BEHAVIOUR OF GFRP REINFORCED CONCRETE DECK SLABS IN STEEL-CONCRETE BRIDGES

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ABSTRACT:

This paper presents the results of an experimental test and a numerical analysis to investigate structural behaviour of concrete bridge deck slabs reinforced with glass fibre-reinforced (GFRP) bars under static patch loads. A series of one-third scaled bridge deck models of concrete slabs supported by longitudinal steel beams were conducted and tested in the laboratory with varying structural parameters, including steel supporting sizes, reinforcement percentages, reinforcing materials, concrete compressive strengths and model storage duration. The presence of longitudinal steel beams and unloaded area of concrete slabs cause loaded deck slabs to be restrained against lateral expansion. As a result, a compressive membrane thrust is developed. The experimental results were presented in cracking pattern, deflection, strain in concrete and reinforcement, loading capacity and failure mode. It was found that compressive membrane action (CMA) inside the slabs had a beneficial influence on loading capacities and service behaviours. Thereafter, a nonlinear finite element analysis (NLFEA) was conducted. The proposed numerical model provided a good capability to accurately simulate behaviour of GFRP reinforced concrete bridge deck slabs.

KEYWORDS

Bridge deck slabs; Experimental tests; CMA; GFRP; Finite element analysis

INTRODUCTION

This paper describes a study on the replacement of steel reinforcement with FRP as an alternative solution to improve the service life of bridges. Currently, GFRP is one widely available material in the reinforcement replacement in existing bridge structures (Hughes Brothers, 2008). Due to low elastic modulus and brittle behaviour of GFRP, deflection criterion tends to control the design of intermediate and long-span sections reinforced with GFRP bars (El-Salakawy et al 2005, AASHTO 2000, ACI-440 2008, CAN/CSA-S6-00 2005). Interestingly, in bridge deck slabs, it is generally laterally restraint stiffness and concrete compressive strength which govern the ultimate strength and independent to percentage and type of reinforcement (Zheng et al. 2009).

Composite steel-concrete bridges are one of the most common types of bridge form. The presence of longitudinal steel beams, together with shear stud connectors, provide restraint against expansion of the deck slab. As a result, compressive membrane forces are developed, which caused an enhancement in loading capacities in concrete girder-slab-type bridge decks (Khanna et al. 2000). The loading-carrying capacities are enhanced significantly due to arching action or compressive membrane action (CMA),
which are far larger than those predicted by flexural methods (BD 81/02 2002, Muthu et al. 2007). Furthermore, research by Kirkpatrick (Kirkpatrick et al. 1984 and Kirkpatrick et al. 1986) has shown that CMA also has a beneficial effect on serviceability of laterally restrained slabs. As a result, it is possible to produce an economic and durable concrete slabs by utilising the benefits of GFRP reinforcement in combination of CMA.

In this paper, structural behaviour of one-third-scaled GFRP reinforced deck slabs of composite steel-concrete bridges were investigated by experimental tests by varying some structural parameters, including sizes of steel supporting beams, reinforcing materials, reinforcement ratios and concrete compressive strength. Due to degeneration of GFRP bars in the alkaline environment of concrete, two deck specimens were tested after two-year storage. Thereafter, a finite element model was conducted to study structural behaviour and failure mechanism of GFRP reinforced concrete bridge deck slabs. This numerical model provided a good collection with experimental results.

**EXPERIMENTAL STUDY**

**Experimental programme**

![Diagram of test load arrangements](image)

As illustrated in Fig.1, all of experimental models and cross-sectional dimensions were typical of a composite steel-concrete bridge deck at one-third scale. As shown in Table 1, structural variables were concrete compressive strength, reinforcing materials, reinforcement percentages and external restraint stiffness (by varying the major and minor axis I value—$I_{xx}$ and $I_{yy}$ value of edge beam). Except those structural variables, two deck specimens with two-year storage duration coded M85MB052Y and
M81BB052Y were conducted to investigate influence of degeneration of GFRP bars. In all the test models, reinforcing bars were located in mid-depth of deck slabs. The 8mm GFRP bar with rupture strength of 636 N/mm² was used in all the GFRP reinforced concrete slabs. With the consideration of CMA in structural design, reinforcement percentages in most of GFRP reinforced concrete deck slabs are just 0.5% (see Table 1), which is smaller than balanced reinforcement percentage (1.25%) predicted by ACI code (ACI-440 2008). The steel bars with the same diameter and yield strength of 345N/mm² was adopted in steel reinforced concrete deck slabs.

