Necessity of Strengthening of Steel Structures with FRP Composites: a Review

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Abstract: Fiber reinforced polymer (FRP) composites are widely used in rehabilitation of RC structures. Lot of research has been done in this field. Application of FRP for similar purpose in steel structures is still at elementary level. Various types of FRP plates, with their properties such as high strength to weight ratio and good resistance to corrosion, represent an ideal material in external retrofitting. This paper reviews available design guidelines for the selection, design and installation of FRP systems for external strengthening of steel structures.

Keywords: FRP (Fiber Reinforced Polymer), Strengthening, Steel structures, bond strength.

I. INTRODUCTION

Steel structures play an important role in civil industry and therefore more attention is required for repairing and rehabilitation of such structures. A large number of steel structures, such as buildings, offshore platforms, large mining equipment and bridges get damaged due to various reasons and need repairing. Conventional method of repairing or strengthening steel structures is to cut the damaged portion and replace it with plating, or attach external steel plates to the damaged portion of the member. These plates are usually bulky, heavy, difficult to fix and prone to corrosion and fatigue. The methods of retrofitting which utilizes steel plates has some disadvantages like use of heavy lifting equipment to lift the plates and due to this additional dead load will be on the structure. So there is a need to look for alternatives. Repairing or retrofitting of steel structures with FRP composites costs far less than replacement, takes less time for construction, and the service interruption time can be reduced [1]

Studies on enhancing structures have significantly increased recently. Different methods exist for strengthening various structures. Use of FRP (Fiber Reinforced Polymer) appears to be an excellent solution. Using FRP is more popular than other materials for strengthening structures because of their high tension strength, low weight, high strength to weight ratios and excellent resistance to corrosion and environmental degradation. It is very flexible and forms all kinds of shapes, and is easy to handle during construction. FRP has been widely used in strengthening concrete structures, and extensive research has already been conducted. Normally, two type of FRP has been produced: (a) Glass Fiber Reinforced Polymer (GFRP) and (b) Carbon Fiber Reinforced Polymer (CFRP). Applying CFRP had been recognized as more appropriate than GFRP for enhancing different structures because of its higher strength [9]

Many studies have been conducted on repair and strengthening of concrete structures using advanced composites. Limited existing work has mainly been concerned with demonstration of effectiveness of FRP strengthening technique for steel structures [17]. This limited existing work has provided a useful understanding of the overall behaviour and identified possible failure modes of FRP-strengthened steel members. Recent experience in USA, UK, Japan and Switzerland showed that there is a great potential for CFRP to be used in retrofitting of steel structures. Use of adhesively bonded carbon fiber reinforced polymer (CFRP) composites to increase the load carrying capacity of metallic elements in aeronautical engineering has been widely examined, field but it is also a promising technique for civil engineering world. CFRP plates have been used to upgrade a significant number of concrete and masonry structures while only a small number of applications to steel or cast iron structures are known and a limited number of specific research projects have been conducted to validate the upgrading of metallic structural elements. However, many issues need to be resolved before this advanced material can be fully utilized to provide confident retrofitting of structures.

II. MECHANICAL PROPERTIES OF FRP

The performance of any engineering material in a specific application is dependent on its mechanical properties, durability, and cost. This section focuses on the mechanical properties of FRPs, including the stress-strain response, and other properties such as creep, fatigue, fracture, and bond. The mechanical properties of FRP depend on a number of factors including:

- The relative proportions of fiber and matrix;
- The mechanical properties of the constituent materials;
- The orientation of the fibers within the matrix; and
- The method of manufacture.

FRP sheets are formed by embedding continuous fibers in a polymeric resin matrix which binds the fibers together. Common fibers used in FRP sheet include carbon, glass, aramid and basalt fibers while common resins are epoxy, polyester, and vinyl ester resins. The most widely used FRP composites are glass fiber-reinforced polymer (GFRP) composites and carbon fiber-reinforced polymer (CFRP) composites, while aramid fiber-reinforced polymer (AFRP) composites and basalt fiber-reinforced polymer (BFRP) composites are less frequently used. Fig.1 shows different types of fiber sheets generally used for retrofitting.

Fig.1 Different types of fiber sheets. (from left Aramid, Basalt, Carbon, Coir)

FRP materials are composed of a number of continuous, directionalized, nonmetallic fibers, bundled in a resin matrix. Normally, the volume fraction of fibers in FRP strips is about 50-70% and that in FRP sheets is about 25-35%. Fibers are the principal stress bearing constituents, while the resin transfers stresses among fibers and protects them [18]. If these volume fractions and properties of constituent materials (fibers and matrix) are known for a particular FRP composite then mechanical properties can be obtained as shown in Table 1.

