Behavior of Laterally Restrained GFRP Reinforced Concrete Slab

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ABSTRACT

The corrosion of reinforcement embedded in concrete bridge deck slabs has been the cause of major deterioration and of high costs in repair and maintenance. Fiber reinforced polymers (FRP) exhibit high durability in combination with high strength and light weight. The majority of research with FRP bars for reinforcing concrete has been on simply supported beams and slabs where the low value of elasticity of FRP has meant that the service behaviors has been critical. These differences have been attributed to the low value of elasticity of FRP compared to steel. However, laterally restrained slabs, such as those in bridge deck slabs, exhibit arching action or compressive membrane action (CMA), which has a beneficial influence on the service behaviors. Based on the previous research on CMA in steel reinforced concrete bridge deck slabs, a series of experimental tests of laterally restrained GFRP reinforced concrete slabs were carried out. Some structural parameters, including concrete strengths, reinforcement and boundary conditions, were investigated. Thereafter, a NLFEA model were established with a proposed failure criteria with consideration of brittle and sudden failure modes of GFRP reinforced concrete slabs. With the validation of experimental results, a good collection was obtained. A comprehensive study of CMA in this structural type was discussed.

KEYWORD

glass polymer fibers bars, concrete slab, compressive membrane action, experimental tests, NLFEA
1. INTRODUCTION

The corrosion of the steel reinforcement caused severe deterioration to reinforced concrete bridge structures which can result in spalling and cracking of concrete. Extreme environmental conditions cause chloride intrusion and carbonation in concrete structures which subsequently lead to expensive corrosion of steel. Fiber reinforced polymer (FRP) reinforcement, stainless steel and epoxy coated steel reinforcement are considered as alternative reinforcement materials to replace high yield steel in reinforcement concrete [1]. In epoxy coated reinforcement, the ordinary steel is used with an epoxy coat to protect the reinforcement from corrosive environments. However, severe corrosion found in epoxy coated bar has been questioned the durability of the protection method [2].

Therefore, non-corrosive reinforcement materials to replace the steel reinforcement are preferable. FRP reinforcement can be made of different fibers such as carbon (CFRP), glass (GFRP), aramid (AFRP). Among these, CFRP and AFRP are the most costly compared with GFRP. Stainless steel is far more expensive than Glass fiber reinforced polymer. Therefore, GFRP is most widely used material which has good strength to price ratio and durable. Although the GFRP has many favorable material properties, this material still has some disadvantages, such as low modulus and brittle behaviors.

Due to the material properties of GFRP, it could cause the high construction cost and complex design [3]. Therefore, a direct substitution of GFRP to replace steel is not recommended [4,5,6,7]. However, research at Queen’s University Belfast [8][9] have found that the laterally restrained slabs, such as bridge deck slabs, demonstrate a stiffer structural response due to compressive membrane action (CMA). Therefore, it is possible to recognize that the benefits of CMA could help to design better GFRP reinforced slab. The larger deflection due to low modulus of elasticity and catastrophic collapse of structures as a result of brittle behavior of GFRP could be eliminated with the benefits of CMA.

The aim of this paper is to study the structural behaviors of GFRP reinforced concrete slabs with lateral restraint stiffness. A series of experimental tests was carried out to investigate the influences from some structural variables on the response of concrete slabs, which included concrete compressive strengths, boundary conditions, reinforcement percentage and type of reinforcing materials. The experimental results were ultimate loads, deflections and reinforcement strains. To this end, a commercial software named ABAQUS [10], which accommodates non-linear 3D FEM models, can be employed. The proposed numerical model showed good convergence ability and an excellent agreement of structural behaviors with the validations of experimental tests by authors.

2. EXPERIMENTAL PROGRAMS

2.1 Details of test models

The experimental investigations were on slabs strips representative of the typical sections of bridge deck slabs at full-scale, see Fig.1. This experimental study focused on one-way spanning slabs with varying reinforcement percentages, concrete compressive strengths, boundary conditions and reinforcing materials (see Table 1). The influences from GFRP reinforcement ratios were investigated by three slabs with percentages varying from 0.3% to 1.4 %. Furthermore, the reinforcement positions and reinforcing material types were also studied in this laboratory test. In the investigation of structural behaviours in the slabs with different concrete compressive strengths, four test models were designed with the strengths changing from 30N/mm² to 80N/mm². To achieve a noticeable arching effect, the comparison of the models with different boundary conditions was required. Therefore, two additional slabs without lateral restraints were established.

