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Use of CFRP for Rehabilitation of Steel Structures: a Review

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Abstract- One of the main problems facing steel structures is corrosion which effectively reduces total section area of steel members thus leading to elevated stresses in the corroded area. Moreover, increase in the service load of metallic structures, such as bridges, as a result of civil development can aggravate the problem. The need for economical and fast rehabilitation solutions reflects the importance of using carbon fibre reinforced polymers (CFRP) as a repair material. This paper reviews the previous work in this area and shows the structural advantages that can be obtained, along with reducing the cost, through application of CFRP on construction steelworks. A brief conclusion summarizes the benefits and drawbacks of this technique and the paper will serve as a good guide for many engineers who are interested in this topic.

Keywords: fibre reinforced polymer (FRP), carbon fibre reinforced polymer (CFRP), rehabilitation, steel structures, retrofit.

I. INTRODUCTION

Fibre reinforced polymers (FRPs), specifically carbon fibre reinforced polymer (CFRP), are being increasingly used in steel structures. Other FRPs have traditionally been used in the rehabilitation of concrete structures. CFRP can be defined as a composite material consisting of carbon fibres, which provide strength, stiffness, and load carrying capacity, and a polymer matrix [1]. The main properties of CFRP composite depend on the type and orientation (transverse or longitudinal direction) of carbon fibre, the type and percentage of resin material and curing conditions. Thus, there are different types of CFRP with different properties.

As steel structures play an important role in civil constructions, more attention is need for repairing and rehabilitation of such structures. Generally, repairing or retrofitting of steel structures costs far less than replacement, takes less time for construction, and the service interruption time can be reduced. The retrofitting method that utilizes steel plates has some drawbacks like using heavy lifting equipment for these plates and additional dead load to the structure. Table 1 shows many types of CFRP mentioned in recent researches [2-6] that have mechanical properties which allow them to be promising candidates for rehabilitation and strengthening of steel structures.

Many experimental works and theoretical studies have been done about bonding CFRP composite on steel members, each one dealing with a different parameter to discover more advantages of this material. This paper will present different aspects of using CFRP to rehabilitate main parts of steel structures. It also provides a good list of references that one can refer to if interested in a special parameter.

TABLE I. PROPERTIES OF DIFFERENT CFRP COMPOSITES

CFRP composite type	Young's Modulus (Gpa)	Tensile strength (Mpa)	Elongation at failure
Unidirectional pultruded Sika Carbodur strips [2]	>200	>280	>0.0135
High modulus unidirectional sheets [3]	640	2650	0.004
M Brace CF 130 sheets [4]	240	3800	0.0155
M Brace CF 530 sheets [4]	640	2650	0.004
Sika Carbodur M 914 pultruded plates [5]	125	1914	
Sika Carbodur H 514 pultruded plates [5]	313	1475	
H S strips [6]	155	2790	0.018

II. STEEL GIRDERS AND BEAMS

Bridge girders and beams are generally subjected to creep effect, but strengthening of tension flange (usually bottom flange) is particularly needed because tension flange undergoes highest level of corrosion, mainly because of debris accumulation [6]. Also, CFRP composites have high tensile strength (see Table 1). The studies described below in this section highlight the role of CFRP in strengthening girders and beam.

A cyclic loading test conducted for naturally corroded bridge girders which were moved aside from deteriorated bridges is reported in [7]. The test included using a single layer of CFRP to reinforce the entire length of the bottom flanges of

two girders which were affected by corrosion more than webs or top flanges. Results of this study showed that CFRP reinforcement increased the elastic stiffness of the girders in the range of 10% to 37%. Also, the ultimate capacities of the two girders increased to 17% and 25%, and the inelastic strains in the bottom of the flange were reduced by 75% compared with unreinforced girders at the same load level.

Three-point bending tests on artificially notched steel beams were conducted at the University of Missouri-Rolla [8]. Four W12*14 (US steel section) with a length of 2438 mm were used in these tests. The first two specimens were tested without CFRP retrofit but one of them contained 106 mm notch in the tension flange to simulate the effect of corrosion. Two CFRP laminates of 100 mm width were used to cover the same notch in the second two specimens but one covered the entire length of tension flange and the other covered one quarter of the beam length. Use of CFRP caused an increase of 60% in the plastic load capacity for the full length specimen and 45% for the one quarter length specimen.

Tavakkolizadeh and Saadatmanesh [9] used four-point bending on two groups of S5*10 (US steel section) steel beam with 1300 mm length which were cut in the middle of tension flange to depths of 3.2 mm for the first group and 6.4 mm for the second group. Both groups were reinforced by different lengths of CFRP sheets with 0.13 mm thickness. The results showed that ultimate load carrying capacity and stiffness of retrofitted specimens were close to their original values in the control specimen regardless of the length of the CFRP patch. The results of the deep cut group showed distinct loss of ductility in comparison with the shallow cut group.

