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Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit systems

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ABSTRACT

Unlike bonded retrofit systems, un-bonded systems do not need any surface preparation prior to bond application, which reduces the overall time and cost of a retrofit plan. Because the carbon fiber reinforced polymer (CFRP) plate in the un-bonded (tendon) systems is not bonded to a metallic substrate, different variants of the retrofit systems can be developed to ease application in the field. This paper presents four different variants of the prestressed un-bonded retrofit (PUR) systems: trapezoidal PUR (TPUR), triangular PUR (TriPUR), Flat PUR (FPUR), and Contact PUR (CPUR) systems. Analytical solutions based on the flexibility approach are developed to predict the behavior of the metallic beams retrofitted with the PUR systems. A finite element (FE) model is created to simulate the behavior of the retrofitted beams. The results of the analytical solutions are compared with those obtained from the FE model. The results from the analytical and numerical models have been compared with the results of an experimental study on steel and aluminum beams retrofitted with the PUR systems. A series of parametric studies are performed to investigate the influence of different parameters such as the type of the PUR system and the CFRP pre-stress level on the behavior of the retrofitted beams. The results show that for a specific CFRP pre-stress level, all four different PUR systems result in approximately the same stress reduction in the steel beam bottom flanges. Therefore, it is possible to use any of the four pre-stressing technique depending on the requirements of the structure to be pre-stressed.

1. Introduction

Over the last few decades, bridges have experienced a massive increase in static and dynamic loads because of developments in transportation technology worldwide [1–4]. While trains and vehicles have become heavier and faster, roads and bridges have become older and their ability to withstand the increased volume of traffic loads has decreased. Because the reconstruction of deficient bridges is expensive and time-consuming, bridge authorities often consider a retrofit option.

1.1. Retrofit with pre-stressed carbon fiber reinforced polymer (CFRP) plates

The usage of FRP materials instead of steel plates or tendons is a new procedure for retrofitting purposes and their pre-stress technics are essentially different. The conventional methods for retrofitting usually utilize bulky steel plates, which are heavy, difficult to install and are prone to corrosion and fatigue of their own. Compared to the CFRP material, steel plates are heavy, and their installation process often requires crane. Furthermore, using heavy steel strands can increase the deadweight of the bridge, which is not good for fatigue, as the mean stress level is increased and it results in higher fatigue failure risks [5,6]. Since the 1990s, CFRP materials have gained much attention for retrofitting and construction purposes [7]. The CFRP material has a high strength-to-weight ratio, high corrosion resistance and excellent fatigue performance [8]. Metallic members have traditionally been strengthened using non-pre-stressed CFRP plates. However, in non-pre-stressed retrofit systems, the dead loads are not transferred to the CFRP plates and only a portion of the live load is transferred to the CFRP plates. As an alternative, by using pre-stressed CFRP plates, a portion of the dead load is transferred to the CFRP plates in addition to the live load [9,10]. The fatigue life of steel members has been substantially increased by using bonded CFRP plates [11–18]. It has been shown that pre-stressed CFRP laminate is capable of preventing fatigue crack initiation in steel members [5,19,20]. Furthermore,