2.2 Test apparatus and instrumentation

The effectiveness of compressive membrane forces is dependent on the stiffness of lateral restraints. As shown in Fig.1, a steel frame was used to provide restraints and was analogous to the boundary conditions of the real bridge deck slabs. To ensure the fully encastre support, provision was made for bolting at each end. A layer of filler was placed on the slab prior to the bedding the end-clamp plates and each bolt were tightened to a similar torque value of 80N.m to provide an even fixity.

In all the test slabs, a line load was applied across the mid-span of each test slab (see Fig.1). Loading was applied through a stiff loading beam with a 20mm knife edge loading plate. The application of load was from an accurately calibrated 500kN
capacity Dartec electro hydraulic actuator. A spherical seating was located between the ram and the loading beam to minimise the effects of any possible misalignment of load. After the test slabs was positioned in the test frame, the strain gauges and transducers were connected to a data acquisition system. Before the experimental test, the sensitivity of the transducers was verified by calibration. Readings were recorded at each load increment. Electrical resistant strain (ERS) gauges were embedded in GFRP bars to assess the strain development in both mid-span and support location. The vibrating strain gauges were configured at mid-span, 1/4 span and support of sides of concrete slabs. Three electronic displacement transducers were located at the mid-span and 1/4 span of the concrete slabs to measure the vertical deflections of test models. The horizontal movements of steel rigs were recorded by using displacement transducers at the end of steel frames.

Table 1 Experimental test variables and results

<table>
<thead>
<tr>
<th>Test Slab</th>
<th>Reinforcement</th>
<th>Boundary Condition</th>
<th>Kr (kN/mm)</th>
<th>$f_{cu}$ (N/mm²)</th>
<th>d (mm)</th>
<th>$P_t$ (kN)</th>
<th>Failure Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG10</td>
<td>0.3% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>73.00</td>
<td>160</td>
<td>215</td>
<td>GFRP bar rupture &amp; concrete crush</td>
</tr>
<tr>
<td>CG11</td>
<td>0.7% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>71.70</td>
<td>160</td>
<td>211</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG12</td>
<td>1.4% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>74.40</td>
<td>160</td>
<td>223</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG13</td>
<td>0.7% C G</td>
<td>FE+LR</td>
<td>460</td>
<td>73.70</td>
<td>100</td>
<td>201</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG14</td>
<td>0.7% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>29.52</td>
<td>160</td>
<td>185</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG15</td>
<td>0.7% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>56.00</td>
<td>160</td>
<td>200</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG16</td>
<td>0.7% B G</td>
<td>FE+LR</td>
<td>460</td>
<td>67.70</td>
<td>160</td>
<td>199</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CG17</td>
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<td>FE</td>
<td>0</td>
<td>73.79</td>
<td>160</td>
<td>120</td>
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</tr>
<tr>
<td>CG18</td>
<td>0.7% TB G</td>
<td>SS</td>
<td>0</td>
<td>73.82</td>
<td>160</td>
<td>87</td>
<td>GFRP bar rupture</td>
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<tr>
<td>CG19</td>
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<td>FE+LR</td>
<td>460</td>
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<td>160</td>
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</tr>
<tr>
<td>C1</td>
<td>0</td>
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<td>460</td>
<td>73.07</td>
<td>0</td>
<td>176</td>
<td>Concrete crush</td>
</tr>
<tr>
<td>CS1</td>
<td>0.7% TB S</td>
<td>FE+LR</td>
<td>460</td>
<td>70.96</td>
<td>160</td>
<td>229</td>
<td>Concrete crush</td>
</tr>
</tbody>
</table>

G—GFRP reinforcement, S—Steel reinforcement
TB—Two layers of reinforcement with covering layer of 40mm
B—One layer of reinforcement with covering layer of 40mm
C—One layer of reinforcement configured at mid-depth
FE—Fixed End
LR—Lateral Restraint
SS—Simply Supported
Kr—Lateral restraint stiffness
* Concrete strength was tested based on 100mmx100mm cubes

