Fatigue Performance of Hybrid CFRP-GFRP-UHPC Beams

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ABSTRACT

The number of experimental investigations into the performance of structural members constructed using a combination of high performance materials have been increasing with recent years. One of the main advantages of high performance materials over conventional building materials is their resistance to corrosion. This research program examined the behaviour of innovative hybrid beams composed of different Fibre Reinforced Polymer (FRP) materials as well as Ultra-High Performance Concrete (UHPC) under cyclic flexural loading. Three beams were tested and it was found that the hybrid beams were capable of sustaining comparable strength under fatigue loading as to when subjected to monotonic loading. The findings also indicated that design considerations should be made for the occurrence of increased strains and deflections during the initial 40,000 cycles of testing as well as for the residual deformations and softening that occurs in the hybrid beam during the period prior to ultimate failure, most probably due to the initiation of internal microcracking in the matrix of the FRP material.

KEYWORD

fibre reinforced polymer, glass, carbon, ultra-high performance concrete, hybrid, fatigue,
1. INTRODUCTION

Research into the use of high performance materials for structural applications, such as the construction of bridges, has grown substantially in recent years [1-6]. The main advantage for the use of such materials is the elimination of long-term structural problems, like corrosion. These problems negatively influence the performance of conventional building materials, such as reinforced concrete and structural steel.

For structural members intended for use in bridge applications, its performance under long-term cyclic loading must be verified. Experimental investigation of hybrid members, which consist of a combination of different high performance materials, has been conducted by various researchers around the world [7-12]. In this experimental program, an innovative hybrid design is subjected to different fatigue loading regimes. The results and findings from this research will be presented in this paper.

2. DESIGN AND BEAM DESCRIPTIONS

The main objective for the design of the hybrid beam is the creation of a light-weight, high strength structural member that is capable of withstanding the typical and expected loading conditions for bridge applications. In this particular design, a combination of Fibre Reinforced Polymers (FRPs) in conjunction with Ultra-High Performance Concrete (UHPC) was used to create a hybrid structural member.

The hybrid FRP-UHPC beams consisted of a pultruded Glass FRP (GFRP) thin-walled hollow box section beam with a thin sheet of Carbon FRP (CFRP) epoxy bonded to the outer surface of the bottom flange. A layer of UHPC was also cast-in-place over the top flange of the GFRP box beam. Composite action was maintained between the UHPC and the GFRP box beam through the use of epoxy adhesives at the interface as well as closely spaced GFRP shear studs.

Due to the linear-elastic behaviour of the types of materials used in the hybrid beams, each component was carefully chosen based on their respective failure strains in order to contain the element of pseudo-ductility in the system at ultimate failure state. Pseudo-ductility allows for the presence of advanced warning signs in a system that is composed solely of linear-elastic materials, which do not ordinarily display symptoms prior to failure, by ensuring that a non-critical structural component will reach its failure strain prior to the overall collapse of the structural system. In this particular system, the rupture of the CFRP sheet prior to crushing of the UHPC was designed to act as the physical symptoms of impending failure prior to its occurrence. The cross-section of the beam is shown in Figure 1.

3. MATERIAL PROPERTIES

The physical properties of the main materials used in the fabrication of the hybrid beams are provided in Table 1. The UHPC was intended solely to perform in compression and therefore compressive strength properties are provided in Table 1; similarly, the tensile properties of the GFRP and CFRP are provided.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus (MPa)</th>
<th>Ultimate Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>27558</td>
<td>321</td>
</tr>
<tr>
<td>CFRP</td>
<td>95800</td>
<td>986</td>
</tr>
<tr>
<td>UHPC</td>
<td>45107</td>
<td>124</td>
</tr>
</tbody>
</table>

3. EXPERIMENTAL PROGRAM

All of the three beams tested were placed under four-point flexural loading configuration. The centre-to-centre span length was 2900 mm, with the centre-to-centre distance between the two loading points equal to 600 mm.

To ascertain the performance of the hybrid beams for bridge applications, three beams were tested. The first beam (Beam C-S) was subjected to monotonic loading to serve as the control beam. The remaining two beams were tested under two different fatigue loading. The first loading regime, applied to Beam C-F1, investigated the effect of...
changing both the minimum and maximum applied stress limits in a step-wise fashion. For Beam C-F2, the second loading regime was used where the minimum applied stress was maintained at a constant value while the maximum stress limit was increased as testing progressed.

