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# Investigation of structural behaviour of GFRP reinforced concrete deck slabs through NLFEA

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## HIGHLIGHTS

- Proposed NLFEA model could predict behaviour of GFRP reinforced concrete bridge deck slabs accurately.
- CMA has a sufficient effect on behaviour of FRP reinforced concrete bridge deck slabs.
- Current design codes underestimate behaviour of FRP bridge deck slabs.
- RP reinforcement percentage provided by design standards is higher than the practical requirement.

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## ABSTRACT

This paper presents a numerical study of the structural behaviour of concrete bridge deck slabs under static patch loads and dynamic traffic loads and an investigation of compressive membrane action (CMA) inside slabs. Those deck slabs were reinforced with Glass Fibre Reinforced Polymer (GFRP) bars. Non-linear finite element analysis (NLFEA) models were established using ABAQUS 6.10 software packages. Experimental data from one-span bridge structures by author and other researchers are used to validate and calibrate the proposed FEM models. A series of parametric study is conducted to investigate compressive membrane action (CMA) in concrete bridge deck slabs. In the simulation of behaviour of GFPR reinforced concrete bridge deck slabs under traffic loads, a field test using calibrated truckloads of Cooshire-Eaton Bridge in Canada was used to validate the accuracy of proposed numerical models in dynamic analysis. Some structural parameters were varied in the dynamic analysis to investigate the influences from the introduction of CMA in structural design. The NLFEA results were discussed and conclusions on behaviour of FRP reinforced concrete bridge deck slabs were presented. The numerical results showed that the benefits of CMA could provide the acceptable service performance of GFRP reinforced concrete bridge deck slabs with low reinforcement percentages.

## 1. Introduction

Due to the non-corrosive properties, fibre reinforced polymer (FRP) bars have been used as the replacement of steel reinforcement in concrete bridge deck slabs, which is an alternative solution to improve the service life of bridges [1]. Currently, Glass Fibre Reinforced Polymer (GFRP) is one popular material used in the existing bridges [2]. Because of the low elastic modulus of GFRP materials, GFRP reinforced sections exhibit higher deformability when compared to equivalent reinforced steel sections. Therefore, the deflection criterion tends to control the design of intermediate and long spanning sections reinforced with GFRP bars [3–6]. Because the current design methods for the bridge decks reinforced with FRP composite bars was originally made with steel bars using flexural design method [4,5], a direct substitution of GFRP to replace steel is not recommended [3,5].

However, bridge deck slabs in typical beam-and-slab-type bridges have inherent strength due to in-plane forces set up as a result of the restraint provided by the slab panel boundary conditions, including beams, diaphragms, and slab continuity. This is known as compressive membrane action (CMA) or arching action. This compressive membrane effects is due to the significant difference between tensile and compressive strengths of concrete. On the application of load, a crack occurs due to the relatively weak tensile strength. Under this condition, the neutral axis moves toward the compression face. If the ends of the slab are restrained by a stiff boundary, an arching thrust develops which ultimately enhances the flexural capacity of the slab. Therefore, in bridge deck

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**Nomenclature**

| | |
|---|---|
| CMA | compressive membrane action |
| $d_c$ | compressive damage in NLFEA |
| $d_t$ | tensile damage in NLFEA |
| $E_c$ | elastic modulus of concrete material |
| $f_c$ | compressive stress |
| $f_{c'}$ | maximum stress |
| $f_{b0}$ | biaxial compressive yield stress |
| $f_{c0}$ | uniaxial compressive yield stress |
| $f_{t0}$ | uniaxial tensile yield stress |
| $f_{cu}$ | compressive strength of concrete |
| $\varepsilon_c$ | compressive strain |
| $\varepsilon_c'$ | strain when $f_c$ reaches $f_c'$ |
| $\varepsilon_c^{in}$ | inelastic compressive strain |
| $\varepsilon_t^{in}$ | inelastic tensile strain |
| $\varepsilon_c^{pl}$ | plastic compressive strain |
| $\varepsilon_t^{pl}$ | plastic tensile strain |
| $h$ | deck depth |
| $n$ | curve fitting factor, as n becomes higher the rising curve becomes more linear |
| $\alpha$ | coefficient determined from the initial equibiaxial and uniaxial compressive yield stress |
| $\beta$ | function of plastic strain |
| $I_1$ | first invariant of stress tensor |
| $I_{yy}$ | second moment of area in minor axis of steel-I beams |
| $I_{xx}$ | second moment of area in major axis of steel-I beams |
| $J_2$ | second invariant of stress deviator tensor |
| $<\sigma_{\max}>$ | algebraically maximum principle stress |
| $\gamma$ | 3 for typical concrete, only appears in triaxial compression |
| $\sigma_{bc}^u$ | ultimate biaxial compression |
| $\sigma_c^u$ | ultimate uniaxial compression |
| $\sigma_{1,2,3}$ | principle stress |
| $k$ | a factor to increase the post-peak decay |
| NLFEA | nonlinear finite element analysis |
| $P_t$ | failure loads in the tests |
| $P_{NLFEA}$ | ultimate strengths predicted by NLFEA |
| $P_{ACI}$ | ultimate strengths predicted by ACI code |

