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Fatigue analysis of concrete bridge deck slabs reinforced with E-glass/vinyl ester FRP reinforcing bars

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Abstract

FRP composites have been widely used as internal reinforcement for concrete bridge deck slabs. However, experimental researches on the behavior of such FRP-reinforced elements in general have been limited, especially those on fatigue performance. This research is designed to investigate the fatigue behavior of concrete bridge deck slabs reinforced with GFRP bars. A total of six full-size deck slabs were constructed and tested under concentrated cyclic loading conditions. Different reinforcement types, ratios, and configurations were used. Also, different schemes of cyclic loading were applied till failure. Finite element modeling was used to investigate the effect of different parameters on the ultimate static capacity. The results showed the superior fatigue performance and longer fatigue life of concrete bridge deck slabs reinforced with GFRP composite bars compared to the steel reinforced ones.

Keywords: A. Glass fibres; B. Fatigue; C. Finite element analysis (FEA); Bridge decks

1. Introduction

The slab-on-girder superstructure is one of the most common structural systems used for North American highway bridges. After the cracking of the deck slab, it is well established that deck slabs (having a span-to-depth ratio $\leqslant 15$) resist traffic loads through arching action. Due to the lateral restraining action exerted by the supporting girders and the continuity of the slab, compressive membrane forces develop and the deck slab behaves like a dome and fails ultimately by punching shear. Since bridge deck slab directly sustains repeated moving wheel loads, it is one of the most bridge elements susceptible to fatigue failure. Consequently, fatigue performance is an important limit state that must be considered by designers of bridge decks [1–3].

Due to their non-corrodible nature, fiber reinforced polymer (FRP) composites have been investigated by researchers as suitable reinforcement for concrete structures to overcome corrosion related problems. Since it is less expensive than other kinds of FRP (Carbon and Aramid), glass FRP composite reinforcement (GFRP, commonly, consists of glass fibers impregnated in a vinyl ester resin) is more attractive to the infrastructure applications and the construction industry. However, due to the relatively low modulus of elasticity and small transverse strength of FRP bars, especially GFRP, the overall shear capacity of concrete members reinforced with FRP bars as flexural reinforcement is lower than that of concrete members reinforced with the same amount of steel [4,5].

Several codes and design guidelines have been recently published, which allow the use of FRP bars as main reinforcement for concrete structures including bridge deck slabs and girders [6–8]. In addition, several concrete bridges were built in North America using GFRP

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composite bars as main reinforcement for their deck slabs [9,10]. Considerable research has been carried out mainly on steel reinforced concrete deck slab specimens or prototypes under pulsating or moving loading to simulate the effect of traveling vehicles on a bridge deck. However, little research has been carried out on concrete bridge decks reinforced with FRP bars.

This research is designed to study the performance of concrete bridge deck slabs reinforced with GFRP bars under fatigue loads. The research includes experimental testing of full size GFRP reinforced concrete deck slabs under cyclic loading only or under monotonic loads preceded with cyclic loads. It also includes analytical investigation using the finite element analysis to evaluate the ultimate static capacity of such deck slabs under monotonic load conditions that will be used to develop an analytical model to predict the fatigue life of such elements. The finite element model is employed to perform a parametric study on the effect of different parameters such as concrete compressive strength, tandem and axle loads, and continuity in the transverse direction. This paper presents the results of the experimental testing under cyclic loading conditions and the finite element model results regarding the behavior of test prototypes under monotonic loading condition.

2. Background

Okada et al. [11] tested seven deck models by applying either stationary pulsating load or moving wheel loads. All deck slabs had top and bottom meshes of steel reinforcement. The reinforcement ratio of the top mesh was equal to half of the bottom mesh. They found that cracks first formed on the bottom surface of the deck. Due to the repetitive moving load, the crack faces rubbed against each other, which resulted in wider crack widths and smoother crack faces. This consequently reduced the shear stiffness of the deck and led to failure associated with the loss of the aggregate interlock at the crack interfaces. Perdikaris and Beim [12] conducted a series of tests on steel-reinforced bridge deck models under static, stationary, pulsating and moving wheel loads. The experimental program included 1/3 and 1/6.6-scaled deck models (with orthotropic or isotropic reinforcement patterns) on simply supported steel girders, with a girder spacing-to-slab thickness ratio of about 10. They recognized that the crack pattern under stationary pulsating load was radial, whereas the crack pattern was of a grid-shape under the moving fatigue load. They concluded that the flexural and shear fatigue resistance of the decks was remarkably decreased under the moving load, especially for the decks with orthotropic reinforcement. Also, one wheel load passage was found to be equivalent to 80–600 load cycles of the stationary pulsating load with the same amplitude. Kumar and GangaRao [13] investigated the fatigue behavior of four full-size concrete bridge decks reinforced with sand coated GFRP bars. All test specimens were subjected to two million load cycles with a frequency of 1 Hz. No bond loss was found between the GFRP bars and concrete in any of the test specimens. The major crack pattern was in the direction parallel to the girder, which could be idealized as flexural cracks in the concrete deck spanning between the steel girders. Effective central deck deflection was set as a measure of global rate of deck degradation during fatigue. This rate of degradation in decks reinforced with GFRP bars was found to be comparable to decks reinforced with steel.

3. Details of the experimental program

3.1. Test prototypes

The experimental program includes construction and testing of six full-size bridge deck prototypes (2500 mm width, 3000 mm length, and 200 mm thick). Five deck slab prototypes were reinforced with different reinforcement ratios and configurations of GFRP bars and one slab prototype was reinforced with conventional steel bars as control. Bottom and top concrete cover of 38 mm was used for all slab prototypes. The main bottom transverse GFRP reinforcement for four decks, S1, S2, S3, and S4 was calculated based on the empirical design method recommended by Section 16 of the Canadian Highway Bridge Design Code (CHBDC) Clause 16.8.7.1, for internally restrained cast in place deck slabs [14]. According to this clause, a minimum FRP reinforcement area in the transverse bottom direction is set to $500d_s/E_{FRP}$ where d_s is the distance from the top of the slab to the centroid of the bottom transverse reinforcement in mm and E_{FRP} is the modulus of elasticity of the used FRP reinforcement in MPa. This reinforcement ratio was calculated to have the same axial stiffness as the average between the minimum and the recommended steel reinforcement ratio (0.25%) allowed by the code, Commentary C.16.8.7.1 [14]. This approach resulted in using No. 19 GFRP bars spaced at 150 mm in the bottom transverse direction with a reinforcement ratio of 1.2%. For the fifth slab, S5, a reduced reinforcement ratio of 1.0% was used for the bottom transverse reinforcement which results in using No. 19 GFRP spaced at 180 mm. The longitudinal bottom reinforcement for the five slabs consists of No. 16 GFRP spaced at 200 mm with a reinforcement ratio of 0.6%.

Different configuration and reinforcement ratio for the top reinforcement mesh were used. For slab S1, S2, and S5, No. 16 GFRP spaced at 200 was used in both directions with a reinforcement ratio of 0.6% (slabs S1, and S2, were identically reinforced). For S3, a minimum reinforcement ratio of 0.35% was used in both directions which results in using No. 13 GFRP spaced at 300 mm in each direction. Slab S4 had no top reinforcement at all. The sixth slab S0 (control), reinforced with steel bars, was designed according to the empirical method of the CHBDC (Section 8 – clause 8.18.4.2) [6], which recommends the use of an isotropic steel reinforcement ratio of 0.3% in all direction for the bottom