The design stress limits for the two fatigue loading regimes were established based on published sustained stress limits for GFRP and CFRP material in existing codes, standards and guidelines. Due to the composite nature of the hybrid beams, it was expected that its actual fatigue resistance would be greater than that of the weakest component (GFRP) and less than that of the strongest component (CFRP). The loading stresses applied onto the hybrid beams were defined to exert no less than 25% of the ultimate strength of the GFRP material and no greater than 50% of the ultimate strength for the CFRP material [14]. The design fatigue loading regimes are presented schematically in Figure 2.

![Fatigue loading regimes](image)

### 4. EXPERIMENTAL RESULTS

#### 4.1 Control Beam (Beam C-S)

Beam C-S was tested under displacement control at a loading rate of 1 mm/min. Though the beam behaved in a predominantly linear-elastic fashion, a major period of debonding at the interface between the top flange of the GFRP box beam and the UHPC layer occurred at a peak load of 222.2 kN, which corresponded to a mid-span deflection of 28.5 mm. With further loading, deviation from linear-elastic behaviour occurred, reaching ultimate failure at an applied load of 187.4 kN with a mid-span deflection of 49.9 mm. At this load (187.4 kN), the maximum strains in the GFRP hollow box beam were reached just prior to failure and were equal to 6486 με in tension (bottom flange) and 6338 με in compression (top flange); the UHPC compressive strain was 1006 με. For the UHPC layer, the maximum compressive strain was reached at the peak load of 222.2 kN at a value of 1922 με. At the peak load, the GFRP strain in tension was 5568 με. Since no debonding occurred at the GFRP-CFRP interface, the strain in the extreme bottom fibre of the GFRP would be equal to that of the CFRP sheet.

#### 4.2 Fatigue Loading Type 1 (Beam C-F1)

Beam C-F1 was subjected to fatigue loading conditions that incorporated changing stress limits in a step-wise manner. Prior to each change in the applied load condition, three quasi-static cycles were administered using the new load limits before continuing on with cyclic loading. Though the initial plan was to test Beam C-F1 up to 2.5 million cycles, it can be seen from Figure 2 that failure had in fact occurred slightly after 2 million cycles were reached. The applied loading range at the time of failure, at 2,301,009 cycles, was between 122 and 195 kN. The corresponding stress range in the GFRP and CFRP at the time of failure, determined based on the initial modulus of elasticity, were 40-56% \( f_{u,GFRP} \) and 46-63% \( f_{u,CFRP} \), where \( f_{u,GFRP} \) and \( f_{u,CFRP} \) are the ultimate tensile strengths of the GFRP and CFRP, respectively.

The changes in mid-span deflection, tensile strain and compressive strain at regular time intervals are presented in Figures 3 – 5. It can be immediately noted that, overall, the beam behaviour during the first 2 million cycles of testing did not show much change. However, once the testing surpassed 2 million cycles, considerable residual strains and beam deflections were detected. Whereas the tensile strain at the extreme tensile fibres began to increase, the compressive strains at the very top of the UHPC layer decreased over time after 2 million cycles.

![Mid-span deflection for Beam C-F1](image)
4.3 Fatigue Loading Type 2 (Beam C-F2)

The third hybrid beam, Beam C-F2, was tested using the second type of fatigue loading conditions, where only the maximum stress limit was changed during testing. The aim for this cyclic load test was to reach 1.5 million cycles; however, once the upper stress limit was changed upon reaching 1 million cycles, the performance of Beam C-F2 began to deteriorate. Beam C-F2 experienced failure, leading to a significant loss in flexural capacity, after 1,000,777 cycles. The load range applied to the beam was between 80 and 200 kN. The corresponding stress range in the GFRP and CFRP, determined using the same method as for Beam C-F1, were 24-56% of $f_{uGFRP}$ and 27-64% of $f_{uCFRP}$.

Due to the relatively brief period of time between the time when the stress limit was changed at 1 million cycles and 1,000,777 cycles, which is when ultimate failure occurred, softening and residual deflection and strains were not exhibited in the beam.

The changes in mid-span deflection, tensile strain in the CFRP as well as compressive strain in the UHPC are shown in Figures 6 – 8. Nearly all of the curves plotted in these figures were co-linear.