<table>
<thead>
<tr>
<th>Model</th>
<th>h mm</th>
<th>Reinforcing Material</th>
<th>ρ (%)</th>
<th>fcu * N/mm²</th>
<th>Ixx cm⁴</th>
<th>Iyy cm⁴</th>
<th>Ixy cm⁴</th>
<th>P₀ kN</th>
</tr>
</thead>
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<tr>
<td>M77SB05</td>
<td>50</td>
<td>GFRP</td>
<td>0.50%</td>
<td>77</td>
<td>280x122x9</td>
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<tr>
<td>M80MB05</td>
<td>50</td>
<td>GFRP</td>
<td>0.50%</td>
<td>80</td>
<td>320x130x10</td>
<td>111100</td>
<td>460</td>
<td>79</td>
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<tr>
<td>M76BB05</td>
<td>50</td>
<td>GFRP</td>
<td>0.50%</td>
<td>76</td>
<td>300x200x8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M78MB10</td>
<td>50</td>
<td>GFRP</td>
<td>1.00%</td>
<td>78</td>
<td>320x130x10</td>
<td>111100</td>
<td>460</td>
<td>85</td>
</tr>
<tr>
<td>M72MB05*</td>
<td>50</td>
<td>Steel</td>
<td>0.50%</td>
<td>72</td>
<td>320x130x10</td>
<td>111100</td>
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<td>77</td>
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<tr>
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<td>GFRP</td>
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<tr>
<td>M85MB052Y</td>
<td>50</td>
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<td>0.50%</td>
<td>85</td>
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<tr>
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<td>GFRP</td>
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<td>84</td>
<td>300x200x8</td>
<td>111400</td>
<td>1600</td>
<td>115</td>
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A 500x25mm knife-edge load was applied at midspan of the slab and parallel to longitudinal supporting beams (see Fig.1). The loading pattern simulated two wheel loads at a spacing of 1.5 m (assumed to be 0.5m at one third scale). Deflection of concrete slabs was measured along the centre
line parallel to supporting beams. Some transducers were placed directly under the slab mid-span. In order to monitor effects of arching thrust on edge beams, three transducers were set as illustrated in Fig. 2 (average of T7&T10, T8&T11 and T9 &T12) to measure any rotations and horizontal deflections. Concrete strains were measured using vibrating wire strain gauges. In an attempt to identify the in-plane or membrane strain, the arrangement of gauges is summarized in Fig. 2. To observe the deformation and stress in reinforcement, epoxy-bonded electrical resistance strain gauges were used.

**Experimental results**

![Image](image1.png)

Fig. 3 Crack patterns observed in test models at ultimate loads

![Image](image2.png)

Fig. 4 Crack patterns observed in test models with two year storage at ultimate loads

Representative crack patterns at failure loads for the different loading levels are illustrated in Fig.3. The overall all crack patterns at bottom and top surfaces of deck slabs were similar. An increasing of steel beam sizes reduced the ductility of slabs. As a result, punching behaviours became more obvious and the failure mode was more localized and sudden. Furthermore, it was observed that more cracks with wider width in the slab reinforced with steel bars than deck slabs reinforced with GFRP bars. This could be caused by better compatibility between FRP materials and concrete materials compared with
steel and concrete (Sherif et al 2005, Sherif et al 2007). In all the experimental modes reinforced with GFRP bars, a brittle behaviour was observed with punching failure. Crushing at the top surface was a significant aspect of failure for all the deck slabs. Due to the existing of lateral restraint stiffness, no rupture occurred in GFRP reinforced concrete bridge deck slabs except model named M77SB05. In the experimental test of deck specimens with long-term storage, it was found the failure mode was similar to those of deck models with one month curing duration. This indicated that failure mode of GFRP reinforced concrete bridge decks was not affected by the storage duration.

