UPGRADING SHEAR-STRENGTHENED RC BEAMS IN FATIGUE USING EXTERNALLY-BONDED CFRP

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Keywords: RC beams, Fatigue, Shear strengthening, Externally-bonded CFRP

ABSTRACT
Research on the behavior of RC beams shear-strengthened with EB FRP under long-term cyclic loading (fatigue) is relatively few and rather limited. The present study has examined two CFRP shear strengthening systems by comparing their effectiveness in extending the fatigue life of RC structures for increased live load (U-wrap sheets versus L-shape laminates). Laboratory tests performed on full-size RC T-beams were conducted. The results confirmed the feasibility of using both EB CFRP systems for shear strengthening under cyclic loading. They also showed an enhanced fatigue behavior of specimens when strengthening with L-shape laminates compared to U-wrap sheets.

1 INTRODUCTION
The use of externally bonded (EB) carbon fiber-reinforced polymer (CFRP) composites for strengthening existing RC structures is now a well-established technology, whether in the form of fabrics (sheets) or plates (laminates). Short-term behavior of CFRP shear-strengthened RC beams subjected to static loading is well-documented for both experimental research and analytical design procedures. In contrast, research data on long-term behavior is very limited, particularly under cyclic loading (fatigue). Moreover, investigations dealing with CFRP shear strengthening under fatigue loading are very few [1-4]. Prefabricated CFRP L-shape laminates have been developed as a new shear strengthening technique that presents a potential alternative to current strengthening systems, i.e. use of CFRP U-wrap sheets. They can be easily bonded to concrete surfaces and require less workmanship for surface preparation. In addition, the laminates do not easily peel off, especially when they are embedded into the flange of T-beams. Various tests have been performed to evaluate the feasibility of the L-shape laminates, but most of them were conducted under static loading. This study compares experimentally the fatigue performance of RC T-beams shear-strengthened with the two EB CFRP schemes (U-wrap sheets versus L-shape laminates). The FRP retrofit was intended to increase the original capacity of deficient RC beams due to an increase in projected applied load. The results are presented in terms of failure modes, deflection and strain responses undergone by internal steel reinforcement and CFRP, stiffness degradation and fatigue damage accumulation. The effectiveness of both EB CFRP systems in extending the service life and enhancing the fatigue behavior of shear-strengthened RC beams is discussed, as well as the influence of internal steel stirrup ratio. Comparison with the upper fatigue limits recommended by design codes is also discussed.

2 EXPERIMENTAL PROGRAM
Six laboratory tests performed on RC T-beams were investigated in this experimental study. The beams had a total length of 4520 mm and a total height of 406 mm. Figure 1 presents the details of test specimens. Two different EB CFRP shear-strengthening systems were used in this study, which corresponded to an equivalent CFRP ultimate strength: (i) Unidirectional CFRP U-wrap sheets applied continuously over the shear span using a wet layup procedure (Figure 1(a)), and (ii) Unidirectional
CFRP L-shape laminates prefabricated by pultrusion in an epoxy matrix; they were applied to the web in intermittent strips spaced at 175 mm and fully embedded into the flange (Figure 1(b)). Each strengthening scheme consisted of three different steel stirrup ratios (S0, S1 and S3 series). The experimental program matrix is presented in Table 1.

The L-shape laminates had a 90 degree bend with an inner radius of 25 mm, a width of 20 mm, and a thickness of 1.4 mm. They were characterized by an ultimate tensile strength of 2250 MPa, elastic modulus of 120 GPa and elongation at rupture of 1.9%. The CFRP sheets were characterized by a thickness of 0.381 mm, ultimate tensile strength of 894 MPa, elastic modulus of 65 GPa and elongation at rupture of 1.33%. The longitudinal steel reinforcement consisted of four M25 (nominal diameter = 25.2 mm) bars with a yield stress of 470 MPa. The transverse steel consisted of M8 (nominal diameter = 8 mm) stirrups with a yield stress of 640 MPa. A concrete compressive strength of 35 MPa on average was obtained by standard compression tests.

