FRP strengthening systems for metallic structures: a state of the art

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ABSTRACT: Metallic structures include steel girder bridges realized during 1900's and all historical constructions made of cast iron and wrought iron such as arch cast iron bridges. A lot of these historic bridges still exist and their conservation enables to preserve an important part of the metallic construction heritage. The traditional methods of strengthening, used for restoring their carrying capacity, are based on the application of steel plates that are bolted or welded to the original structure. Some problems, due to the use of these techniques, are overcome in the interventions that are characterized for the use of fiber-reinforced polymers (FRP). In the last decade the research efforts have been dedicated to test the efficiency of FRP strengthening systems on metallic structures. In the present paper the authors present a reasoned review of the research work and of the applications in light of the available literature.

1 INTRODUCTION

The metallic structures constitute fundamental part of the architectural heritage. They had a fundamental role in the growth of the industrial civilization and they contributed to the development of the theory of structures and of the studies on the resistance of materials. The first realizations that employed cast iron and wrought iron were afterwards abandoned because of the discovery of steel and of new fusion techniques. The motivations for the restoration of the first constructions concern the possibility to preserve the origins of the metallic construction history. Shared typologies of damage are recognized in these structures according to the properties of the used materials. Cast iron can show cracks due to the impact of heavy bodies and to the thermal starts that induce tensile stresses. Wrought iron used in tension elements can show the reduction of the resistant section because of the corrosion. The steel structures of the 20th century represent a consistent part of the existing vehicular bridges. In these cases the lack of a suitable maintenance, the corrosion and sensitive structural details to the fatigue phenomenon represent the most diffused causes of deterioration. Moreover the increase of vehicular traffic makes necessary the adjustment of the existing structures to the new live loads. In these cases the restoration rather of the demolition and reconstruction generally costs less also from a social point of view. The interventions of strengthening and repairing of existing structures require reduced times, which correspond to reduced times of deviation of the traffic.

Currently the methods of strengthening used for restoring the carrying ability are based on the application of steel plates bolted or welded to the original structure. These typologies of intervention have some negative effects. The steel plates introduce further permanent loads, which reduce notably the effectiveness of the intervention of restoration. Moreover they can be interested equally from phenomena of corrosion. From the point of view of the effectiveness of the intervention the use of welding can cause fatigue cracking at the cover plate ends. It is necessary to define with precision the constructive detail to set in work.

Some problems, owed to the use of these "traditional methods", are passed in the interventions that are characterized for the use of fiber-reinforced materials (FRP). The fibers that compose these materials have superior mechanical and physics characteristics and are distinguished for the notable tensile strength.

The advantages in the use of FRP in comparison to steel are the following: from an economic point of view the high strength and rigidity in comparison to the weight allows to handle them with great facility and, therefore, the interventions of restoration need less time; the traditional techniques based on welding are critical since they ask for the dismantlement of the existing structure with an inevitable increase of costs.

The use of FRP for the strengthening and repairing of steel structures is not developed as in the case of concrete, and the attention of the researchers is mainly focused on some themes for which the FRP strengthening system is promising. Three areas of
interest are distinguished based on structural aspects that characterize the metallic structures:

- The intervention on the connections that allows to reduce notably the growth of cracks due to fatigue phenomenon. These interventions are necessary in the oldest metallic structures and on riveted connections.
- The strengthening of tension elements that allows to decrease notably stresses in the original structure. The employment of FRP is well suited to oldest metallic constructions since the outstanding tensile strength of the fibers supplies to the low strength of cast iron, and the resistance to corrosion makes durable the intervention.
- The application to the historical cast iron arch bridges that allows to improve the brittle behavior of the cast iron.

The FRP application on metallic structures consists in the drafting layers of fabrics or tape alternated by thermosetting resins through the technique of wet-lay-up, or in the bonding of thin plates. In the choice of the type of fiber to be employed, the high resistance carbon is the most suitable since it is characterized of Young’s modulus close to steel one. In this case it is necessary, however, to put between two materials a layer with the function of insulator to avoid the galvanic corrosion.

This paper begins with a review of the several experimental studies conducted, in which FRP have been used as strengthening system for metallic structures. In the second part, the paper focus on practical experiences of this technique and interventions of restoration on steel structures and cast iron historic construction will be presented.

