GFRP-REINFORCED CONTINUOUS BEAMS

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ABSTRACT

The non-corrodible Fibre-reinforced polymer (FRP) reinforcement has recently become a viable alternative to steel reinforcement especially for concrete structures in harsh environments, where steel-corrosion is a major concern. Indeterminate structural elements such as continuous concrete beams are common in structures like parking garages and over passages which might be exposed to extreme weather conditions and the use of de-icing salts. However, due to the linear-elastic behaviour of FRP materials up to failure, the ability of such materials to redistribute loads and moments in indeterminate structures is questionable. Understanding the full range of behaviour of continuous beams reinforced with FRP bars is required to provide reliable models that represent their actual structural response with acceptable accuracy. This paper presents the experimental results of two reinforced concrete beams continuous over two spans with rectangular cross-section. Each span was loaded with a concentrated load at mid-span. The longitudinal reinforcement of one beam was traditional steel bars, while the other beam was reinforced with glass FRP (GFRP) bars. Both beams were reinforced for shear with steel stirrups. The experimental results of the tested beams were used to evaluate the flexure response of the GFRP-reinforced continuous beam compared to the control steel-reinforced counterpart. It is concluded that the GFRP-reinforced concrete beam was able to redistribute the connecting moment over the intermediate support.

KEYWORDS

GFRP, concrete beams, continuous beams, moment redistribution, failure mode.

INTRODUCTION

Recently, using FRP bars as internal reinforcement became one of the main alternatives to steel to overcome corrosion-related problems. Due to their non-corrodible nature, FRP bars are commonly used in aggressive environments such as water treatment plants, coastal environments and structures exposed to harsh environments. In recent years, FRP bars have been used in Canada in bridge decks especially those exposed to de-icing salts. Some special applications make use of the non-magnetic nature of FRP bars such as Magnetic Resonance Imaging (MRI) rooms in hospitals and research laboratories. Extensive research in the last ten years studied the behaviour of simply-supported concrete beams reinforced with FRP (Benmokrane et al. 1996; Grace et al. 1998; Toutanji and Saafi 2000; Vijay and GangaRao 2001). On the other hand, very little though important research studied the behaviour of continuous concrete beams reinforced with FRP bars. Steel-reinforced continuous beams are usually capable of redistributing stresses between critical sections. This redistribution gives the structure more favourable ductile behaviour and ample warnings before failure. This capability is mainly referred to the yielding plateau that the steel material exhibits. However, as a result of the linear-elastic behaviour of FRP materials up to failure, there are concerns on the ability of such materials to redistribute loads and moments in continuous beams. Therefore and due to the lack of research, design codes and guide lines do not allow for moment redistribution in FRP-reinforced continuous beams.

BACKGROUND

FRP-reinforced continuous concrete beams were studied experimentally and analytically to evaluate their structural behaviour. Signs of moment redistribution were observed in previous studies. Grace et al. (1998) presented experimental results of seven continuously supported concrete beams with T-section. The beams were reinforced with different combinations of longitudinal and shear reinforcement made of steel bars, GFRP bars and carbon FRP (CFRP) bars. The study concluded that beams with different FRP reinforcement arrangement
demonstrated same load capacity as steel-reinforced beams; however, the ductility and failure modes were different. Also, Razaqpur and Mostofinejad (1999) reported experimental results of four CFRP-reinforced continuous beams with shear reinforcement made of steel or CFRP. The research indicated that over-reinforced sections with FRP bars in continuous beams exhibit a semi-ductile behaviour. This was demonstrated by experimental results of the tested beams which did not collapse after reaching the failure load of the section at internal support. Furthermore, Habeeb and Ashour (2008) introduced experimental results of three GFRP-reinforced continuous beams with different combinations of reinforcement ratios at mid-span and internal support. Signs of moment redistribution were observed.

On the analytical side, Gravina and Smith (2008) conducted a theoretical study on the flexural behaviour of statically indeterminate concrete beams with FRP bars. The study was performed using a local deformation model developed by the authors. They applied the theoretical model to continuous beams reinforced with FRP to predict the bending moment distribution, flexural cracks, crack spacing and crack width. The theoretical results were found to be mainly dependent on the bond characteristics the FRP bars and the surrounding concrete.

This paper presents experimental results of two continuous concrete beams; one reinforced with sand-coated GFRP bars and the other with traditional steel bars. The study aims to investigate the range of moment redistribution that can be achieved by GFRP-reinforced continuous beams.