The load vs. vertical deflection at midspan of concrete bridge deck slabs are shown in Fig.4. It can be seen that, for the slabs with higher restraint stiffness, a delay in stiffness degradation was evident. This characteristic was associated with the deformation response of a laterally restrained slab. The load-deflection curves were bilinear. The first part up to cracking loads represents behaviour of the
uncracked slabs using the gross inertia of the concrete cross section, while the second part represents the cracked slab with reduced inertia. It can be noted in Fig.4 that load vs. deflection responses in the models named M80MB05 and M72MB05* were similar. This indicates that reinforcing materials can not influence ultimate state and serviceability of concrete bridge deck slabs significantly. In the comparison of two models coded M80MB05 and M78MB10, a stiffer structural response was found in the bridge deck slabs with higher reinforcement percentage, particularly after the cracks occurred at the top surface of concrete slabs (at around 50kN). In the investigation of models with different supporting beams sizes, it can be found that structural responses in three models were similar before the occurrence of cracks. As shown in Fig.5, the load-deflection responses in the deck model with two-year storage presented stiffer behaviour than those with 28-day curing time. It could be concluded that behaviour of GFRP reinforced concrete bridge deck slabs was not be affected by the long-term storage of GFRP bars in concrete. Fig. 6 shows the deflected shape at the mid-section at the same level of applied load (50kN) in the transverse direction for the models M77SB05 and M76BB05. The deflections have been magnified by 10 times with respect to the cross-sectional dimensions. The deflected shapes clearly show the horizontal deflections in the supporting beams, which is the result of membrane action. Furthermore, it can be seen that the vertical deflection in the mid-span was lower as the size of the steel supporting beams increased.

![Graph](image1.png)  ![Graph](image2.png)

(a) Load against strain in GFRP bars  (b) GFRP bars after failure tests in model M81BB2Y

Fig. 7 Status of GFRP bars

The maximum measured strains in FRP reinforcement at midspan are shown in Fig.7a. At the service loads (around 25kN), the measured strains in all GFRP reinforced bridge deck slabs were in the range of 0.000255 and 0.00184, which is equivalent to FRP reinforcement stress of 11.4N/mm² to 82.2 N/mm². Those stress values are approximately 1.7% to 12% of rupture strength of adopted GFRP bars (636 N/mm²). In the experimental study of deck specimens with two-year storage, concrete at the loading position were removed to investigate the status of GFRP bars. As shown in Fig.7b, GFRP reinforcing bars did not rupture. Because reinforcement percentage in those models was just 0.5%, which is lower than the balanced percentage (1.25%) predicted by ACI 440R 06 (ACI 440 2008), it can be concluded that the negative effect of FRP bars degeneration in concrete bridge deck slabs was exaggerated by current design standards.
All the tested deck slabs failed in punching behaviours around loaded area. As expected, the concrete bridge deck slabs with larger steel beam and higher strength concrete had the highest ultimate capacity. This enhancement was partly due to increased compressive membrane action. As shown in Table 1, although $I_{xx}$ values of steel I-section beams were increased by 15 times without significant changes of $I_{yy}$, loading-carrying capacity in two models of M78SB05 and M80MB05 were similar. In the comparisons of test specimens coded as M80MB05 and M76BB05, ultimate strength was enhanced by around 40% when the $I_{yy}$ values were increased by 3.5 times. It can be concluded that the increasing of horizontal restraint stiffness is an effective way to improve ultimate strength in GFRP reinforced concrete bridge deck slabs. However, reinforcing materials and reinforcement percentages could not influence ultimate strength in concrete bridge deck slabs significantly. As shown in Table 3, current design standard underestimated loading capacity of GFPR reinforced concrete bridge deck slabs, because the influence of lateral restraint stiffness was not considered. In the comparison of test specimens with different storage duration, it was found that ultimate strength of deck slabs were enhanced with increase in storage time. This could be due to the increase in concrete strengths. The experimental test results indicated that degeneration of GFRP bars in alkaline environment could not reduce ultimate strength of deck slabs.

Table 3 Comparison of NLFEA, ACI code and experimental test results

<table>
<thead>
<tr>
<th>Model</th>
<th>$P_t$ kN</th>
<th>$P_{NLFEA}$ kN</th>
<th>$P_{ACI-flexural}$ kN</th>
<th>$P_{ACI-shear}$ kN</th>
<th>$P_{NLFEA}/P_t$</th>
<th>$P_{ACI}/P_t$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>72</td>
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<td>0.93</td>
<td>0.31</td>
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<tr>
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<td>79</td>
<td>31</td>
<td>25</td>
<td>1.00</td>
<td>0.32</td>
</tr>
<tr>
<td>M76BB05</td>
<td>108</td>
<td>102</td>
<td>32</td>
<td>24</td>
<td>0.94</td>
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<td>90</td>
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<td>61</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<td>0.05</td>
<td>0.12</td>
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NUMERICAL MODEL DEVELOPMENT, CALIBRATION AND VALIDATION