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Nomenclature

CFRP	carbon fiber reinforced polymer
PUR	pre-stressed un-bonded retrofit
TPUR	trapezoidal PUR
TriPUR	triangular PUR
FPUR	flat PUR
CPUR	contact PUR
PBR	pre-stressed bonded reinforcement
FE	finite element
DOF	degree of freedom
e_p^i	initial deflection of CFRP plate(s)
e	deviator height (eccentricity of CFRP plate from beam)
$\theta_A,\ \theta_B,\ \theta_C$	slope of the beam at A, B and C cross sections, respectively
φ	complementary angle of the angle between deviator and CFRP plate
$\delta_B,\ \delta_C$	deflection of the beam at B and C cross sections, respectively
L_b	beam length
L_e	effective beam length between C and C'
L	length of the CFRP plate after system deformation
L_i	initial length of the CFRP plate
L_0^i	initial length of the CFRP plate before pre-stressing (in FPUR and CPUR systems)
Δ	change or elongation in the initial length of the CFRP plate: $\Delta = L - L_i$
l	loading distance from the deviator point (i.e., node C)
$\delta_{BC}^F,\ \delta_{BC}^T$	vertical displacement of node B relative to node C because of the external force F and tensile force of CFRP plate T, respectively
δ_i	vertical displacement at node i
δ_{ji}	relative vertical displacement between i and j nodes
δ_M	beam mid-span deflection
σ_p^U	tensile strength of the CFRP material
$E_p,\ E_s$	Young's modulus of the CFRP plate and steel beam, respectively
$A_p,\ A_s$	cross-sectional areas of the CFRP plate and steel beam, respectively
I	moment of inertia of the beam cross-section
G_s	transverse shear modulus of steel
F	external vertical load applied by an actuator
T	tensile force in the CFRP plate
K	shear coefficient (equal to 0 or 1)
PSL	pre-stress level (in percentage)
$\sigma_P,\ \varepsilon_P$	stress and strain in the CFRP plate
$\sigma_b^u,\ \varepsilon_b^u$	stress and strain in beam upper flange
$\sigma_b^l,$	stress and strain in beam lower flange
$\delta_{BC}^F,\ \delta_{BC}^T$	vertical displacement at node B relative to node C because of the external force F and tensile force at CFRP plate T, respectively
δ_i	vertical displacement at node i
δ_{ji}	relative vertical displacement between i and j nodes
δ_M	beam mid-span deflection

Ghafoori et al. [21,22] have shown that it is possible to arrest fatigue crack growth (FCG) in metallic members using pre-stressed CFRP plates. CFRP materials have good long-term behavior. It has superior fatigue behavior, much better than steel, and they have high corrosion resistance.

1.2. Bonded vs. un-bonded retrofit system

The majority of the existing research on CFRP strengthening of metallic members has used CFRP material bonded to the steel substrate. The efficiency of the bonded retrofit system is mainly dependent on the behavior of the CFRP-to-steel bond joint. Sophisticated surface preparation is required prior to bonding the CFRP to the steel member to maximize the efficiency of the composite system and reduce the risk of debonding. Many studies have raised concerns about the influence of environmental conditions (e.g., elevated or subzero temperatures, water and moisture and ultraviolet light) and dynamic loads (e.g., fatigue, impacts and earthquakes) on the behavior of the CFRP-to-steel bond joint (e.g., [18,23,24]).

Because of these concerns, which are mainly associated with the long-term performance of the CFRP-to-steel bond joints, Ghafoori and Motavalli [25–27] have designed and tested a pre-stressed un-bonded retrofit (PUR) system. In contrast to the bonded system, the un-bonded system works without using any bond; instead, it uses a pair of friction clamps to connect the CFRP plates to the steel member.

1.3. Advantages of the PUR systems

The developed un-bonded system has advantages over the traditional bonded systems that are briefly mentioned in the following. The PUR system offers a fast installation procedure because there is no need for extensive surface preparation prior to the bond application. It has been shown that the required amount of time to prepare the metallic beams that were retrofitted with the bonded retrofit system was nearly twice that required for the preparation of beams that used the un-bonded retrofit system [25]. The un-bonded retrofit system can be used for strengthening of metallic members with rough (e.g., because of corrosion) or obstructed (e.g., because of rivet heads) surfaces. In particular, the proposed retrofit system is suitable for retrofitting of cultural structures, where no additional element is allowed to be attached or bonded permanently to the original members. In contrast to CFRP bonded systems, the elements of the un-bonded retrofit systems can be easily detached from the original structures.

The un-bonded retrofit systems need mechanical clamps to connect the CFRP plates to the steel member. The clamps are constructed from steel that is compatible with the steel member to be retrofitted. The concerns related to corrosion of the steel clamps are irrelevant because the system is used for retrofitting of a steel structure. Bridge authorities usually apply anti-corrosion coatings and paints to bridge members every few years. Similar measures can be taken to protect the clamps against corrosion.

1.4. Different variations of the PUR systems

In the bonded retrofit systems, CFRP plates are always attached to the steel member using a type of adhesive bond. Unlike bonded retrofit systems, un-bonded retrofit systems offer different varieties of retrofit configurations. A trapezoidal PUR (TPUR) system has already been developed and tested [27]. The system was used for fatigue strengthening of riveted girders in a 120-year-old railway metallic bridge in Switzerland [28]. In this paper, analytical and numerical models are developed to estimate the behavior of the TPUR system. The results from modeling are then compared