Patnaik and Bauer [10] used four I-sectioned undamaged beams. Two beams were reinforced by CFRP strips along the tension flange and exposed to flexure failure test. The other two beams were reinforced by CFRP strips along their webs and exposed to shear failure test. The first two recorded about 14% increase in the capacity of flexure strength. For two shear-strengthened beams, one failed while the other recorded 26% increase in strength.

Mertz and Gillespie [11] dealt with different reinforcing schemes for W8x10 members which are 1.52 m long each. Fig. 1 shows the different retrofit schemes used for the specimens. All tested specimens showed noticeable increase in strength and stiffness.

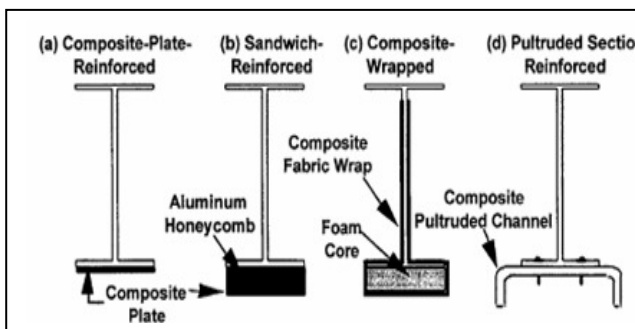


Figure 1. Different retrofit schemes [11].

The increase in the ultimate strength of retrofitted steel girders corresponding to different CFRP reinforcement ratios are shown in Fig. 2 [12]. According to this figure, the effect of CFRP on increasing the ultimate strength is seen clearly when the yield strength of steel is low.

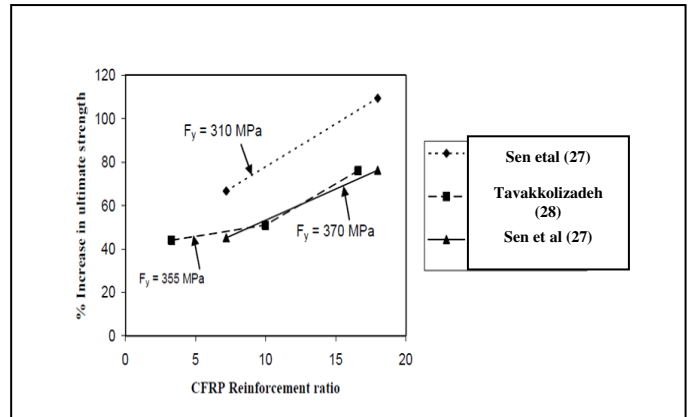


Figure 2. Effect of CFRP reinforcement ratio and yield strength on the ultimate strength of retrofitted steel girders [12].

III. TUBULAR STEEL SECTIONS

According to Vatovec et al [13], 50 mm*1.2 mm CFRP strips were used to reinforce the tension and compression flanges of rectangular steel tubes which were filled with concrete and submitted to a simple beam test. The results showed increase in the ultimate moment capacity from 6% for specimens with one strip bonded to the compression flange to 26% for specimens with two strips bonded to the tension flange and one strip to the compression flange.

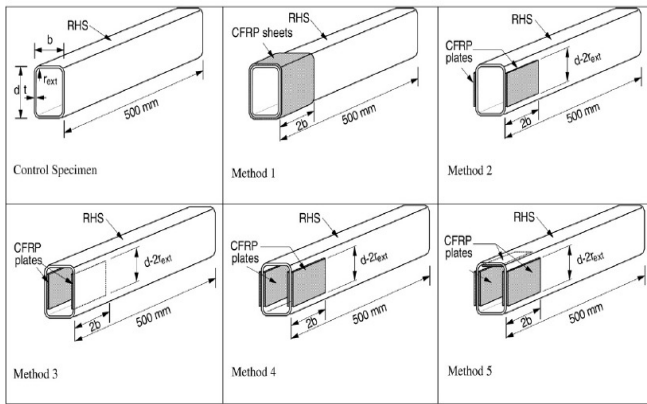
A theoretical study by Toutanji and Dempsey [14] proved that using CFRP sheets around damaged steel pipe lines (circular steel section) improve the internal pressure capacity of pipes better than other types of FRP sheets (glass or aramid). Four-point bending test was done by Seica et al [15] on circular tubes wrapped with two layers of CFRP composites and cured in different conditions (in air and underwater). In spite of the fact that the research was dealing with different parameters, but the general conclusion presented an increase in the ultimate bending strength, rotation capacity and flexural stiffness of the wrapped beam compared with the reference beam.

