate (F-2). The other three were curved soffit beams; one was un-strengthened (C-1) and two identical beams were strengthened with CFRP laminate (C-2 and C-3). The curved soffit beams were constructed with a 20 mm per 1-meter degree of curvature as illustrated in Figure 1.

![Diagram of 20 mm per 1 meter degree of curvature.](image)

2.1 Material Properties

All the above beams were constructed from the same concrete batch and similar deformed steel bars (10 and 12 mm in diameter). Tests were carried out on the constituent materials to determine their mechanical properties. The design concrete cylinder compressive strength at 60 days was 48.7 MPa in accordance with ASTM [11]. The steel average modulus of elasticity and yield strength for both N10 and N12 were, 202000, 201000, and 580, 554 MPa, respectively in accordance with ASTM [12]. The CFRP laminate of thickness 1.4 mm, width 50 mm and elastic modulus 165000 MPa as reported by the manufacturer.

2.2 Test specimens details

All beams were designed in accordance with AS5100 [13] and ACI 318-14 [14]. The beams’ configurations and reinforcement details are shown in Figure 2. All tested beams were 2700 mm in length and 140 mm in width. All beams were designed with equal dimensions at mid-span section (140 mm wide x 260 mm deep). So, the cross-sectional dimensions of the curved soffit beams near the ends were different from the flat soffit beams. All beams were reinforced with three N12 in tension and two N10 in compression. Tension steel reinforcement was bent to provide consistent cover along the beam. N10 shear stirrups were provided at 90 mm c/c spacing.
2.3 CFRP installation

All strengthened beams were flipped upside down for ease of installation. The process of applying the CFRP laminate consisted of two major steps: surface preparation and CFRP bonding. In the first step, the RC beam’s bonding surface was sandblasted to give a sandpaper surface. The surface was cleaned from dirt and a primer was applied to the surface of all strengthened beams with a brush to seal gaps and small cracks. The primer was left to cure for 60 minutes to give a tacky, nonporous surface. The second step was application of CFRP laminate to the beams. The CFRP laminate was cut into plates, 50 mm wide and 2000 mm long. The laminate adhesive was prepared by mixing its two parts using a mixer for 3 to 5 minutes. The laminate adhesive was equally applied to the CFRP plates to form a layer 3 mm thick. Next, the CFRP laminate was placed on top of the primer and pressed down by hand to form a thin layer of adhesive with 1.5 mm thickness. All specimens were left to cure for eight days at room temperature.

2.4 Testing arrangements

The test configuration was designed upside-down, as shown in Figure 3, this was due to some limitations of monitoring the beam soffit with the FRP plate. The beam was held from the top by two steel support blocks, while the hydraulic actuator was placed underneath the beam and the stroke was upward. All beams were tested under monotonic static loading with a clear span of 2300 mm. The beams were loaded using an MTS actuator with 500 kN load capacity. For all beams, the loading rate during testing was equal to 2 mm/min. Micro-laser displacement sensors were placed at the two supports and at mid-span sections.
2.5 Test results and discussion

Flat soffit control beam F-1 exhibited a typical under-reinforced flexural failure; as the load increased beyond the cracking load, flexural cracks started to propagate. The internal strain gauges indicated that the steel in the tension zone yielded at 68 kN and the peak failure load was 78 kN. Curved soffit control beam C-1 failed in a similar manner to beam F-1, the peak load for C-1 was lower than that for F-1 (73 kN) due to the existing bend in the tension reinforcement. Beam F-2 failed by intermediate span-induced crack de-bonding (IC) at 107 kN, as shown in Table 2. Similar failure was observed in beams C-2 and C-3 at 88 kN and 90 kN, respectively. Figure 4 shows the mode of failure for F-2 and C-2. All strengthened beams showed a reduction in deflection (Figure 5) and crack width and an increase in the load carrying capacity compared to their control beam. The maximum strain readings in the CFRP at the mid-span section were recorded. Beam F2 reached 43% utilization level as the maximum CFRP strain was 7414 $\mu\varepsilon$ of the 17000 $\mu\varepsilon$ CFRP laminate ultimate strain. While beam C2 and C3 reached a 27.2% and 30.6% utilization level, respectively. The maximum CFRP strain recorded in beams C2 and C3 was 4622 $\mu\varepsilon$ and 5213 $\mu\varepsilon$, respectively.

The increase in load capacity of the strengthened beams attained 20.5 – 37.2%, compared to the un-strengthened control beams. As load kept increasing, flexural and shear-flexural cracks increased, leading to high interfacial stresses between the concrete substrate and the laminate. This resulted in complete CFRP delamination starting from the mid-span section and propagating towards the supports. It was observed that the 20 mm/m curvature reduced the load carrying capacity of strengthened concavely curved reinforced concrete beams by 15.9 – 17.8%, due to the concentration of the direct transverse tensile stresses on the interface between the concrete substrate and the applied laminate adhesive.
Figure 4. Crack patterns of flat and curved soffit beams at failure.

Table 2. Summary of results

| Beam ID | Soffit Type | CFRP Type | Cracking Load $P_{cr}$ (kN) | Failure Load $P_u$ (kN) | Effect of Strengthening (%) | Effect of Curvature (%) | Max. CFRP Strain ($\mu$e) at Mid-span |
|---------|-------------|-----------|-----------------------------|-------------------------|-----------------------------|-------------------------|-------------------------------------|
| F-1     | Flat        | None      | 18                          | 78                      | Reference                   | Reference               | -                                   |
| F-2     | Flat        | Laminate  | 33                          | 107                     | +37.2                       | Reference               | 7414                               |
| C-1     | Curved      | None      | 15                          | 73                      | Reference                   | -                       | -                                   |
| C-2     | Curved      | Laminate  | 27                          | 88                      | +20.5                       | -17.8                   | 4622                               |
| C-3     | Curved      | Laminate  | 28                          | 90                      | +23.3                       | -15.9                   | 5213                               |
3. Conclusions
This paper has reviewed available studies on the behavior of strengthening curved soffit RC bridge girders using CFRP materials. An experimental program has been presented to establish a better understanding of the effect of curvature on the utilization level of CFRP flexural strengthening compared to flat soffit beams. The following conclusions can be drawn:

1. Flat soffit beams strengthened with CFRP laminate achieved a 37% increase in strength over the control flat soffit beam.

2. Curved soffit beams strengthened with CFRP laminate achieved a 22–25% increase in strength, compared with the control curved soffit beam.

3. Curved soffit beams of 20 mm per 1-meter curvature strengthened with CFRP laminate was found to reduce the strain to initiate IC de-bonding from 7414 με to 4917 με (28.9%).

It was observed that 20 mm/m curvature is detrimental to the capacity of strengthened concavely curved RC beams. Therefore, further investigation of different degrees of curvature is needed to fully understand curvature’s effect on the different CFRP strengthening systems. All beams retained their original strength after the CFRP plate delaminated.

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