**EXPERIMENTAL PROGRAM**

**Test Specimens**

Two reinforced concrete beams continuous over two spans were tested in flexure. One reinforced with GFRP bars and the other with traditional steel bars. The beams were 6.0 m long with a rectangular cross-section of 200 mm width and 300 mm depth. The beams were continuously supported over two equal spans of \( l = 2800 \text{ mm} \) each (Fig. 1). Both beams were designed to have similar flexural capacity at corresponding critical sections; mid-span and over the middle support. The steel-reinforced continuous beam (SS1) was designed to fail due to steel yielding at both mid-span and internal support sections. This was achieved by providing both sections with reinforcement ratio less than the balanced reinforcement ratio (\( \rho_b \)). On the other hand, the GFRP-reinforced continuous beam (GS1) was designed to have compression failure (concrete crushing) at both critical sections as recommended by the CSA/S806-02 code (CSA 2002). Therefore, it was provided with GFRP reinforcement ratio of approximately \( 2\rho_b \). Based on elastic analysis, the connecting moment over the middle support \((0.188P)\) is higher than that at the middle section \((0.156P)\), where \( P \) is the applied load at the middle of each span. However, a 20% moment redistribution was assumed to occur at the middle section, which resulted in changing the moment distribution to be \((0.15P)\) and \((0.175P)\) for the sections at mid-support and mid-span, respectively. Therefore, the flexural reinforcement in both beams was designed to provide the required strength considering the moment redistribution. This design concept resulted in the following reinforcement. Beam SS1 was reinforced with three No.15M steel bars (bar area = 200 mm\(^2\)) as top reinforcement at the mid-span section and four No.15M steel bars as bottom reinforcement. While Beam GS1 was reinforced with two No.16 GFRP bars (bar area = 198 mm\(^2\)) at the top side and three No.16 GFRP bars at the bottom side of the beam as shown in Figure 1. The reinforcement ratios of the tested beams and their design capacities are given in Table 1. Both beams were provided with 8-mm diameter steel stirrups spaced at 120 mm all over the entire length. The mechanical properties of the bars used in the tested beams are shown in Table 2. Ready-mix concrete with 20-mm maximum aggregate size and a targeted compressive strength of 35 MPa was used to produce the specimens. Compression and splitting cylinder tests were carried out on standard cylinders (150 mm diameter \( \times \) 300 mm high) to determine the actual 28-day compressive and tensile strength of the used concrete. The obtained results were 28 and 4 MPa for the compressive and tensile strengths, respectively.

![Figure 1. Details of beam GS1](image)

Table 1. Reinforcement details of tested specimens
### Table 2. Reinforcement properties used in the tested beams

<table>
<thead>
<tr>
<th>Bar material</th>
<th>Bar diameter (mm)</th>
<th>Tensile strength, $f_y$ (MPa)</th>
<th>Modulus of elasticity, $E$ (GPa)</th>
<th>Ultimate strain, $\varepsilon_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal steel bars</td>
<td>15.9</td>
<td>$f_y = 400^*$</td>
<td>200</td>
<td>$\varepsilon_y = 0.002^*$</td>
</tr>
<tr>
<td>Steel stirrups</td>
<td>8.0</td>
<td>$f_y = 300^*$</td>
<td>200</td>
<td>$\varepsilon_y = 0.002^*$</td>
</tr>
<tr>
<td>GFRP bars</td>
<td>15.9</td>
<td>731</td>
<td>46</td>
<td>0.016</td>
</tr>
</tbody>
</table>

* $f_y$ and $\varepsilon_y$ is the yield stress and yield strain of steel, respectively

### Instrumentations and Test Procedure

The tested continuous beams consisted of two equal spans supported on two roller supports at both ends and one hinged support at the middle. A 1000-kN hydraulic actuator bolted to an independent loading frame was used to apply monotonic concentrated loading on the middle of a rigid steel spreader beam. This spreader beam was used to deliver two equal concentrated loads to the mid-point of each span. Two load cells were used to measure the reactions at the two end-supports. Deflection was measured, using linear variable differential transformers (LVDTs), at three different locations in each span, at mid-point, one-quarter and three-quarters of the span length. Electrical strain gauges were fixed on the internal reinforcement bars embedded in the concrete section to record the strain at different loading levels. The sensors were provided on both top and bottom reinforcement at all critical sections (internal support and mid-spans). All load cells, LVDTs, and strain gauges were connected to a Data Acquisition System (DAQ) where all readings were recorded automatically. The load was applied to the beam monotonically with a load-controlled rate of 10 kN/min. The tested beams were considered to be failed when no additional applied load can be resisted. At that point, the loading was stopped and no more data was collected.

