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Investigation of structural behaviours of laterally restrained GFRP reinforced concrete slabs

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ABSTRACT

The corrosion of reinforcement in concrete bridge deck has been the cause of major deterioration and of high costs in repair and maintenance. Glass fibre reinforced polymer (GFRP) reinforcement is a more durable alternative to steel reinforcement and has higher strength to weight ratio. Due to the low value of elasticity and brittle behaviour of GFRP, the service behaviour of GFRP reinforced concrete structure is critical. 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 behaviour such as the deflection. This paper presents the results of experimental tests and numerical analysis of laterally restrained GFRP reinforced concrete slabs with varying some structural variables. The analysis results are discussed and conclusions on the compressive membrane action in GFRP reinforced concrete slabs are presented.

1. Introduction

It has been increasingly evident that the corrosion of steel reinforcement due to the de-icing salts has one of the major factors in the deterioration of reinforced concrete bridge decks [1,2]. One solution to these corrosion problems is the use of alternative non-corrosive materials to replace steel reinforcement, such as fibre reinforced polymers (FRPs) [3]. Because glass FRP bar is more economical than the available types (carbon and aramid) of FRP reinforcing bars [4], it is more attractive for infrastructure applications and to the construction industry. However, the majority of recent research using GFRP reinforcement has concentrated on simply supported slabs. Due to the low elastic modulus and brittle behaviours of GFRP, the deflection in the GFRP reinforced sections is greater compared to steel reinforced concrete slabs. Therefore, the deflection criterion tends to control the design of intermediate and long spanning sections reinforced with GFRP bars [5–8]. Conversely, it is the ultimate strength governing the structural design of steel reinforced concrete sections. Interestingly, in laterally restrained slabs, such as bridge deck slabs, it is generally laterally restraint stiffness and concrete compressive strength which govern the structural behaviours and independent to the percentage and type of reinforcement [9].

It has been recognised for some time [10–12] that laterally restrained slabs exhibit strengths far in excess of those predicted by most design codes. The load capacities are enhanced significantly due to the arching action or compressive membrane action (CMA), which are far larger than those predicted by flexural methods [13]. Furthermore, research by Kirkpatrick et al. [14,15] has shown that CMA also has a beneficial effect on the 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.

The aim of this paper is to study the structural behaviours 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 [16], which accommodates non-linear 3D FEM models, can be employed. The proposed numerical model showed good convergence ability and an excellent agreement of structural behaviours with the validations of experimental tests by authors. Subsequently, the observed structural behaviours of laterally restrained slabs and effect of CMA in this non-metallic structure were presented.

2. Experimental program

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. The

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Nomenclature

f_c	compressive stress
f_c'	maximum stress
ε_c	compressive strain
ε_c'	strain when f_c reaches f_c'
n	curve fitting factor (as n becomes higher the rising curve becomes more linear)
E_c	elastic modulus of concrete material
$\sigma_{1,2,3}$	principle stress
α	coefficient determined from the initial equibiaxial and uniaxial compressive yield stress
β	function of plastic strain
I_1	first invariant of stress tensor
J_2	second invariant of stress deviator tensor
$\langle\sigma_{\max}\rangle$	algebraically maximum principle stress
γ	for typical concrete, only appears in triaxial compression
f_{b0}	biaxial compressive yield stress
f_{c0}	uniaxial compressive yield stress
f_{t0}	uniaxial tensile yield stress
b	width of the slab
h	full depth of the slab
d	effective depth of the slab
As	area of the reinforcement
f_y (σ_y)	yield stress of steel reinforcement
ε_y	yield strain of steel reinforcement
f_{cu}	compressive strength of concrete
ε_{ft}	strain of concrete under ultimate tensile strength
σ_{ft}	the maximum tensile stress of concrete
d_c	compressive damage components of concrete
d_t	tensile damage components of concrete
ε_c^{pl}	compressive plastic strain
ε_c^{in}	compressive inelastic strain
ε_t^{pl}	tensile plastic strain
P_t	loading capacity obtained in experimental tests
P_p	loading capacity predicted in NLFEA
P_{AASHTO}	loading capacity predicted by current AASHTO standard
K_r	lateral restraint stiffness
Δ_t	vertical deflection at midspan of concrete slabs from experimental tests
Δ_p	vertical deflection at midspan of concrete slabs from NLFEA
Δ_{AASHTO}	vertical deflection at midspan of concrete slabs predicted by current AASHTO standard
Mcr	cracking moment [7]

dimensions of slabs are shown in 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 30 N/mm^2 to 80 N/mm^2. To achieve a noticeable arching effect, the comparisons of the models with different boundary conditions were required. Therefore, two additional slabs without lateral restraints were established.

The eleven slabs were made according to the trial mix results and the experimental variables are summarised in Table 1. The GFRP reinforcing bars with 9 mm diameter were tested for their ultimate strength and elastic modulus. The test method was configured according to the research by Castro and Carion [17] with the loading rate of 0.2 N/s. The test results are compared with the manufacturer's reported strength and modulus of elasticity as shown in Table 2.

2.2. Test apparatus and instrumentation

The effectiveness of compressive membrane forces is dependent on the stiffness of lateral restraints. As shown in Figs. 1 and 2, 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 torqure value of 80 N 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. 2a). Loading was applied through a stiff loading beam with a 20 mm knife edge loading plate. The application of load was from an accurately calibrated 500 kN 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 were positioned in the test frame, the strain gauges and transducers were connected to a data acquisition system (see Fig. 2b). 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 (see Fig. 3). 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 (see Fig. 4a). The horizontal movements of steel rigs were recorded by using displacement transducers at the end of steel frames (see Fig. 4b).

2.3. Test procedure

All of the test slabs were required to be accurately positioned in the restraining rig and the positioning the slabs relative to the loading frame should be taken care to minimise the eccentricity. In the loading procedure of each slab, two preliminary test loads were applied the recovery was measured. Thereafter, the tests slabs loaded incrementally to failure. In the GFRP reinforced concrete slabs, serviceability behaviour can be more significant than ultimate strength. Therefore, deflection of the slabs, crack width development, strain in GFRP bars and concrete slabs were measured in all the experimental models.

3. Behaviours and discussion 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. 5 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 100 kN, the crack patterns and crack widths were very similar among slabs CG10, CG11 and CG12. The structural