The specimens were tested in three-point load bending and subjected to fatigue loading up to 6 million load cycles at a rate of 3 Hz. The specimens that did not fail in fatigue were then tested monotonically up to failure. The applied cyclic loading ranged between 35% and 65% of ultimate static load, $P$, which corresponded to the total shear resistance of the specimen under study (i.e., including the contribution of CFRP). Table 2 presents the applied cyclic loads for each series of both strengthening schemes. The upper and lower limits, $P_{\text{min}}$ and $P_{\text{max}}$, evolve with respect to a mean value estimated at 50% of ultimate, which corresponded to passage of a standard vehicle at a crawling speed. As for the post-fatigue static tests, they were performed under displacement control conditions at a rate of 2 mm/min. The vertical displacement of specimens was measured under the applied load. The longitudinal steel was instrumented with a strain gauge at the location where the load was applied. Strain gauges were also affixed to the stirrups located in the loading zone along the anticipated plane of shear failure. The strains in CFRP were measured using crack gauges, which were fixed vertically onto the lateral faces at the same positions as the internal stirrup strain gauges.
3 DISCUSSION OF TEST RESULTS

3.1 Failure modes

Specimens with steel stirrups strengthened using U-wrap sheets failed in flexure by rupture of longitudinal steel. The two specimens sustained more than 5 million cycles, the ultimate failure in S1-Sheet and S3-Sheet occurred, respectively, at 5.03 and 5.62 million cycles. No yielding or rupture of steel-stirrups was observed in these specimens before failure.

Specimens with steel stirrups strengthened using L-shape laminates endured 6 million cycles without failure. No yielding of the internal steel reinforcement (longitudinal and transverse) was observed during the whole course of the fatigue tests. The specimens failed in shear under static loading; they exhibited a considerable yield plateau due to longitudinal steel yielding, accompanied by yielding of transverse steel and followed by a major shear crack.

Specimens without transverse steel reinforcement (S0 series) of both CFRP systems did not fail in fatigue, but in shear under static loading; they failed by concrete strut crushing before reaching their flexural elastic limit (i.e. yielding of longitudinal steel).

A comparison between both CFRP schemes of the same series, which were subjected to the same cyclic loading conditions, revealed that strengthening in shear using L-shape laminates was more effective in extending the fatigue service life of RC beams than using U-wrap sheets. However, despite the flexure fatigue failure exhibited by the latter specimens, they nevertheless sustained more than 5 million cycles. This confirms the effectiveness of both EB CFRP schemes in enhancing the fatigue behavior of RC beams strengthened in shear for increased service load.

3.2 Deflection response

Figure 2(a) illustrates the variation of the deflection with the number of cycles for the maximum applied load, \( P_{\text{max}} \). All specimens exhibited an initial increase in deflection during the early cycles, followed by a stable phase in which the deflection slowed significantly with increasing number of cycles. For specimens S1-Sheet and S3-Sheet that failed in flexure fatigue, the response featured a sudden increase in deflection due to longitudinal steel yielding before ultimate failure. For both CFRP systems, the specimens exhibited an increase in deflection levels with the increase in steel stirrup ratio (S0 versus S3 versus S1 series), which can be attributed to higher shear resistance and hence higher applied fatigue loadings. As shown, all specimens strengthened with L-shape laminates followed almost the same trend, but exhibited slightly lower deflections and sustained 6 million cycles without failure compared to specimens with U-wrap sheets. Comparing the specimens of series S0 (without steel stirrups), S0-Laminate exhibited an increase in deflection from 2.25 mm at the first cycle to 3.07 mm at 0.5 million cycles to reach 3.55 mm at the last cycle; this represents a total increase of 58%, in which about 37% occurred during the first 0.5 millionth cycles. In contrast, specimen S0-Sheet exhibited a deflection increase from 2.29 mm to 3.58 mm at 0.5 million cycles to 3.96 mm at 6 million cycles; this represents a total increase of 73% and reflects severe damage accumulation, starting with 56% during the early cycles. This demonstrates the greater efficiency of shear strengthening using L-shaped laminates under cyclic loading in enhancing the fatigue behavior.

