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A Brief Review of Fatigue Strengthening of Metallic Structures in Civil Engineering using Fibre Reinforced Polymers

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Abstract. There is a great potential in using fibre reinforced polymer (FRP) to strengthen aging metallic structures. This paper briefly describes the benefit of using FRP to strengthen metallic structures. It then addresses how fatigue load affects the bond between FRP and steel. FRP fatigue strengthening of cracked steel plates and connections are discussed. Furthermore, effects of using prestressed FRP on flexural and fatigue behaviours of a FRP-steel composite system are addressed. Bonded and un-bonded FRP-to-steel applications, as two different approaches for steel strengthening, are discussed. Finally fatigue strengthening of metallic riveted bridges using un-bonded pre-stressed FRP plates is presented. A comprehensive list of references is provided.

Introduction

A large amount of steel structures are aging, such as road and railway bridges, offshore structures, pipelines, communication towers and mining equipment. Most of these structures are subjected to fatigue loading. The increasing service loads and harsh environmental conditions make these structures even more vulnerable. There is an urgent need to repair and strengthen aging steel structures especially bridges to avoid catastrophic collapse and loss of lives. The conventional method of repairing or strengthening aging steel structures often involves bulky and heavy plates that are difficult to fix and prone to corrosion, as well as to their own fatigue. It has been shown recently [1-4] that an advanced material CFRP (carbon fibre reinforced polymer) has great potential to strengthen steel structures in terms of increased strength, ductility, energy absorption and fatigue life.

This paper starts with a brief summary of the benefit of using FRP to strengthen metallic structures subject to various types of loading. It then focuses on the fatigue strengthening of steel plates, connections and bridges. FRP prestressing technique is discussed. Finally fatigue strengthening of metallic riveted bridges using un-bonded pre-stressed FRP plates is presented.

Benefit of using FRP to Strengthen Metallic Structures

The benefit of using FRP to strengthen metallic structures includes increased strength, ductility, energy absorption and fatigue life. Some examples are given in Table 1. Steel plates and connections under fatigue loading are described later in the paper.

The Influence of Fatigue Loading on Bond Strength

The influence of fatigue loading on the bond between steel and CFRP has been studied by Matta [29], Liu et al. [30] and Wu et al. [31]. Both normal and high modulus CFRP sheet and CFRP plate were adopted in the test program. The specimens were tensioned to failure after enduring a pre-set number of fatigue cycles that ranged from 0.5 to 10 million at different load ratios ranging from 0.15 to 0.55. The load ratio is defined as the ratio of the maximum value of the applied load to its static bond strength. It was found that fatigue loading could reduce the bond strength between normal modulus CFRP and steel by about 20 to 30%, whereas nearly no reduction in bond strength was found in the case of high modulus CFRP. Wu et al. [31] introduced a concept called "local fatigue damage zone" (which is less than 1% of the bond length) to explain why the influence of fatigue loading is very small in the case of high modulus CFRP plates. Miller et al. [25] conducted fatigue tests on two full-scale bridge girders rehabilitated with CFRP plates for 10 million cycles at a stress range that might be expected in the field. No evidence of debonding was observed by visual inspection even after the 10 million cycles.

Table 1 Examples of benefits of using FRP to strengthen metallic structures

Area of strengthening	Improved performance (References)
Flexural Members	Increased moment capacity and ductility in general. For circular hollow sections, slender sections could become non-compact sections [5-8]
Compression Members	Compression strength increases about 20% for steel hollow sections, 70% for thin cylindrical shells and 15% for channel sections. Increased energy absorption under large deformation compression force. [9-12]
Beam Web	Web buckling capacity increases about 1.5 to 2.5 times for cold-formed rectangular hollow sections (RHS), 3 to 5 times for Lightsteel beams and 3.5 times for aluminium RHS. [13-15]
Composite Members	The static strength increased by 55% and 140% when the number of CFRP layers was 2 and 4 respectively. Recovered certain compression strength of concrete-filled tubes after exposure to fire. [16-18]
Welded VHS tubes	Recovered the full yield capacity lost due to HAZ softening in very high strength (VHS) tubes. [19]
Damaged aluminium truss	Full strength restored using CFRP and 70% strength restored using Glass Fibre Reinforced Polymer (GFRP). [20]
Cast iron bridges	Increased load capacity [e.g. 21-24]
Steel bridges	Increased fatigue life [25-28]

Fatigue Strengthening of Cracked Steel Plates and Connections

Extensive research has been carried out to illustrate the improved fatigue performance due to FRP strengthening for cracked steel plates and welded connections. The increased fatigue life ranges from 3 to 10 times. They can be categorized into 3 groups.