4.4 Failure Modes

Regardless of the loading type used, all of the three hybrid beams tested displayed physical symptoms of failure at the same locations. Firstly, there were visible longitudinal cracks in the webs of the GFRP hollow box beam,
positioned at the mid-height of the box beam, along with outward web buckling, particularly directly below the location of the point loads. Secondly, rupture at the intersection between the flanges and webs occurred, causing the GFRP hollow box beam to “open”. Lastly, interface debonding between the top flange of the GFRP hollow box beam and the UHPC layer occurred, which appeared as horizontal cracks of varying sizes along the length of the bond interface. The photographs provided in Figures 9 – 11 show the failure areas in their presented order in this section. Since failure occurred in the same areas for all of the hybrid beams, typical photographs are provided.

5. DISCUSSION

5.1 Effect of Fatigue Loading

In general, the results obtained from the three hybrid beams under different loading conditions provided consistent findings in relation to its flexural capacity. Neither of the hybrid beams tested under fatigue loading exceeded the maximum load reached by the control beam, Beam C-S, equal to 222 kN. However, more in-depth comparison between the experimental results from the two hybrid beams tested under fatigue loading showed significantly different values for the mid-span deflection and strains at ultimate failure.

For Beam C-F1, it was subjected to a less intense loading regime, with gradual increases in the average stress applied and smaller stress amplitudes exerted. This allowed for damage to slowly accumulate in the hybrid beam, resulting in the increases in residual strains and deflections that were observed from Figures 3 – 5. At 2,030,000 cycles, which was the last cycle at which data readings were taken, the maximum tensile strain in the CFRP was 6525 με alongside a maximum mid-span deflection of 46.2 mm. This set of structural conditions is very similar to that of Beam C-S at ultimate failure, with tensile strain and mid-span deflection of 6486 με and 49.9 mm. Looking more closely at the tensile strain and mid-span deflection of Beam C-F2 at 1,000,300 cycles, when the last set of data was collected, the values were 6566 με and 27.2 mm, respectively. The value for mid-span deflection reached by Beam C-F2 just prior to ultimate failure is quite similar to the deflection recorded in Beam C-S prior to the occurrence of interface debonding.

Analysis of the results indicate that the hybrid beams would be expected to have a longer fatigue life if subjected to the step-wise, incremental loading style used in Fatigue Loading Style 1 as compared with the more dramatic load changes used in Fatigue Loading Style 2. Though both of the hybrid beams attained very similar maximum loads, the slow transitional stress changes applied to Beam C-F1 allowed for the damage to be slowly absorbed, resulting in softening of the beam, whereas the dramatic load changes placed on Beam C-F2 caused rapid failure without any indications of softening.
5.2 Additional Considerations

One common element that is observed for both of the hybrid beams tested under fatigue loading is the noticeable jump in deflection and strain from the beginning of testing (0 cycles) to the next adjacent curve. In all of the related figures (Figures 3 – 8), there is a horizontal shift between the initial curve at 0 cycles (blue line) and the next curve (red line), after which the subsequent gaps between all of the following curves are much harder to detect. This finding suggests that the hybrid beams are more susceptible to accumulate damage from cyclic loading when the load is first applied, resulting in residual strains and deflections in the beam. It is speculated that internal microcracking in the matrix of the GFRP hollow box beam caused the initial drop in stiffness though this could not be confirmed by general visual inspection of the GFRP hollow box beam outer surface. This rate of damage accumulation decreases dramatically within the first 20,000 to 40,000 cycles, after which changes in the residual strain and deflections become more difficult to detect.

6. CONCLUSIONS

(1) The hybrid beam tested in this experimental program is capable of supporting maximum loads under fatigue loading that are comparable to its capacity under static loading.

(2) The fatigue stress limit of the hybrid beam is higher than the published sustained stress limit for GFRP material and lower than the published sustained stress limit for CFRP material, indicating that the performance of the hybrid beam is influenced by all the material components and not just that of the weakest component.

(3) A fatigue life exceeding 2 million cycles can be achieved with the use of variable amplitude load cycles within the allowable stress limits of its material components.

(4) Gradual and progressive fatigue damage will result in the development of residual strains and deflections in the hybrid beam, prolonging the fatigue life. Sudden and dramatic stress changes during cyclic loading will exceed the hybrid system’s ability to absorb damage, resulting in rapid failure.

(5) Design for bridge applications using hybrid beams should take into consideration strains and deflections at the beginning of the service life that is in addition to those predicted using linear-elastic theories caused by the onset of fatigue loading.

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