2 BACKGROUND

Studies conducted on metallic structures strengthened externally with FRP materials have shown the possibility of enhancing the performance of structural members. They are focused on the improvement of carrying capacity, stiffness, ductility, environmental durability and performance under cyclic and fatigue loading. Experimental tests have been conducted on various typologies of structural members such as cast iron struts and arches, steel bridge girders and pillars. Since the application is realized directly on site, a fundamental aspect to consider is the possibility to assure an adequate bond between substrate and FRP. Numerous research efforts have been dedicated also to the issue of bonding.

2.1 Bonding of FRP strengthening systems to metal surfaces

The strengthening system based on FRP consists in the bonding of plates or laminates to the surface of the member. The efficiency of the strengthening is associated with the adhesive capacity of transmitting forces between two materials. To quantify the force transfer between FRP and steel surface experimental and analytical studies were performed. Six 914 mm long steel specimens were strengthened with a carbon fiber reinforced polymers (CFRP) plate of 457 mm length, bonded on both sides and subjected to tensile load. Test results showed that approximately 98% of the total force transfer occurs within the first 100 mm from the end of the CFRP plate (Miller et al. 2001).

The surface of the element to reinforce has an important role in promoting the adhesion of the FRP laminate. The preparation of the substrate can be realized with sandblasting or surface grinders that can remove all rust and paint. Before the application of the first layer of epoxy, the surface is treated using an adhesion promoter or a primer whose characteristics depend on the type of adhesive used. This first layer creates also an obstacle to the penetration of humidity and assures a long term durability.

In the application to the Corona bridge in Venice, the cast iron arches were treated with a particular tool, named “needles-hammer”, with the function of eliminating from the surface the deposits due to corrosion. These parts have also been submitted to a cleaning with the brush and with a solvent very similar to the trichloroethylene (Figs 1, 2).
In the greatest part of the FRP applications to steel girders the type of reinforcement used consists of CFRP plates to bond to the outer and/or inner part of the tension flange. In these cases also the surface of the plate, that will come directly in contact with steel, is pre-treated with sandblaster and cleaned with acetone. This treatment must be conducted carefully, because an excessive removal of the plate surface could expose the carbon fiber to the contact with steel. Before the application of the CFRP plate to the steel flange, the adhesive is placed upon both surfaces to bond. Because galvanic corrosion can occur when carbon fibers and steel became in contact, usually a thin insulator layer is placed between two materials. To assure the adhesion at the interface between FRP and steel, CFRP plates can be applied with the use of clumps at close interval that could be removed when the adhesive has cured.

The FRP strengthening system used in practical experiences on arch cast iron bridges has been based on the application, through the technology of wet lay up, of fabric or tape that well suited to the bent member composing these bridges. The cast iron arches of Corona bridge were reinforced with aramid multiaxial and interlaced fabric, while the rectangular openings were coated with aramid tape. The thermosetting resin used was composed of two parts and could be applied within 90 minutes.

2.2 Debonding

Failure of FRP strengthened flexural members can happen through different mechanisms depending on the beam and the way of application of FRP strengthening system.

An experimental study by Buyukozturk et al. (2003) shows the failure modes of an FRP strengthened steel member. They are illustrated in the Figure 3 taken from this research: top flange buckling in compression, web buckling in shear, FRP rupture and FRP debonding. Debonding takes place in areas of stress concentration that are always associated with the presence of cracks and discontinuities in the material (Fig. 4). In the FRP reinforced steel members the debonding can occur at the interface between adhesive-FRP or adhesive-steel girder and within the reinforcing material (Fig. 5). The favoured path of debonding requires the least amount of energy however a great influence is due to the adequate surface preparation of the substrate.

Studies have demonstrated that the failure mode in the epoxy, that occurs at the ends of the CFRP cover plate, is due to the high peel stresses normal to the surface. Several techniques have been developed to avoid this phenomenon. The solution most used in the existing application was proposed by Vinson & Sierakowski (1987). The CFRP plates must be beveled to a 45° angle at the ends of the plate. In order to avoid this mode of failure, Liu et al. (2001) proposed of wrapping longitudinal laminates around the tension flange and part of the web and of applying GFRP sheets perpendicular to the longitudinal axis of the girder.