Group (i) steel plates strengthened by FRP plates or FRP sheet [e.g. 32-39]:

For FRP plate strengthening normally only one layer of FRP was used, whereas the number of FRP sheets varied from 1 to 5. The modulus of FRP ranged from 155 to 552 GPa. The forms of initial cracks adopted in the research includes (a) a hole with an initial cut, (b) edge notches and (c) saw cut as initial crack and stop holes. Wu et al. [37] summarized FRP configurations into five schemes (see Figure. 1) in terms of the location of FRP in relation to the initial cracks. It was found that the higher the FRP modulus is, the more increase in fatigue life will be. The research also demonstrated the importance of covering the initial cracks with FRP. Yu et al. [40] also studied the strengthening with different damage level (i.e. different length of initial cracks) and showed the benefit of strengthening at early stage. Numerical simulation using boundary element method program BEASY was carried out by Liu et al. [41]. The conventional fracture mechanics theory was extended to predict the FRP strengthened steel plates by considering modification to the stress intensity factor and stress range due to FRP [42].

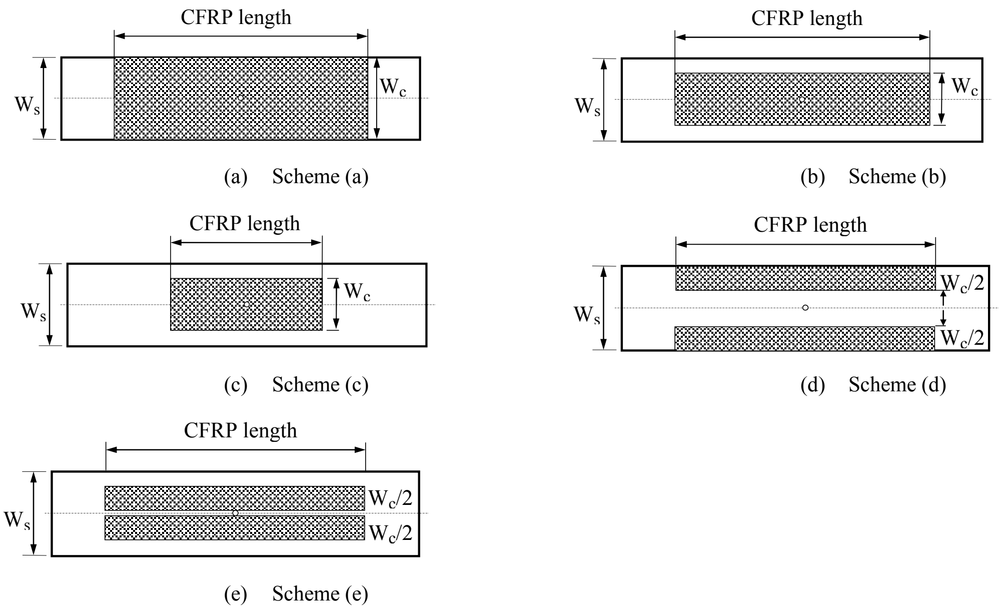

Figure 1 Schematic view of CFRP strengthening schemes (adapted from [37])

Group (ii) steel I-beams with initial cracks in the tension flange strengthened by FRP plates or FRP sheet:

Tavakkolizadeh and Saadatmanesh [43] used CFRP plate with a modulus of 144 GPa, whereas Jiao et al. [44] used 4 layers of CFRP sheet with a modulus of 230 GPa. The stable crack growth rate reduced 65% for the former and the fatigue life increased up to 4 times for the latter.