3.3 Strains in transverse steel

Figure 2(b) shows the curves representing the maximum strains achieved in steel stirrups versus number of cycles for \( P_{\text{max}} \). As shown, transverse steel strains increased as stirrup spacing decreased
during the whole course of the fatigue tests. However, for both strengthening systems, an enhanced fatigue behavior of the transverse steel was obtained in S1 specimens compared to S3 series. A more ductile behavior was thus obtained with increasing the ratio of steel stirrups. A comparison between the CFRP shear strengthening schemes of the same series, which were subjected to the same loading conditions, revealed a reduction in the rate of increase in stirrup strains between the first and last cycles when strengthening using L-shape laminates, and hence a reduction in the rate of fatigue damage accumulation.

The maximum strain recorded at the last cycle represented 49% (1620 µε) of the yield strength in specimens with L-shape laminates and 56% (1860 µε) in specimens with U-wrap sheets. The ACI 440.2R-08 [5] guideline states, in this context, that the stress in longitudinal steel under fatigue service load should be limited to 80% of the yield stress. No specific limits were provided for steel stirrups; however, research seems to indicate that the service life of steel reinforcement is similar whether it is longitudinal or transverse [6].

Figure 2: Deflection and strain responses for $P_{\text{max}}$.

### 3.4 Strains in longitudinal steel

Figure 2(c) represents the curves of the maximum strains in longitudinal steel recorded at the load application point for $P_{\text{max}}$. Specimens with steel stirrups strengthened using U-wrap sheets, i.e. S1-Sheet and S3-Sheet, exhibited a sudden increase in strain due to longitudinal steel yielding, respectively, at 4.35 and 5.47 million cycles. The highest strains were achieved in specimens of S1 series of both strengthening techniques. However, the increase in the amount of steel stirrups resulted in an enhanced ductile behavior of strengthened RC beams, even if higher stress range was applied.

The maximum strain recorded in S1-Laminate at 6 million cycles (2020 µε) represented more than 84% of the yield strength, which exceeded the upper limit of 80% imposed by ACI 440.2R-08 [5]
The longitudinal steel stress range achieved by S1-Sheet (that failed in flexure) at the first cycle was 151 MPa compared to 168 MPa achieved by S1-Laminate (without failure). This confirms the greater potential of shear strengthening technique using L-shape laminates over U-wrap sheets in extending the service life and enhancing the fatigue performance of existing RC beams. The reached stress ranges lies between (and exceeded) the upper limits of 125, 138 and 162 MPa recommended, respectively, by standards CSA-S6-06 [7], ACI 215R-74 [8], and AASHTO [9]. This may indicate that code specifications for fatigue limit-state design of unstrengthened RC members may also be used for structures shear-strengthened with CFRP U-wrap sheets.

3.5 Strains in CFRP

Figure 2(d) illustrates the strains in CFRP versus number of cycles for $P_{\text{max}}$. The curves represent the highest strains achieved by the L-shape laminates along the shear span. The response for all specimens is characterized by a rapid increase in strain during the early cycles, followed by a stable region in which the strain increase progressed gradually. For the same stirrup series, under the same loading conditions, an enhanced fatigue behavior of the CFRP was obtained when using L-shape laminates compared to U-wrap sheets. This reflects a reduction in the rate of fatigue damage accumulation of RC beams shear-strengthened with L-shape laminates. The fact that no sign of failure by debonding was observed during the fatigue tests clearly demonstrates the effectiveness of both EB CFRP shear strengthening techniques under cyclic loading.

For both CFRP systems, a substantial reduction in the rate of increase in CFRP strain range between the first and last cycles was obtained with the decrease in stirrup spacing, despite the higher applied loads experienced by specimens of S1 series. In terms of presence of steel stirrups, specimens with no steel stirrups (S0) exhibited much higher rates of increase in CFRP strain range than those with steel stirrups (S1 and S3). This confirms the existence of an interaction and hence of a stress redistribution between internal shear reinforcement and EB CFRP under fatigue loading.

The highest CFRP strains attained at the last cycle in U-wrap sheets (2430 $\mu$strains) and L-shape laminates (2690 $\mu$strains) represented, respectively, 18% and 14% of their ultimate strains. The ACI 440.2R-08 [5] guideline states, in this context, that the strain in CFRP for flexural strengthening under fatigue service load should be limited to 55% of its ultimate strength. No specific recommendations were provided for FRP fatigue stress limits with respect to shear strengthening.