### RESULTS AND DISCUSSIONS

#### Behaviour and modes of failure

Beam SS1 demonstrated the conventional ductile behaviour of steel-reinforced continuous concrete beams. The first crack was observed at the internal support followed by a crack at the mid-span section. The tensile steel reinforcement at the middle support yielded first followed by the tensile reinforcement at the mid-span section, as discussed in the following paragraph. As the load was increased, shear stresses became influential. Tensile flexure cracks near the mid-span diagonally propagated towards the compressive side at the loading location as shown in Figure 2. For beam GS1, the cracking behaviour was similar to beam SS1. The first crack was observed at the middle support followed by the mid-span. However, cracks in beam GS1 were wider than those in beam SS1. The failure of beams GS1 was initiated by concrete crushing in mid-span section, at the same time wide cracks were observed at the middle support section. Both critical sections were reinforced with an over-reinforcement ratio, which was the reason behind concrete crushing before reaching the ultimate strain of the GFRP bars. As the load increased, wide cracks near the middle support propagated diagonally towards the support, which led to the rupture of bottom GFRP bars in dowel action. The failure shape of beam GS1 is shown in Figure 2.

For beam SS1, as expected, the section at the middle support yielded first and further loading was redistributed to the mid-span section till it reached its flexural capacity. Also, a similar behaviour was observed for beam GS1 as it did not fail when the applied load reached the flexural capacity of the section at middle support. Instead, the beam continued to resist more load till the section capacity at the mid-span was reached. This indicates that part of the bending moment over the middle support was redistributed to the mid-span.
Cracking pattern and strains in reinforcement

Generally, the flexural cracking pattern in the span of both beams was similar. Vertical flexural cracks were predominant at early loading stages. As the load increased, shear stresses became effective and flexure cracks propagated diagonally towards the compression side. Figure 3 shows the tensile strain in the bottom reinforcement at the mid-span and the top reinforcement at the internal support against the total applied load for the tested beams. It can be seen that the strains in GFRP bars increased suddenly after concrete cracking and section at middle support cracked before the mid-span section. As expected, due to the low axial stiffness of GFRP reinforcement compared to steel, the tensile strains in GFRP bars were higher than those in the steel bars at all loading levels prior to yielding. In beam SS1, top steel reinforcement at the middle support yielded before the bottom reinforcement at mid-span. Furthermore, the measured strain in the top reinforcement over the middle support was larger than the strain in the bottom reinforcement at mid-span in both beams. This observation is in good agreement with the moment redistribution, which occurs due to large deformations at the middle section.

Figure 3. Load-strain relation for tested beams
**Load deflection response**

The relation between the total applied load and the recorded deflection at mid-span is shown in Figure 4. As the deflections observed in the two spans of each beam were similar, one side mid-span deflections are reported. Both beams demonstrated linear load-deflection behaviour before cracking. Upon cracking, stiffness of both beams was reduced as the load increased. Once again, as expected, due to the low axial stiffness of the GFRP bars, beam GS1 demonstrated wider cracks compared to beam SS1 and consequently exhibited higher mid-span deflection as shown in Figure 4.

![Figure 4. Load-deflection response of the tested beams](image)

**Load redistribution of tested beams**

Figure 5 shows the recorded end reactions of the tested beams. The elastic end reaction assuming uniform stiffness along the entire beam length was plotted at the same figure to evaluate the load redistribution. In steel-reinforced continuous concrete beams, significant load redistribution is expected after yielding of tensile reinforcement at the middle support. In beam SS1, however, it was observed that redistribution started before steel yielding. This might be attributed to the difference in stiffness between mid-span and middle support sections. As the reinforcement ratio at mid-span is higher than reinforcement ratio at middle support, stiffness of the beam cross-section at mid-span is higher. Beam GS1 was similarly designed as beam SS1 with higher reinforcement ratio in mid-span compared to section at middle-support.

Similar load redistribution behaviour was observed for beam GS1. In fact, beam GS1 utilized all the available load redistribution provided by the existing reinforcement configuration. As can be seen in Figure 5, the maximum measured reaction at the end-support corresponding to the failure load, $P = 121$ kN, was around 43 kN. Based on the elastic analysis, the end support reaction was calculated to be 37.8 kN. Therefore, the actual bending moment at the middle support, calculated from the measured end reaction, was 49.0 kN.m, which represents 77% of the calculated elastic moment of 63.7 kN.m at the failure load $P = 121$ kN. In other words, it was found that about 23% of the elastic bending moment at middle support was redistributed to the mid-span at the failure load.
CONCLUSIONS

The following points can be concluded based on the work presented in this paper:
1. The tested GFRP-reinforced continuous concrete beam demonstrated wider cracks and larger deflections compared to the control steel-reinforced beam with the same flexural capacity;
2. The tested GFRP-reinforced continuous beam, with over-reinforced sections at mid-span and middle support, exhibited moment redistribution of 23%;
3. The tested GFRP-reinforced beam showed ample warnings before failure in the form of wide cracks and large deflections.

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REFERENCES