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FRP strengthening of 60 year old pre-stressed concrete bridge deck units

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ABSTRACT

Over the past few decades fibre reinforced polymers (FRPs) have gradually gained recognition as an effective material for the strengthening of reinforced concrete (RC) structures. FRP strengthening techniques provide an attractive alternative to the existing cumbersome traditional bridge strengthening methods due to FRPs superior properties, such as lightweight, easy to install, and highly resistant to corrosion. FRP strengthening has been sought as an option for strengthening pre-stressed concrete deck unit bridges in Queensland, Australia. This paper presents an investigation in to the effectiveness of two different FRP strengthening techniques on increasing flexural capacity and flexural stiffness of pre-stressed RC deck units. Two different FRP strengthening schemes, one with adhesively bonded carbon FRP (CFRP) pultruded plates and another with adhesively bonded and mechanically fastened glass FRP (GFRP) I beam and adhesively bonded CFRP pultruded plates were investigated. Three 60 years old pre-stressed RC deck units taken from a bridge in Queensland, Australia were tested. One beam was tested as the control specimen, while the other two were strengthened with the two different FRP strengthening techniques. FRP strengthening using the two proposed systems found to increase the loads at serviceability limit by 10% and 31%, while ultimate strength was increased by 54% and 105%. A section analysis based on perfect composite section assumption was found to predict the moment curvature behaviour of the FRP strengthened specimens quite accurately. Existing design code methods were found to provide conservative design strength of the FRP strengthened pre-stressed RC deck units.

1. Introduction

Bridges are a key structural component in transportation networks. During their service life the load carrying capacity of bridges may become inadequate due to many factors such as deterioration, overloading, increase in load demands, etc. In such cases bridges may require retrofitting or rehabilitation to meet the required level of load carrying capacity. Often existing traditional bridge strengthening methods such as external bonding of steel plates, steel or concrete jackets, external post tensioning, etc. are cumbersome, and possess disadvantages such as long construction times resulting in traffic disruptions, high resource requirements and thus high costs.

Fibre reinforced polymer (FRP) composite materials have gained wide acceptance as an attractive material for retrofitting reinforced concrete (RC) structural elements [1–3]. The use of FRP, which is a lightweight, easy to install, and highly resistant to corrosion material, provides an attractive alternative to the existing cumbersome traditional bridge strengthening methods. Many types of FRP strengthening methods have been proposed and applied to adapt to the various requirements in practice, such as externally bonded (EB) FRP strengthening, near surface mounted (NSM) FRP strengthening and so called hybrid bonded FRP system [4–7]. Amongst these strengthening methods, EB FRP and NSM FRP strengthening systems have been studied extensively for flexural strengthening of RC beams. Although there is an ever-expanding research database of RC structures strengthened with different FRP systems, information on various strengthening techniques for pre-stressed concrete structures is very limited. Amongst the existing studies, use of EB carbon FRP (CFRP) plates [8,9] and the use of NSM CFRP [10] have shown to significantly increase the flexural strength of pre-stressed concrete girders. In many of these studies, the use of U-wraps in conjunction with EB CFRP plates or NSM CFRP is advised to avoid premature debonding failures. Although the majority of research on FRP strengthening of RC elements concerns small-scale tests, some large scale tests and field applications have also been performed [11–16]. Design for the strengthening of RC elements with FRP materials is now covered in many design codes such as ACI 440.2R [17], FIB 14 [18], and CECS 146 [19] to name a few.

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This paper discusses an experimental investigation in to the strengthening of pre-stressed RC bridge deck units (called PC deck units for brevity) taken from a decommissioned bridge in Queensland, Australia using two different FRP strengthening systems. PC deck unit bridges were commonly used in the construction of roadway bridges in Queensland, Australia. Many of the existing PC deck unit bridges were designed and constructed over 60 years ago. With industrial development, these bridges are now required to carry heavier and larger vehicles than those they were designed for. Additionally, the continual evolution of bridge design codes have introduced more stringent design requirements, which many of these bridges do not now meet. An assessment carried out by the Queensland Department of Transportation and Main Roads (TMR) has identified that some of the PC deck unit bridges do not satisfy design code requirements and require interventions. Conventional strengthening options available for methods used in RC bridge strengthening are cumbersome, require long time periods to complete, and result in traffic disruptions driving the costs of such interventions quite high. Therefore, strengthening solutions which are less cumbersome and do not involve long periods of traffic disruptions are required to address the current strengthening needs of these bridges. FRP strengthening is sought as an alternative to existing cumbersome strengthening solutions for PC deck unit bridges. Three PC deck units were taken from a decommissioned bridge and tested in laboratory conditions to investigate the effectiveness of FRP strengthening in increasing the load carrying capacity as well as the flexural stiffness of the PC deck units.