slabs, it is generally lateral restraint stiffness and concrete compressive strength which govern the ultimate strength and independent to the percentage and type of reinforcement [7–9]. It has been recognized for some time [10–12] that concrete bridge deck slabs exhibit strengths far in excess of those predicted by most design codes. Furthermore, research by Kirkpatrick [13,14] has shown that CMA also has a beneficial effect on the serviceability performance of bridge deck slabs. As a result, it is possible to produce an economic and durable concrete deck slabs by utilizing the benefits of GFRP reinforcement in combination of CMA [9].

In the past research, most of research works on the structural behaviour of GFRP reinforced concrete deck slabs has focused on experimental tests [3,7,15,16]. However, due to the high cost and significant time requirement in conducting experimental testing, particularly in developing dynamic traffic loading tests, it is hard to establish comprehensive investigations of this non-metallic bridge deck slabs. Furthermore, some structural variables were difficult to be obtained by experimental tests, such as stress–strain relationship through the depth of slabs and stress distribution at the slab surfaces. Therefore, refined and completed studies are required to investigate the structural behaviour of deck slabs reinforced with GFRP bars. The availability of high-speed computers and commercial finite element packages facilitate the development of these tools through 3D FEA [7].

The aim of this paper is to study how GFRP reinforced concrete deck slabs work under static patch loads and dynamic truck loads with consideration of CMA. In this study, a commercial software named ABAQUS [17] was employed. The proposed numerical model showed good convergence ability and an excellent agreement of structural behaviour with the validations of experimental tests in the laboratory and field tests [1,3,15,18]. Subsequently, the observed structural behaviour of deck slabs were presented. Thereafter, some parametric studies are conducted to investigate the effects of CMA on this structural type.

## 2. Numerical model development, calibration and validation

### 2.1. Physical model

In the study of behaviour of GFRP reinforced concrete deck slabs under static loads, two groups of test models were used. A series of one-third scaled concrete bridge model tests was conducted by authors at Dongguan University of Technology [18], as shown in Fig. 1. The other series of full scaled concrete bridge decks tested by Sherif et al. [15] was also used in this NLFEA study (see Fig. 2). A summary of the experimental variables is presented in Tables 1 and 2. Both series of test models were designed to be an external bay of a typical composite steel–concrete bridge. As illustrated in Figs. 1 and 2, a static patch load was applied at the midspan of the concrete bridge deck slabs to study the ultimate capacity of this structural type.

An existing bridge named Cookshire-Eaton Bridge in Canada was used to study the dynamic behaviour of GFRP reinforced concrete bridge deck slabs under traffic loads. This bridge was tested for service performance using calibrated truck loads [3]. The Cookshire-Eaton Bridge is a beam-and-slab type bridge, which has five main girders continuously over two spans of 26.04 m. The deck is a 200 m thick concrete slab continuous over five supporting beams spaced at 2.70 m with an overhang of 1.4 m on each side, see Fig. 3. One full span including the deck slab, curbs and sidewalks, was totally reinforced with GFRP bars. GFRP bars with diameter of 19.1 mm at 75 mm and 100 mm in the top and bottom transverse directions, respectively, were used. GFRP bars with diameter of 15.9 mm at 150 mm were used in the longitudinal direction at the top and bottom. The other bridge span was reinforced with two identical mats of steel bars (diameter = 15.9 mm) spaced at 150 mm and 225 mm in the transverse and longitudinal directions, respectively. Only the bridge span reinforced with GFRP bars was modelled and investigated in this numerical analysis. The configuration of traffic loads (truck loads) was illustrated in Figs. 4 and 5.

### 2.2. NLFEA bridge model

In 3D numerical modelling, the bridge deck can be built used shell or solid elements. The steel supporting beams can be simulated as shell, solid or beam elements. Based on the previous research by authors [7], the shell element (S8R or S4R) was selected to model concrete bridge decks, steel supporting beams and diaphragms, as shown in Fig. 6. These elements considered transverse shear flexibility and membrane strains. Full composite action between the RC bridge deck slabs and steel supporting beams was assumed and developed using beam type multipoint constraints (MPC beam [7]) between the top flange of steel I beam and concrete slabs, which assures the nodal compatibility at those locations.