Experimental research has confirmed that environmental exposure and surface preparation significantly influence bond durability. It has pointed out, in particular, the potential galvanic corrosion in the CFRP-steel coupling (McKnight 1994, Karbhari & Shulley 1994, Buyukozturk & Gunes 2000, Tavakkolizadeh & Saadatmanesh 2001). Although the FRP strengthening system is corrosion resistant if adhesive with high
resistance to moisture and chlorides is chosen, when carbon fiber comes in contact with steel, galvanic corrosion can occur.

Another important issue when considering bond durability is fatigue resistance. The tests conducted to determine the fatigue resistance of the cover plate detail show that, in practical applications, the CFRP-steel bond should not to be the limiting detail in terms of fatigue durability (Miller et al. 2001). Debonding between CFRP strips and steel plate at crack tip was studied by Bassetti et al. (2000) comparing fatigue tests results on specimens where two different epoxy adhesives were used. They show no significant difference in fatigue behavior and life. Gillespie et al. (1996) tested two fatigue girders for 10 million cycles monitoring CFRP plates. From these inspections cover plates debonding was not found.

### 2.3 Fatigue strengthening

Metal bridges are subjected to cycle loads and those constructed during 19th and 20th century are now reaching the end of their expected fatigue life. Moreover, the traditional technique of repairing existing steel structures is based on the application of steel plates that, in the case of use of welding, are sensitive to fatigue loads. The research efforts have demonstrated the effectiveness of bonding carbon fiber laminates in reducing crack propagation and extending fatigue life.

The application of bonded composite patch to repair cracked metallic structures started in the late 1960s in aircraft industries. It was first investigated in aluminum members, which are characterized by stiffness two times and more smaller than that of composite patch. In civil engineering field, Bassetti et al. (2001) proposed a system based on prestressed carbon fiber laminates to slow down or stop crack propagation. In this case the ratio of composite stiffness to steel stiffness is not favorable. Therefore, in order to increase the efficiency of the CFRP application, the laminate has been prestressed.

Crack propagation is influenced by closure effects that are originated in the crack tip. Elber first recognized that only a part of the stress range causes crack propagation and introduced $\Delta \sigma_{\text{eff}}$ that can be estimated with this formula:

$$ U = \frac{\Delta \sigma_{\text{eff}}}{\Delta \sigma} = 0.69 + 0.45R $$  \hspace{1cm} (1)

$$ \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} $$  \hspace{1cm} (2)

$$ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} $$  \hspace{1cm} (3)

where $\sigma_{\text{max}}$ = maximal stress in fatigue cycle; $\sigma_{\text{min}}$ = minimal stress in fatigue cycle; $\Delta \sigma_{\text{eff}}$ = effective stress range.

Crack growth is described by using the modified Paris-law:

$$ \frac{da}{dN} = C(\Delta K_{\text{eff}}^m - \Delta K_{\text{eff,th}}^m) $$  \hspace{1cm} (4)

where $a$ = crack length; $N$ = number of cycles; $\Delta K_{\text{eff}}$ = effective stress intensity factor range; $\Delta K_{\text{eff,th}}$ = effective crack growth threshold range; $C, m$ = constants of the material.

The FRP strengthening system is based on the bonding of prestressed plates perpendicularly to the crack path. The benefits of this system are: stress range reduction, $\Delta \sigma$, due to the high stiffness of CFRP plates; local reduction of crack opening displacements thanks to the strips disposed perpendicularly; crack closure effect induced by effects of prestressing.

Small and full scale fatigue tests were performed to demonstrate the effectiveness of the system. Central notched steel plates of 10 mm thickness with two initial transverse cracks were used to simulate rivet holes of aging bridge girders. The reinforcement consisted of two 50 mm wide CFRP strips placed at a distance of 10 mm from the cracks, on both side of the steel plate. All the specimens were tested using a stress range of 80 MPa, a high stress level (R = 0.4), and using also non-prestressed CFRP plate. Results from these small scale tests showed that the prestressed CFRP system increased the fatigue life of specimens by a factor of about twenty, if stiffer CFRP plates were used.

The efficiency of the method was shown by full scale tests carried out on a cross girder taken from a dismantled 91-year-old bridge. The girder was pre-cracked and then reinforced by applying five CFRP plates on the bottom flange. Two plates were placed in the upper face and three on the bottom face. These last ones were prestressed and then bonded to the girder. After repair, the fatigue test was continued with the same load cycle used for pre-cracking and showed that no crack growth happened up to 20 million cycles. This test demonstrates that it is possible to transfer compressive stresses by bonding CFRP plates directly on steel members.