Group (iii) welded connections strengthened by FRP plates or FRP sheet:

Nakamura et al. [45] and Wu et al. [46] studied the strengthening of welded longitudinal attachment with an initial crack (see Figure 2 (a)) with up to 5 layers of CFRP plate (188 GPa modulus) and one layer of ultra-high modulus (478 GPa) CFRP plate, respectively. The increased fatigue life was found to be 4 to 10 times for the former and 140% for the latter. Welded cross-beam connections (already damaged under fatigue loading, see Figure 2 (b)) were strengthened by Xiao and Zhao [47] using CFRP sheet (230 GPa modulus). Fatigue life was extended up to twice as the original fatigue life. Nadauld and Pantelides [48] performed tests on welded aluminium K-joints strengthened by GFRP sheet (30 GPa modulus, see Figure 2 (c)). The repaired connections exceeded the fatigue limit of the aluminium welded connections with no known cracks. The repaired connections with 90% of the weld removed satisfied the constant amplitude fatigue limit threshold.

FRP Prestressing Systems

Structures are always carrying permanent loads such as their dead-weight and the rails. Strengthening using a non-prestressed CFRP plate has been traditionally used to reinforce a flexural steel member. However, none of the permanent loads are transferred into the strengthening element and the CFRP is efficient to carry only live loads applied to the structure. By strengthening using a prestressed CFRP plate, a portion of the permanent loads will also be transferred to the CFRP plate. There are several studies which have shown the effectiveness of using prestressed CFRP plates to improve the flexural and fatigue behavior of metallic members, as will be mentioned in the following.

Improved Flexural Behavior Due to Prestressing. Laboratory experiments from several studies have shown the effectiveness of using the prestressed CFRP plates to improve the yield and ultimate load carrying capacities of metallic structures.