3. BEHAVIOURS OF THE TEST SLABS

3.1 Crack formation and crack width development
In all the test slabs, the first crack appeared directly below the load point and propagated towards compressive face. Fig.2 illustrates the crack patterns in the restrained slabs with different reinforcement percentages. The cracking was more pronounced in the slabs with higher reinforcement ratios. Before the applied load reached the service load (about 100kN), the crack pattern and crack widths were very similar among slabs CG10, CG11 and CG12. The structural performances were independent of the reinforcement percentages (see Fig. 2 and Fig.3a). However, at an applied load of ultimate strengths, the crack
widths were smallest in the model with highest reinforcement percentages (see Fig.3a), which could be due to the strongest bond effect. Fig.3b shows the influence from reinforcing materials on the development of crack widths. It was found that the crack widths in steel reinforced slabs (2.5 mm) were larger than GFRP reinforced slabs (1.2mm) at ultimate loads, which was due to the better compatibility between GFRP and concrete compared to steel. As shown in Fig.3c, regardless of service load and ultimate load, the crack width development in the model with two layers of reinforcement are smaller than those in the models with one layer of reinforcement. Due to the improved service cracking performance, reinforcing slabs with two layers of GFRP bars could be recommended.

Unlike the simply supported slabs, the restrained slabs had a negative support moment which was highlighted by the development of tension cracks in the top surface adjacent to the support (see Fig.2). When the applied load reached close to the failure load, crushing occurred in both mid-span and support compression faces. This meant that arching thrust developed completely inside the concrete slabs.

Fig. 2 Typical crack distribution at the sides of test slabs with different reinforcement percentage

3.2 Slab deflections
The load vs. deflection behaviours of all the GFRP reinforced concrete slabs are shown in Fig.4. The load vs. deflection behaviours clearly indicates that all the slabs are under linear behaviours until the first crack occurs and non linear behaviour is recorded beyond the first crack. At an applied load of 100 kN, an approximate service load for the laterally restrained slabs, the load vs. deflection response were very similar in the comparisons of models with different reinforcement percentage and positions. However, this structural response was influenced by the concrete compressive strengths. After the applied load reached the service load, the load-deflection response in the slabs with high strength concrete was stiffer than that with normal strength concrete (see Fig.4). At an applied load of 48kN, which was an approximate service load for simply supported slabs, the mid-span deflection was 8mm. This deflection is equivalent to span/267. If the allowable service deflection is span/350, the deflection in the simply supported GFRP slab exceeds this limit. This is attributed to the low modulus of elasticity of GFRP bars. Conversely, at an applied load of 100kN, mid-span deflections of all the laterally restrained concrete slabs reinforced by GFRP were less than the allowable service deflection. This improved serviceability is due to the existing of compressive membrane action. Fig. 5 shows the comparison of load vs. deflection in the slabs with different reinforcement
types. The similar responses were obtained before the occurrence of cracks. Thereafter, the global stiffness of slabs without any reinforcement reduced dramatically compared with the other two slabs. At the same value of 100kN, the deflections in slabs with steel and GFRP reinforcement were similar. When the load reached the ultimate strengths, a load-deflection response in steel slabs was a bit stiffer than that in GFRP slabs.

3.3 Strain in GFRP reinforcement
Strain in each GFRP bar was measured using ERS gauges. The strain experienced by each bar was recorded in the mid-span region and restrained edge region. The load vs. micro strain at mid-span was plotted for each GFRP test slab (see Fig.6) and the maximum strain in each slab was verified with the rupture strain of GFRP bars. The rupture of GFRP bars occurred in the model with lowest reinforcement percentage and two models without lateral restraints. This suggests that failure mechanism in the most of laterally restrained concrete slabs is by concrete crushing. Due to the development of arching action, there was no catastrophic failure observed for any lateral restrained GFPR reinforced concrete slab. After loading was removed, all laterally restrained GFRP slabs could return almost to the initial position.