Table -1 Comparison of Typical Approximate Properties for Reinforcing Materials

Property	**Steel**	**GFRP**	**CFRP**	**AFRP**
Density (Kg/m^3)	7900	1200-2100	1500-1600	1200-1500
Tensile Strength (MPa)	483-690	517-1207	1200-2410	1200-2068
Tensile Elastic Modulus (GPa)	200	30-55	147-250	50-74

Ultimate Elongation (%)	>10	2-4.5	1-1.5	2-2.6
Compressive Strength (MPa)	276-414	310-482	N/A	N/A
CTE* (10-6/°C)	11.7	9.9	0	-1 - -0.5
Specific Gravity	7.9	1.5-2.0	1.5-1.6	1.25

III. CONTRIBUTION OF VARIOUS RESEARCHERS

A number of experimental and theoretical researches have been conducted to find the behavior of FRP/steel bonding systems. Some of the studies related to strengthening of steel sections are discussed in short in the further paragraphs.

Fernando et al. (2009) [3] examined end load bearing of sixteen rectangular steel tubes that were strengthened using CFRP with different adhesives. They also used Finite element modeling for better examination of effects of CFRP strengthening on tube end bearing. They found that four different failure modes were observed in tests: Adhesion failure, Cohesion failure, Combined adhesion and cohesion failure, Interlaminar failure of CFRP plates.

Harries et al. (2009) [7] researched on web, strengthening of flanged steel sections using CFRP strips. Non strengthened control and four retrofitted scenarios specimens were examined using either HSCFRP strips or ultra-high modulus (UHM) GFRP strips. For each material, two cases were considered. FRP strips were applied to each side of sections. Their tests were experimented for short length specimens. It indicates that they loaded the specimens directly under compressive load. In this case, specimens behaved only in shear. They used slenderness ratio of d/tw=29.8. They pasted only one strip on each side of web (one or two layers), and they did not compare the effects of different percentage of CFRP. As indicated, using mentioned value of CFRP could increase load capacity up to 9%. Also, they used cyclic loading that help to examine the effects of CFRP strengthening under this kind of loading.

Patnaik et al. (2008) [13] apply CFRP strips for strengthening six specimens. They enhanced two specimens for flexural and two specimens for shear. Two non strengthened beams also were tested as control beams. The beams had ratio of a/d=1270/330=3.85, where a is width of shear zone or distance of first point load to the closest support, and d is height of web. Using this amount of a/d caused that beams behaved more flexural. The same ratio of a/d for both flexural and shear strengthening cases were chosen. Three failure mode shapes in shear behavior were observed: Local web buckling, web crippling, and sideway web buckling. Ratio of d/tw in beams was 103.13, where tw is the web's thickness. CFRP strips were pasted on full length of shear zones and on both sides of web. They described the effects of using CFRP on load bearing appropriately. Using CFRP strips, load capacity of the specimens is increased up to 26%.

Teng et al. (2012), [8] discussed the use of FRP in strengthening of steel structures where advantages of FRP are appropriately exploited. Then a critical review and interpretation of existing research on FRP-strengthened steel structures is enlightened. Topics covered by the review include steel surface preparation for adhesive bonding, selection of a suitable adhesive, bond behavior between FRP and steel and its appropriate modeling, flexural strengthening of steel beams, fatigue strengthening of steel structures, strengthening of thin-walled steel structures against local buckling, and strengthening of hollow or concrete-filled steel tubes through external FRP confinement.

Toutanji and Dempsey (2001), [5] proved that using CFRP sheets around damaged steel pipe lines (circular steel section) improve 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 on circular tubes wrapped with two layers of CFRP composites and cured in different conditions (in air and underwater). In spite of fact that the research was dealing with different parameters, but general conclusion presented an increase in the ultimate bending strength, rotation capacity and flexural stiffness of wrapped beam compared with reference beam.

Zhao and Mahaidi (2009) [21] researched on web strengthening light steel beams using CFRP subjected to end load bearing. They used three types of strengthening methods; applying CFRP plates on outer side or inner side or both sides of the web. As the light steel sections had high web slenderness, they were able to study only web crippling of specimens. As mentioned: It was found that CFRP strengthening significantly increases the web-buckling capacity especially for those with large web depth-to-thickness ratio.

IV. BOND BEHAVIOUR OF FRP TO STEEL

There has been relatively little research conducted on the bond behavior of FRP-steel joints in the context of civil engineering applications. In addition to conventional modes of failure, FRP-strengthened steel members may exhibit debonding of the FRP laminate. In considering debonding failures, the thickness of the adhesive layer plays a significant role in the failure mode. Typically a thin uniform adhesive layer is desirable. Such adhesive layers of reasonable thickness (say less than 2 mm thick) will exhibit relatively ductile debonding failures within the adhesive layer. Thicker adhesive exhibit brittle delamination failures along the steel-adhesive interface. Additionally, Xia and Teng [19] have shown that FRP-steel interfacial behavior is accurately modeled using relatively simple load-slip relationships. Indeed, for thin adhesive layers, a bilinear load-slip relationship approximates observed experimental behavior well. Additionally, debonding behavior in such cases is closely related to adhesive tensile properties and is relatively independent of adhesive layer thickness. Interfacial stress discontinuities occur at the termination of the adhesive layer. Based on experience gleaned from the aerospace industry, a variety of termination details may be used to reduce these discontinuities.

