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Engineering Structures 26 (2004) 2219–2230

ENGINEERING STRUCTURES

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Structural behavior of strengthened bridge deck specimens under fatigue loading

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Received 7 March 2004; received in revised form 4 August 2004; accepted 11 August 2004

Abstract

The deterioration of concrete bridge decks that have been directly damaged by traffic loads affects their durability, safety, and function. It is therefore necessary to strengthen the damaged concrete structures. Even though there have been many experiments performed to investigate the static behavior of strengthened structures, few experiments or analyses have considered their fatigue behavior.

In this study, fatigue tests were conducted on bridge decks strengthened using various fiber-reinforced polymer plastics, such as carbon fiber sheet, glass fiber sheet, and grid-type carbon fiber reinforced plastic. All of the strengthened specimens were shown to have an improved resistance to crack propagation and better stress distributions. The Weibull distribution was adopted to analyze the fatigue life of the decks. The fatigue life limits of the strengthened bridge decks were determined at higher stress levels, and the grid-type carbon reinforced plastic specimens proved to be the most effective.

Keywords: Bridge deck; Fatigue life; Fiber reinforced polymer plastic; Structural strengthening; Weibull distribution

1. Introduction

Reinforced concrete bridge decks receive traffic loads directly. Structural damage can increase, such as residual deformation and numerous cracks, which eventually decreases the life of the deck as well as its load carrying capacity [1–5]. In South Korea, there are many deck panels that have deteriorated after almost 20 years of service and which must now be rehabilitated. Many of these were designed for relatively low traffic loads rather than the heavy traffic (over HS25) found nowadays, and are only 18 cm thick. When such decks are strengthened, the overall structural performance must be improved, including their serviceability and fatigue resistance as well as the load carrying capacity. The flexural strength of a deck can be improved easily by applying external bonding techniques, using materials such as carbon fiber sheet (CFS) and carbon fiber reinforced plastic (CFRP) attached to the tension side of the concrete. However, it is fairly difficult to rehabilitate the fatigue resistance of a deck because the shear strength that has been decreased by repeated loads must be improved with the flexural strength. Previous research by the authors experimentally verified that the fatigue resistance of a deck that was externally strengthened with CFSs was improved even if no additional sectional enlargements of the deck were made [6]. This result presented the possibility of extending the life cycle of a deck panel without adding deadloads by using either mortar overlay or an additional internal stiffener.

Although numerous research programs over the past decade have attempted to understand fatigue response and to establish a fatigue model for concrete subjected to repeated loads, the fatigue failure characteristics of strengthened concrete structures are not yet systematically established on a scientific foundation [7–12]. Much of the research for concrete structures has been limited to either a simple *S*–*N* relationship or a mechanical approach, because the analysis is too

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doi:10.1016/j.engstruct.2004.08.006

complicated to extend to an entire structural system from either the microscopic element or material points of view.

The experimental and theoretical work presented in this paper is the result of successive research programs conducted at the Hanyang University in Korea to verify the structural efficiency of various fiber reinforced polymer (FRP) composites for strengthening concrete structures [6,12,13]. The authors have persisted in developing rehabilitation techniques for deteriorated concrete structures for the past decade [6,12,14]. A recent focus has been how to achieve additional benefits by applying FRPs to a deteriorated concrete member, either by extending its fatigue life or enhancing its serviceability. Improvements to both the fatigue and flexural resistance must be considered when rehabilitating a deteriorated concrete bridge deck.

The experiments reported in this paper were conducted to find structural differences and efficiencies between slabs strengthened with various FRPs and subjected to cyclic loading [13]. We also attempted to verify the theoretical *S–N* relationship of strengthened deck panels through a probabilistic approach based on the test results.

In this paper, CFS, glass fiber sheet (GFS) and grid-type carbon fiber reinforced plastic (GCFRP) were used as the strengthening materials.

2. Experimental program

2.1. Materials

The concrete used in the specimens consisted of ordinary Portland cement, natural sand, and crushed coarse aggregate with a maximum size of 25 mm. The mixture had a 28-day cylinder strength of about 22.5 MPa. Deformed bars, 15.9 mm in diameter with an average yield strength of 300 MPa, were used in the slab panels and beams. The shear reinforcement of the girders consisted of 9.35-mm diameter closed stirrups. The material properties are listed in Table 1.

2.2. Test program

For the experimental test program, a prototype deck panel with dimensions of 160 × 240 cm was selected to simulate a real bridge deck supported by two girders, as referenced in [13]. In order to determine the dimension of deck specimen, 3-dimensional non-linear finite element analyses in which various dimensions of deck considered to simulate either the deformation or deterioration of real bridge deck were carried out before the physical experiments. As a result, the selected dimension of deck from the FE analysis was similar to the real deck size used in Korea. The concrete slab was modeled with eight-node solid elements, reinforcing bars with beam elements, and the CFS was represented by membrane elements with stiffness properties only in the appropriate directions [15–19]. Both beam and membrane elements were assumed to be perfectly bonded to the concrete. The material properties were obtained experimentally. The rubber supports were simulated by spring elements with a hyperelastic material law.

The slab thickness was 18 cm, which is the same as that of secondary bridge decks in Korea. The tensile rebar spacing in the transverse direction was 10 cm and the reinforcement spacing in the longitudinal direction was 15 cm. The specimen details and strengthening methods are depicted in Figs. 1 and 2.

The CFS and GFS materials were bonded to the prototype deck panel in an upside-down position. Each fiber sheet was attached to the epoxy-coated surface by pressing it into the epoxy. The GCFRP material was first fixed to the concrete surface in an upside-down position using 2.5-cm length anchor bolts spaced every 50 cm. Then, the repair mortar suggested by the manufacturer was overlayed on the concrete surface.

The 12 specimens listed in Table 2 were subjected to cyclic loads to investigate their fatigue failure characteristics. CON means the unstrengthened reference panel. The stress level of each specimen, except CON-40 and GFS-40 designed to verify the structural response in service state, was designed to assess the endurance limit of deck specimens and compare the

Table 1
Physical properties of materials

	Thickness or diameter	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)	Ultimate strain
Concrete		–	22.5	0.232×10^5	–
Rebar	13 mm	300	400	1.96×10^5	–
Epoxy		–	88.3	0.07×10^5	–
Carbon fiber sheet	0.11 mm	–	3500	2.31×10^5	0.015
Glass fiber sheet	1.3 mm	–	450	0.227×10^5	0.02
GCFRP	4.0 mm	–	1170	1.00×10^5	0.0117
Mortar for GCFRP			27.0	0.14×10^5	–