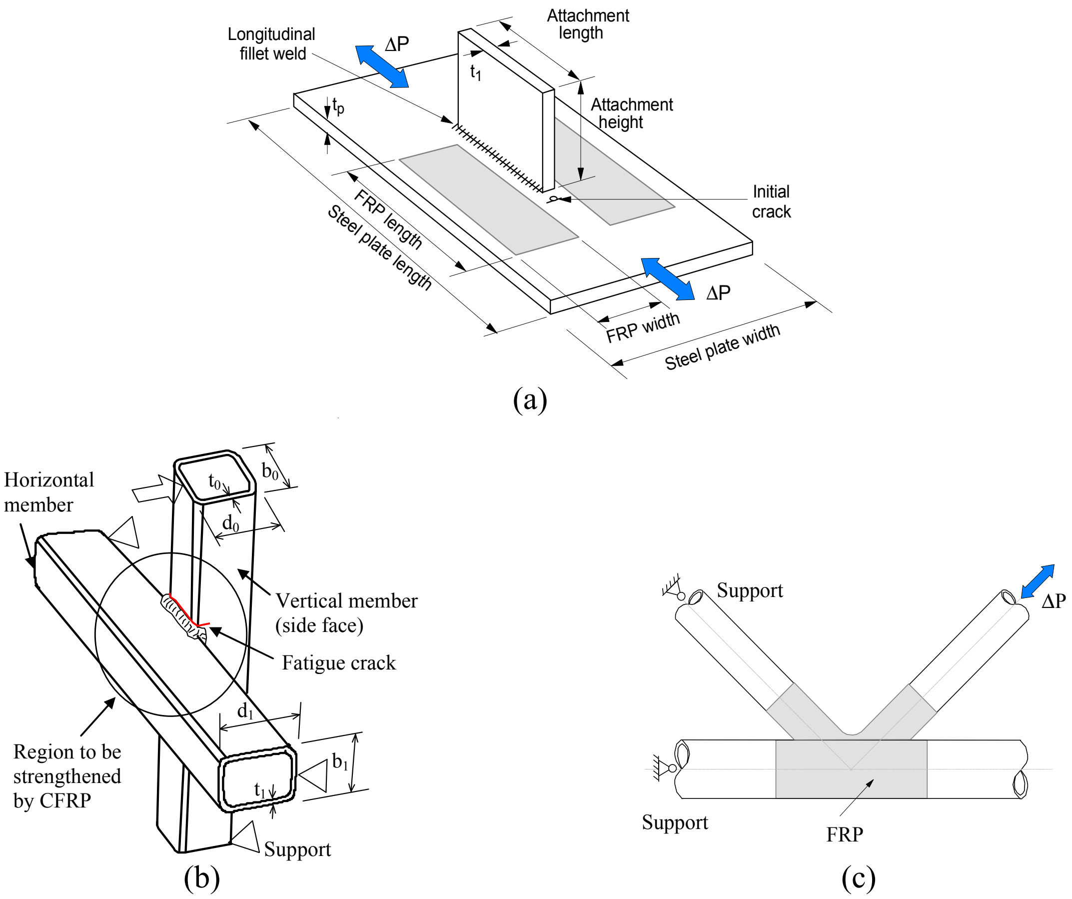

Figure 2 Schematic view of welded connections strengthened by FRP

Schnerch and Rizkalla [8] conducted an experimental study on the feasibility of different strengthening approaches. Large-scale steel-concrete composite beams were strengthened using a prestressed bonded reinforcement (PBR) system. Experimental results showed an economical use of CFRP laminates by prestressing that provided substantial flexural behavior improvement. Soudki et al. [49] conducted an experimental study on the effectiveness of using adhesively bonded CFRP laminates with different prestressing levels to enhance the static flexural strength of the steel members. In this study three strengthened steel beams were tested quasi-statically with different prestressing levels of 27%, 40% and 60% and two control beams that were kept unstrengthened. Results showed a range of increase in the yield strength between 7% to 13%, and an increase in the ultimate strength between 18% to 28% depending on the grade of steel (235 or 355 MPa).

Ghafoori et al. [50,51] have developed closed form solutions for flexural and interfacial behavior of steel beams strengthened by prestressed CFRP plates and compared with experimental results. The effect of different parameters such as the prestressing level, steel grades and geometric and mechanical properties of the plate on both the interfacial shear stress and the flexural behavior of the plated beam were discussed. Their results from both theory and experiments showed that although the geometric and mechanical properties of the FRP plate have influence on the stiffness and the yield load capacity of the plated beam, prestressing does not affect the stiffness of the plated beam but increases the yield load capacity.

Improved Fatigue Behavior due to Prestressing. The results of several studies have shown that using prestressed CFRP plates significantly decreases the fatigue crack growth (FCG) rate and in some cases leads to a crack arrest.

Huawen et al. [52] conducted an experimental and theoretical investigation on the fatigue behavior of tension steel plates strengthened by bonded CFRP laminates with different prestressing levels. Experimental results demonstrated that as the prestressing level increases, the fatigue life of cracked beams increases substantially. Täljsten et al. [35] considered four different configurations of strengthened steel plates with a center notch under fatigue load. They demonstrated the possibility of extending the fatigue life of steel plate nearly four times with non-prestressed plates compared to an unstrengthened plate, and, in some cases, completely arresting the crack growth by using prestressed plates. Colombi et al. [33] studied the effect of a bonded prestressed CFRP composite patch on damaged steel members. The authors studied the effect of different parameters such as the stiffness of the composite plate, the prestressing level, the adhesive layer thickness and the size of the debonded zone on the performance of the reinforced system. Bassetti et al. [53] have performed a systematic study on the fatigue performance of FRP-to-steel bonded joints whereby the behavior of the FRP-to-steel bonded interface under fatigue cyclic loading was investigated.

Previous test results showed the positive effect of prestressing on fatigue life extension of metallic members, however, Ghafoori et al. [54, 55, 56] used a fracture mechanics based model to justify the reasons why in some cases prestressing could arrest the FCG and, in other cases, could only decrease it. Their model can estimate the required prestressing level needed to arrest the crack propagation in the notched beams (see Figure 3). Several strengthened beams were tested under different fatigue loading ranges and the experimental results showed the validity of the proposed fracture model.

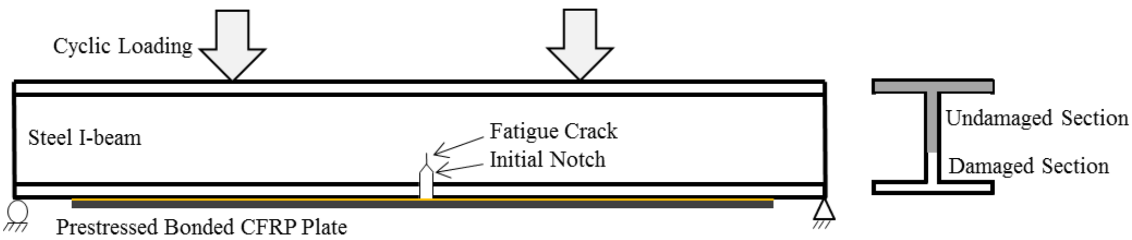

Figure 3. Prestressed bonded CFRP plate to arrest fatigue crack propagation (adapted from [56])