Introduction

To develop the further study of CMA and failure mechanism, a finite element model was established to simulate structural behaviour of GFRP reinforced concrete bridge deck slabs. A commercial software named ABAQUS 6.10 (Hibbitt Karlsson & Sorensen 2010) was used. Due to arching effects and brittle properties of GFRP bars, failure mode of GFRP reinforced concrete slabs is sudden. This can cause numerical instability and convergence problems by the traditional static analysis—implicit analysis (Zheng et al. 2009). Therefore, the explicit method was used with very small load increments to develop quasi-static analysis. However, the analysis procedure does not terminate, after ultimate
strength is reached. Therefore, a failure criterion based on balances of forces was used in this paper (Zheng 2008, Zheng et al 2012). According to the previous research on concrete bridge decks (Zheng et al. 2009), this paper adopted Concrete Damaged Plasticity Model (Lubliner et al. 1989) and shell element to simulate concrete deck slabs. Because of significant difference between the tensile and compression strength in GFRP, Hyperelastic model was used in this numerical analysis to define the tensile and compressive behaviour respectively. Plastic multi-linear model was use to simulate steel materials.

![Graph](image)

**Fig. 8** Comparison of load vs. displacement responses obtained from experimental test and NLFEA (specimen named M80MB05)

![Plastic strain distribution](image)

**Fig. 9** Principle plastic strain distribution in NLFEA (Model M80MB05)

**Validation with experimental tests**

Based on the proposed numerical configurations presented above, nonlinear finite element analysis (NLFEA) of author’s experimental model was carried out. The comparison between ultimate load from experimental tests and numerical analysis are shown in Table 3. It was found that predictions of collapse loads from NLFEA showed a good correlation with those from experimental test. In the comparison between the load-displacement responses in experimental test and NLFEA as shown in Fig.8, it can be seen that the adopted numerical model had an excellent ability to predict structural responses of composite bridge deck when the adopted failure criterion was used. The trends of the load-displacement responses in experimental test and numerical analysis are similar. Fig.9 shows crack propagation simulation in nonlinear finite element analysis. In the adopted numerical models, the crack patterns were visualised by plotting the principal plastic strain vectors (Fig. 9). The black arrows...
represent the minimum plastic strain signifying compressive strains and the red ones represent the maximum plastic strain signifying tensile strains. When compared with the crack patterns observed in the experimental tests (see Fig. 3), the proposed nonlinear finite element models show accurate prediction in locations and directions of the crack propagations. From the analysis of plastic strain and crack pattern (see Fig. 3 and Fig. 9) obtained from NLFEA and experiments, it can be seen that, due to arching system, GFRP reinforced bridge deck slabs under the wheel footprint fail in punching rather than flexure, which was also investigated by some Canadian researchers (Sherif et al. 2005 and Sherif et al. 2007).

CONCLUSIONS

Based on the study in this investigation, following conclusions can be obtained:

1. Experimental results indicate that loading capacity and serviceability of GFRP reinforced concrete bridge deck slabs are influenced by CMA significantly;

2. The increasing of horizontal restraint stiffness due to enhancement in minor axis bending stiffness ($I_{yy}$ values) of steel supporting beams was an effective way to enhance ultimate strength of GFRP reinforced concrete deck slabs in steel-concrete composite bridges. The increasing of $I_{xx}$ values could not influence structural behaviour of this structural type. The reinforcement percentage of FRP bars could affect the ultimate strength of concrete deck slabs.

3. Current design standard for FRP reinforced concrete structures could not provide an accurate prediction for ultimate strength for laterally restrained concrete deck slabs reinforced by GFRP bars.

4. Loading carrying capacity of FRP reinforced concrete bridge deck slabs could not be affected by degeneration of GFRP bars in concrete deck slabs with a long-term storage. The negative influence of degeneration of GFRP bars in concrete deck slabs is exaggerated by current design code.

5. The proposed NLFEA model is capable of predicting structural behaviours, such as ultimate capacity, load vs. deflection response and crack patterns of bridge deck slabs reinforced with GFRP.

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