V. SURFACE PREPARATION

The reliability of the joint is highly dependent upon the surface treatment processes for bonding the fiber-reinforced composite to the steel structural elements. The surface preparation and the strength of the applied CFRP overlay can significantly affect the fatigue performance. Bond to steel, regardless of the application, requires a clean and sound surface, and practical field application requires a relatively simple procedure. The typical application involves abrasive (grit) blasting followed within a few hours with a primer/conditioner to ensure that corrosion product does not form and contaminate the newly exposed steel [2]. Since epoxy adhesives will be used, the primer will typically be a (matching) silane-based product which can also serve as an “adhesion promoter”. The adhesive, protective GFRP layer (see below) and CFRP are then installed. Research associated with the previously discussed investigated the quality of steel-to-CFRP and recommend the use of a silane primer; although no specific mechanical surface preparation was recommended [26]. The results from the research however are inconclusive as to whether the silane primer itself improved (promoted) bond performance. It is possible that the primer enhanced bond performance simply by inhibiting the formation of corrosion product between the time of surface preparation and that of CFRP application. [4] reports a curved I-girder completely wrapped in CFRP; in this case silica gel packs were used to protect the prepared surface from moisture and thus corrosion.

Thermoset epoxy adhesives are developed specifically to offer good adhesion to metals. They interact strongly with the adherands and promote excellent bonding. [15] indicates a clear benefit from curing the epoxy adhesive at elevated temperatures (around 93^{o}C) during the initial cure (10 to 20 minutes). The resulting bond is stronger, tougher and more durable when subject to adverse environments [11]. Furthermore, because the epoxy cures faster, it is less likely to sag (requiring falsework) or be affected by vibrations or loading that may be present during an in situ application (Moy 2007). To this end, [10] have proposed the concept of using induction heating of the steel surface to assist in the accelerated cure of the epoxy adhesive.

VI. SCOPE OF THE WORK

The number of civil infrastructures which have deteriorated and no longer fulfill the requirements of safety standards is continuously increasing day by day. The reasons for deterioration may include progressive ageing, increased daily traffic and severe environment effects, or a combination of all these. Over the past few decades, there has been increasing interest in applying adhesively bonded composites to repair existing and/or strengthen new civil engineering structures. Extensive research has been conducted on FRP strengthening of concrete structures, whereas relatively less work has been done on FRP strengthening of steel structures [6]. Research interests in the field of retrofit of steel structures using FRP materials are gradually increasing. Although using FRP for retrofit of steel structures has not yet gained the same popularity and wide spread use as in concrete structures, the literature to date shows positive and promising evidence of success.[16] However, there are still many issues that need to be investigated. A number of potential research needs can be noted:

1. In order to increase the strength of the member, various bonding techniques need to be investigated further to avoid the premature FRP delamination, and consequently increase the retrofitted member’s capacity and maximize the benefits of the superior FRP properties. These techniques could be based on adhesive or mechanical bonding.
2. Further research is needed to develop low cost carbon fibers/resin system with superior strength and stiffness characteristics compared to conventional CFRP, in order to decrease the number of required layers. High modulus

CFRP materials with superior stiffness could be a good alternative.
3. Further studies on the long-term performance of bonded FRP are needed, particularly the issue of galvanic corrosion and the effects of different thermal coefficients of FRP and steel on the bond strength and durability.
4. In general, further research is needed to produce sufficient experimental data in order to develop design guidelines for strengthening steel members using FRP materials.

VII. CONCLUSION

Due to the promising performance and other advantages of bonding FRP laminates to steel structures, this technique is becoming increasingly popular. If the cost constraint is kept aside, the fiber wrapping system proves to be advantages over conventional strengthening processes. As the economy is moving ahead and infrastructure development is catching its pace, demand for fiber reinforced polymer in civil construction is slowly increasing and becoming acceptable. Study of literatures shows that:

1. CFRP is better material to strengthen the steel members out of various forms of FRP composites.
2. Using FRP to steel structures (say CFRP) enables steel section to restore lost capacity and take additional loads.
3. Using FRP to steel sections increases the fatigue life of steel structures and reduces the crack propagation.
4. When the steel section is reinforced by CFRP, the total service load on the structure get increases.
5. Using CFRP can increase the moment capacity and shear strength of steel section.

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