A research programme for Bassetti et al [16] proved that using CFRP plates of 1.2 mm thickness to reinforce central-notched specimens can sharply decrease crack growth and increase fatigue life by a factor up to twenty. Zhao and Fernando [17] used different styles of CFRP strengthening technique to improve web crippling capacity of cold-formed rectangular hollow section. It was found that CFRP composite remarkably increase the web crippling capacity, especially when the ratio of web depth-to-thickness is large. Fig. 3 shows the adopted methods of CFRP strengthening and the typical behaviour of each method comparing with the bare specimen.

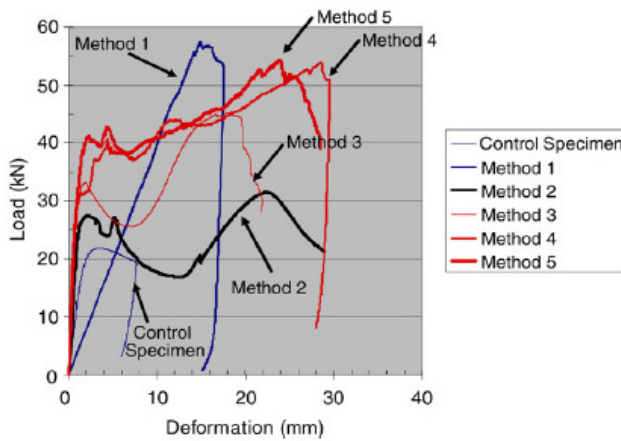
IV. BONDING BETWEEN STEEL AND CFRP COMPOSITE

Some researchers focused on the effect of the adhesive materials because the success of this technique depends mainly on the ability of the adhesive material to keep transferring the load between steel and CFRP composite. This transferring is affected by many factors such as surface preparation, bonded length, type of adhesive material, thickness of adhesive and thickness of CFRP laminate. Steel surface needs to be prepared

by using abrasive disks or sand blasting to remove rust and paint and then cleaned by acetone or degreased with a xylene based solvent to exist clean, rough and chemically active surface. At the same time, the surface of CFRP strips can be treated by very fine sandpaper (grit P240) to provide sufficient roughness and more bond strength [2].



(a) Methods of strengthening



(b) Load-deflection curves

Figure 3. Methods of CFRP strengthening and their load-deflection curves [17].

It is recommended for bare steel to be pretreated by adhesion promoter or a primer/conditioner which leaves a thin layer attached to the oxide surface of steel. Because water displacement is unlikely to happen through this coating, this bond remarkably improves the long-term durability [18]. These surface treatments are very important to ensure strong bonding between CFRP and steel. An experimental study on fatigue failure showed that debonding of the CFRP plates started in the zones of high stress concentration which were the plate ends or the gap in case of joints [2]. A study performed by Youssef [19] concluded that maximum value of the adhesive shear stress was at the edges of the FRP sheet.

Miller [20] in his analytical studies found that nearly 98% of the total transferred force was within the first 100 mm of the end of CFRP bonded plate which was a 457 mm plate attached to the tension flange of a steel girder. Many different types of adhesive materials are available nowadays. Colombi and Poggi [21] used two different adhesives (Sikadur 30 and Sikadur 330). Each one consisted of two-part epoxy and they were used to bond CFRP strips to the steel substrate. It was noticed that application of Sikadur 30 produced a ductile behaviour

implying that the yielding of the steel plates occurred before the debonding of the strips, while the application of Sikadur 330 showed a brittle behaviour since the recorded failure mode was an inter-lamina composite strip delamination.

In another study [22] eight types of adhesive materials were subjected to lap shear tests in order to choose the type that can achieve the highest load resistance. Thus, the Methacrylate product: MA420 was chosen for its superior performance. Generally, the adhesive material for rehabilitation scheme must have adequate strength for bonding, sufficient durability for environmental conditions and must be easy to use under field conditions [12].

V. FAILURE MODES

The characteristics of each type of the three components involved in the rehabilitation, namely, CFRP composite, steel member and adhesive material, can affect failure modes of this technique. So, the low or high elastic modulus CFRP composite, circular or rectangular steel section, long or short steel column, compressed or tensile steel member, mild or structural or high carbon steel type, low or high quality and thickness of adhesive material can lead to different types of failure modes. Zhao and Zhang [23] studied the possible failure modes associate with bonding of CFRP composite to steel subjected to a tensile force. These failure modes are shown in Fig. 4 and they can include that:

- a- Interfacial debonding between steel and adhesive layer.
- b- Failure of adhesive layer.
- c- Interfacial debonding between CFRP and adhesive layer.
- d- Delaminating of CFRP composite.
- e- Rupture failure of CFRP composite.
- f- Yielding of steel member.