2. Experimental program

2.1. Pre-stressed RC deck unit bridges

A typical PC deck unit bridge consists of ten PC deck units and two PC kerb units connected together through transverse pre-stressed bars (Fig. 1a and b). A typical PC deck unit is shown in Fig. 1c. In construction of these bridges, first the PC deck units and PC kerb units are put in place and mortar is applied to the gaps between each unit. Then transverse bars are placed through the transverse holes of units and transverse pre-stressing is applied. The aim of the transverse connections through ten PC deck and two PC kerb units in a bridge is to provide effective load distribution amongst the units, thus allowing them to act as a single system rather than as individual units. More information on the installation process can be found in MRTS74 [20].

2.2. Test girders

As a part of an ongoing research program in collaboration with Queensland TMR, three 9.05 m long PC bridge deck units were tested in the Structures Laboratory at the University of Queensland (UQ). One PC deck unit was tested as the control specimen and the two other PC deck units were strengthened with separate FRP strengthening options (strengthening scheme 1 and scheme 2). For the ease of reference, control specimen will be denoted by "CS" hereafter while strengthened scheme 1 and 2 specimens will be denoted by "SS1" and "SS2" respectively. All PC deck units were of rectangular cross section with two rows of internal voids of 150 mm diameter along their longitudinal axis (Fig. 2a–d). The PC deck units were taken from a decommissioned bridge in Queensland, Australia which was erected between 1963 and 1970 (exact date unknown) and were in good condition upon delivery to the UQ Structures Laboratory. Each PC deck unit is pre-stressed with twenty-two 9.7 mm diameter pre-stressing strands. According to the fabrication drawings, a pre-stressing force of 70 kN was applied to each strand. The camber at mid-span due to pre-stressing was measured to be 21 mm.

2.3. Strengthening schemes

Through discussions with TMR it was revealed that such PC deck unit bridges may fail due to inadequate flexural capacity of the PC deck units or due to shear failure through the transverse pre-stressed bars that connect the individual units. Differential movements between the adjacent PC deck units are resisted by the transverse bars, thus the forces in transverse bars are directly related to the flexural stiffness of each PC deck unit. Once the load-displacement behaviour of a PC deck unit becomes nonlinear, due to the reduction of flexural stiffness, the forces transferred through the transverse pre-stressed bars may increase significantly. This increases the risk of failure in the PC deck unit near the transverse pre-stressed bar locations or in the transverse pre-stressed bar itself. Therefore, a strengthening system which could increase both the flexural capacity and flexural stiffness (especially once the behaviour becomes nonlinear) is required for the effective strengthening of these bridges. Two different strengthening schemes were investigated in this study. SS1 (Fig. 3) consisted of four (maximum number of CFRP plates which can be applied on the soffit without much difficulty) 8 m long CFRP pultruded plates that were adhesively bonded to the soffit of a PC deck unit using MBrace laminate adhesive. The CFRP used were commercially available normal modulus (170 GPa elastic modulus in fibre direction) pultruded plates with a width of 102 mm and thickness of 1.4 mm (Fig. 3b).

SS2 (Fig. 4), consists of three (maximum number of GFRP I beams which could be applied on the soffit of the PC deck unit, with adequate access to the top flange of the GFRP I beams) 8 m long glass FRP (GFRP) I beams adhesively bonded and mechanically fastened to the soffit of a PC deck unit and three 8 m long CFRP pultruded plates which were adhesively bonded to the soffit of the GFRP I beams. Commercially available GFRP I beams, with a longitudinal elastic modulus of 29 GPa, were used in this study. The nominal cross sectional dimensions of a GFRP I beam used in this study are given in Fig. 4b. GFRP I beams were bonded to the soffit of the PC deck units using MBrace laminate adhesive. Due to the relatively high flexural stiffness of the GFRP I beam (compared to that of commonly used CFRP pultruded plates), high interfacial peeling stresses may result near the GFRP I beam termination points. In addition, during the testing cracks may appear on the soffit of the PC deck unit resulting in high peeling stresses within the bonded interface near those cracks. A preliminary finite element (FE) model was used to estimate the peeling forces expected near the GFRP I beam termination points. FE models were created using ABAQUS [21] for the SS2 deck unit with the exact dimensions and support conditions (i.e. simply-supported boundary conditions). PC deck unit was modelled using 3D-solid elements, while the strands were modelled using truss elements. The steel was defined as an embedded region in the concrete. Adhesive layer was assumed to be of uniform thickness and modelled using 3D solid elements. GFRP I beams and the CFRP plates were modelled using general purpose shell elements. All bi-material interfaces were connected together using tie constraints, assuming perfect bonding. Elastic material properties were used for all materials. Such an elastic assumption is expected to yield higher interfacial peeling stresses compared to a nonlinear analysis with adhesive layer experiencing softening behaviour, thus is conservative in obtaining the forces for anchor design. Total peeling force was calculated by integrating the peeling stresses at the plate ends at 600 kN applied load (i.e. three times the ultimate load experienced by CS). Such a conservative approach was used due to lack of knowledge in designing such anchors to resist debonding. Based