Fatigue Strengthening of Metallic Members using Un-bonded Pre-stressed FRP Plates

As mentioned before, the theoretical and experimental results of several studies have proven the effectiveness of using CFRP-bonded reinforcement techniques (with or without prestressing) to improve the load carrying capacity and service life of metallic members. Nevertheless, there are still concerns about CFRP-bonded systems generally associated with the long-term performance of the adhesive between the metallic substrate and CFRP plate, as will be briefly discussed here:

a. High temperature: compared to concrete, steel has a high thermal conductivity (about 50 W/mK) and has significant ability to transfer heat rapidly to the adhesive. The rate of sunlight absorption by steel is also much greater than the rate of steel electromagnetic radiation; therefore, steel members exposed to direct sunlight on a hot day will easily become much hotter than the ambient temperature. This effect makes the adhesive adjacent to a hot steel surface soften excessively when the service temperature of the steel substrate approaches the glass transition temperature of the adhesive.
b. Galvanic corrosion: although CFRP is a non-corrosive material, when carbon fibers come into contact with steel they can form a galvanic cell. Tavakkolizadeh and Saadatmanesh [57] investigated the galvanic corrosion between steel and carbon with different thicknesses of epoxy coating in different electrolytes, such as de-icing salt solution and ocean water. More research is needed to quantify the its influence on bond strength.
c. Metallic riveted bridges: due to the flat configuration of FRP plates, they cannot be bonded to the surface of structures that are not sufficiently smooth, for example, in the case of riveted bridges when there is a high rivet density.
d. Heritage structures: the components of strengthening systems for heritage structures need to be designed for easy removal when there is a need to restore the structure to its original unstrengthened construction design. In a bonded reinforcement system, FRP strengthening materials cannot be easily separated from the beam due to the applied adhesive [58].

Moreover, based on Teng et al. [59], in the FRP-strengthened steel structures, interfacial failure should occur within the adhesive layer in the form of cohesion failure to maximise the effectiveness of FRP strengthening and minimise variations of the interfacial bond capacity as a result of different surface preparations. Inappropriate surface preparation of the steel substrate prior to the bond application will result in an adhesion failure at the steel-to-adhesive interface. Assuming the adhesive as the weakest element of a FRP-steel bond joint, Ghafoori et al. [55,60] have developed a prestressed unbonded reinforcement (PUR) system that can be used as an alternative to the bonded FRP reinforcement. The developed PUR system functions without using any adhesive layer, thus the performance of the system is no longer dependent on the fracture energy of the adhesive. Reinforcement using the PUR system is recommended for cases when the surface of the structure, that need to be strengthened, is not smooth enough to be bonded to FRP plates, or when there is concern about the effects of high ambient temperatures, moisture, water and fatigue loading on the FRP-to-metal bond behavior.

Strengthening using PUR system substantially reduces the required time for strengthening since there is no need for surface preparation which normally includes removing all paint and corrosion coatings from old metallic bridge substrates.

An innovative strengthening system based on the PUR approach has been developed and tested at Empa [61]. The system will be applied on a 120-years-old riveted metallic railway bridge in Switzerland. The advantages of the system includes: fast installation procedure (no gluing and surface preparation), no traffic interruption for bond curing, easy to prestress (no need for hydraulic jacks), applicable to unsmooth surfaces (e.g, riveted members), adjustable prestressing (to compensate relaxation effects), minimum damage on structure (no need to make hole, grinding or gluing on metallic member) and easy for removal (if necessary).

Conclusions

This paper started with a brief summary of the benefit of using FRP to strengthen metallic structures. It showed that the influence of fatigue loading on bond strength depends on modulus of CFRP. It summarized the work on the fatigue strengthening of steel plates, connections and bridges using FRP. Discussion was made on fatigue strengthening of metallic riveted bridges using un-bonded pre-stressed FRP plates.

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