Failure mode type (b) is a common failure which is usually associated with thin or low quality adhesive layer. Failure mode type (d) could happen when there is a separation of carbon fibres from the resin matrix of CFRP which means low elastic modulus CFRP composite, while failure mode type (f) is rarely to happen because there is often a sufficient thickness of steel member. The other modes of failure are affected by the parameters mentioned previously.

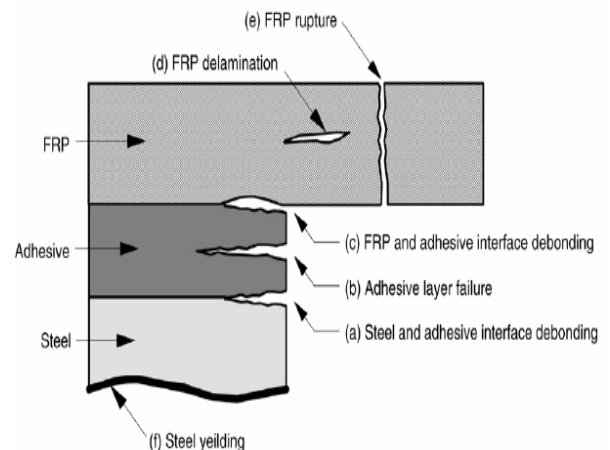


Figure 4. Possible failure modes of bonding CFRP to steel system[23].

VI. DISADVANTAGES OF THIS TECHNIQUE

First of all, bonding failure or delamination between steel and CFRP composite is considered the most common failure due to the weakness of the adhesive bond. Figure 5 shows a picture of this failure. A study by Jones and Civjan [24] showed that the adhesive bond is the weakest point of this system.

A good adhesive material is that one which allows loads to transfer from steel to CFRP composite efficiently, so that the CFRP composite material can be utilized optimally. Laboratory tests can provide a good indication to select the suitable adhesive material. Another weak point is result from the high electric conductivity of CFRP composite when it contacts steel directly, and called galvanic corrosion. This problem can only happen when these three factors are available [25]: an electrolyte like salt water links the two materials (carbon fibre and steel), an electrical connection must be between the materials and there must be a sustained cathodic reaction on the carbon. This problem can be avoided by removing any one of those factors.

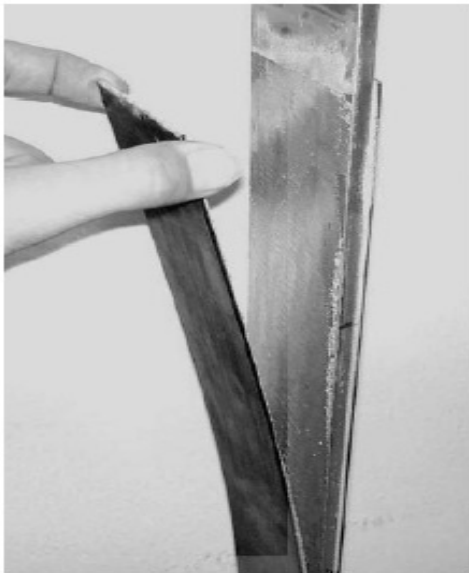


Figure 5. Delamination at the steel-adhesive interface [2].

Fortunately, structural adhesives are mostly insulators and providing a continuous layer when they use to bond CFRP with steel which means disrupting the galvanic cell. An experimental study [26] recommended some applications to eliminate galvanic corrosion such as using isolating epoxy film or nonconductive layer of fabric between the two bonded materials (steel and carbon), or applying moisture barrier to the bonded area. Finally, there is a lack of information about the behaviour of this new technique when it is exposed to different ambient conditions. Therefore, research is needed in this area.

VII. CONCLUSIONS

This paper presented a review of the studies undertaken in repair and rehabilitation of steel structures by using carbon fibre reinforced polymers. The review showed that:

- Using CFRP to rehabilitate steel structures enable steel section to restore the lost capacity and resist additional loads.
- Using CFRP can extend the fatigue life of steel structures and effectively reduce the crack propagation.
- Yielding load can be increased when the steel section is reinforced by CFRP, so the total service load will increase.
- Using CFRP can increase the moment capacity of steel I-section when it is attached to the tension flanges while attaching it to the webs can increase shear strength of the section.

It was also found from the review that the increase in the capacity of the rehabilitated steel member depends on the amount of damage in the steel member, the type of CFRP composite (high or low modulus of elasticity), the size of CFRP composite (length, width and thickness), the type of the adhesive material and the environmental conditions.

Generally, research reported on applying this new technique showed remarkable signs of success, but only few drawbacks such as bonding failure and galvanic corrosion. Some studies mentioned several procedures on how to avoid these drawbacks. Research is still being conducted to investigate many issues on this promising technique and to provide design guidelines for using CFRP to rehabilitate steel structures.

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