3.4 Ultimate capacity of slabs and failure mode
Table 1 summarises the ultimate strengths and the corresponding failure modes. With the development of arching thrust inside the laterally restrained slabs, crushing of concrete occurred in mid-span and support compression faces. At the ultimate loads, all the restrained slabs failed by crushing of concrete at top face at mid-span as shown in Table 1. This structural performance was more pronounced in the slabs with higher concrete strength or larger reinforcement percentage. Due to the development of CMA, the rupture of GFRP bars did not occur in most of restrained slabs except CG10 which is the model with lowest reinforcement percentage. The failure mode of simply supported slabs was the rupture of GFRP bars. This indicates that behaviours of lateral restrained slabs are similar to over-reinforced slabs, which is caused by the arching action from horizontal restraint stiffness.

Fig. 4 Load vs. deflection at mid-span of the GFRP reinforced test slabs

Fig. 5 Load vs. deflection at mid-span of the test slabs with different reinforcement types

Fig. 6 GFRP bar strains at mid-span

Fig. 7 Load plotted against displacement results by test CG11

(a) Load vs. deflection at midspan

(b) Horizontal displacement in steel rig (model CG11)
The load against deflection results for the test slabs named CG11 are shown in Fig. 7(a) and (b). It was noted that the arching action enhanced the loading capacity significantly, which was far larger than the bending strength predicted by flexural theory (see Fig.7a). After the applied load reached the bending strength of 90kN, the horizontal displacement at the end of the rig started to increase significantly indicating the corresponding development of CMA (see Fig.7b).

As shown in Table 1, the failure loads of restrained GFRP slabs are independent of reinforcement percentages. Fig.8 illustrates that the horizontal displacements of restraint rigs are increased with the reducing reinforcement ratios. This suggests that compressive membrane effects can be cut down by the increasing of this structural variable. It was found in Table 1 that the ultimate strength was increased by around 14% after the concrete strength was enhanced by 60%. The increase in loading capacity with increasing concrete strength and evidence of high compressive forces characterised by concrete crushing indicated the development of compressive membrane action.

However, the analysis procedure does not terminate, after the ultimate strength is reached. Therefore, a failure criterion based on balances of forces was used in this paper.

In this study, the experimental model mentioned above was used as the analytical models. The relationship between concrete slabs strips and steel clamp was simulated as contact analysis. The lateral restraint stiffness was reflected by sprint elements (see Fig.9).

As shown in Fig.10 and 11, it was found that results from the established NLFEA model showed a good collection with the structural behaviours obtained from experimental tests, including the loading capacities, load-deflection responses and crack patterns. Therefore, this NLFEA model is capable of being used to investigate the compressive membrane action in the concrete slabs.

4. NONLINEAR FINITE ELEMENT ANALYSIS OF EXPERIMENTAL MODELS

The focus of this study was to attempt to establish NLFEA model to simulate the arching effects in laterally restrained GFRP reinforced concrete slabs. As a result, NLFEA could be used to optimize the design of such slabs with some further parametric study, such as lateral restraint stiffness. A commercial software named ABAQUS [10] was used. Due to the arching effects and brittle properties of GFRP bars, the failure mode of GFRP reinforced concrete slabs is sudden. This can cause numerical instability and convergence problems by the traditional static analysis—implicit analysis [11]. Therefore, the explicit method was used with very small load increments to develop quasi-static analysis.
5. CONCLUSIONS

The aim of this study was to extend the existing research on compressive membrane action in laterally restrained slabs with GFRP bars as reinforcement. From the experimental and numerical results, the following conclusions have been drawn:

(1) The experimental observations were consistent with the development of compressive membrane action in the laterally restrained GFRP reinforced concrete slabs.

(2) Due to the existing of compressive membrane action inside the laterally restraint slabs, the GFRP reinforcement percentages could not influence the serviceability and ultimate strengths significantly. The ultimate strengths of laterally restrained GFRP reinforced slabs were more dependent on the concrete compressive strength and horizontal restraint stiffness than reinforcement percentage.

(3) The deflections in the slabs without lateral restraints were significantly great which were larger than the service allowable deflection. The provision of lateral restraint reduced the mid-span deflection and the restrained GFRP reinforced slabs with low reinforcement percentages showed better service behaviour compared to the equivalent laterally restrained steel reinforced slabs.

(4) The ultimate capacity obtained from NLFEA showed excellent agreement with the experimental results. The quasi-static analysis used in this paper showed a good convergence.

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