3.6 Stiffness degradation

The stiffness measurements of test specimens at regular 0.5-million-cycle intervals are presented in Figure 3. It is defined as the ratio of the applied load range to the achieved deflection range, corresponding to $(P_{\text{max}}-P_{\text{min}})$. Most of the stiffness loss occurred between the first and the 0.5 millionth cycles, followed by a stable phase in which the stiffness remained relatively constant until more than 5 million cycles. For instance, the stiffness in S0-Laminate decreased from 72 kN/mm at first cycle to 52 kN/mm at 0.5 million cycles to reach 50 kN/mm at 6 million cycles. This reflects a severe degradation with a total stiffness loss of 31%, in which 28% occurred in the first 0.5 million cycles.

A comparison between S1-Sheet and S1-Laminate, which were subjected to the same cyclic loading, revealed that both specimens followed the same trend and exhibited almost the same levels of stiffness loss, up to the failure of S1-Sheet when a sudden decrease in stiffness occurred. The same was observed for specimens of S3 series, although S3-Laminate exhibited lower stiffness levels than S3-Sheet and sustained 6 million cycles without failure. This demonstrates the superior performance of L-shape laminates in extending the service life of shear-strengthened RC beams compared to U-wrap sheets.

For both CFRP systems, the stiffness levels decreased with the presence of steel stirrups during the whole course of the fatigue tests, which can be attributed to the increase in shear resistance, and hence the applied cyclic loads.
3.7 Static test results (post-fatigue)

Table 3 presents the results from tests under static loading on specimens that did not fail in fatigue. The results revealed a substantial gain reduction in shear resistance due to CFRP with the transverse steel ratio (S0 versus S3 and S1 series). In fact, the gain in shear resistance due to CFRP decreased from 138% in S0-Laminate to 59% in S3-Laminate to 25% in S1-Laminate. This confirms the findings of other researchers on the inverse interaction between internal shear reinforcement and EB FRP under static loading since 2002 [10], but not yet captured in the guidelines. A comparison between both shear strengthening systems revealed a 138% gain in CFRP shear resistance for S0-Laminate compared to 52% gain for S0-Sheet. This demonstrates the superior potential of shear strengthening using L-shape laminates over U-wrap sheets in enhancing the load carrying capacity of RC T-beams.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( P_s ) (kN)</th>
<th>( V_n ) (kN)</th>
<th>( V_c ) (kN)</th>
<th>( V_s ) (kN)</th>
<th>( V_{frp} ) (kN)</th>
<th>Gain due to CFRP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0-Sheet</td>
<td>209</td>
<td>138</td>
<td>91</td>
<td>0</td>
<td>47</td>
<td>52</td>
</tr>
<tr>
<td>S0-Laminate</td>
<td>328</td>
<td>217</td>
<td>91</td>
<td>0</td>
<td>126</td>
<td>138</td>
</tr>
<tr>
<td>S3-Laminate</td>
<td>468</td>
<td>310</td>
<td>91</td>
<td>104</td>
<td>115</td>
<td>59</td>
</tr>
<tr>
<td>S1-Laminate</td>
<td>456</td>
<td>302</td>
<td>91</td>
<td>151</td>
<td>60</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3: Test results under static loading.

4 CONCLUSIONS

On the basis of the results of the present study, the following conclusions can be drawn:

- A typical cumulative degradation trend of fatigued RC beams was observed in all test specimens; they exhibited an accelerated rate of damage during the early cycles, characterized by an initial increase in deflection and strain in various components, followed by a stable phase in which the rate of damage progressed gradually.
- Use of L-shape laminates for shear strengthening under cyclic loading has been shown to be more effective than use of U-wrap sheets in enhancing the fatigue behavior and extending the service life of RC beams.
Specimens strengthened with CFRP U-wrap sheets also behaved well since they sustained more than 5 million cycles. However, the longitudinal steel may be the weakest link and should be looked at with caution for this application technique, especially for extended service life, where it may govern the upper limit of the projected capacity.

The existence of an interaction and hence of a stress redistribution between internal shear reinforcement and EB CFRP was confirmed under fatigue loading, as well as under static loading.

REFERENCES