### 2.4 Flexural strengthening

Flexural tests have been performed on structural cast iron beams taken from an arch cast iron bridge in Venice dated from 1851. Four bridge girders with a T section were notched in the middle and another one was used as control specimen without notch. One beam was prepared with resin glued into the notch and other two girders were reinforced with one and two layers of FRP that covered the 1/3 of its length. The aramid fiber reinforced polymers (AFRP) fabric used was wrapped around the web of the section. The reinforced girders were tested with four points bending tests. During the tests, lateral supports were used to avoid
Notched steel girders have been used at the University of Rolla (Liu et al. 2001) to simulate the corrosion due to environmental factors. The objective of the work was to restore the original ultimate flexural strength with the application of FRP to the tension flange of the beam. Four units (W12 × 14) were tested in a three points bending test. One beam was used as control specimen while the other three were notched in the middle of the girder. The notch was realized in the tension flange. Two units were reinforced with FRP laminates. In one case the reinforcement covered the total length of the girder, in the other case one quarter of the beam length. Experimental results indicate that the failure mode was peel off of the laminates, due to high stress concentration near the girder's mid span, and an increase in stiffness of corroded steel members.

Experimental work on new steel girders was done at the University of Southampton by Moy and Nikoukar (Moy 2002, Moy & Nikoukar 2002). Three points bending tests were conducted on specimens of 127 × 76UB13 steel beams 1.2 m long. The specimens were reinforced with ultra high modulus carbon fibers plates. These were bonded to the flange of steel beam with thin layers of adhesive. G clamps were used to lightly hold the surfaces together during adhesive cure. The specimens were subjected to cycling loading, and some of these also during adhesive cure. Results show that adhesive cure under cycling can affect the bending stiffness and failure mode of the reinforced beam. To avoid this phenomenon the maximum adhesive shear stress during curing should be limited to 1.0 N/mm².

The effectiveness of this strengthening system has been tested also for steel girders in bridges with concrete deck. The presence of the concrete acting together with steel girders can prevent torsional buckling. The feasibility of epoxy bonding of pultruded carbon fiber sheets, on restoring the ultimate load carrying capacity and stiffness of composite girders, was examined by Tavakkolizadeh and Saadatmanesh (2002). Three large-scale girders were prepared with three different damage levels of 25%, 50% and 100% loss of tension flange. These girders were repaired by bonding one, three and five layers of CFRP to the tension flanges. Four points bending tests were performed...
with monotonic loading. Test results demonstrated that 
this system improved the ultimate loading carrying 
capacity by 20%, 80% and 100% for 25% damaged 
and one layer, 50% damaged and 3 layers and 100% 
damaged and five layers repaired units. The CFRP 
bonding was not able to restore the elastic stiffness 
of all cases. The repairing recovered the elastic stiff­
ness of the girder to 91%, 102% and 86% of the intact 
girder for 25% loss and one layer, 50% loss and three 
layers and 100% loss and five layers repaired units.

3 APPLICATION TO METALLIC 
STRUCTURES

In Europe some historical bridges have been restored 
to their load carrying capacity with an intervention 
based on FRP. The technology used for bonding 
the FRP reinforcement to the tension flange of the 
structural members are different and it can be dis­
tinguished wet lay up, prestressing and bonding of 
pultruded plate. The great advantage of using FRP 
is the possibility to design the intervention that is 
well suited to the characteristics of the bridge mod­
ifying the type, the direction of the fibers and the 
technology of application. In England Hythe Bridge 
(Mouchel 1999), Tickford bridge (Maunsell 1999), 
Slatton Canal bridge (Mouchel 2000), King Street 
bridge (Tony Gee & partners 2001) and Acton bridge 
(Moy & Nikoloukar 2002) still exist carrying heavy load 
of vehicular traffic thanks to intervention based on 
FRP. Also cast iron struts on the London Underground 
(Moy et al. 2000, Hill 2000, Leonard 2002) have been 
strengthened with FRP In Italy Corona bridge (Zerbo 
2002), a pedestrian cast iron arch bridge, has been 
strengthened with the application of aramid fiber rein­
forced polymers. In USA Christina Creek bridge l-704 
has been reinforced with CFRP plates (Miller et al. 
2001). Further examples of FRP strengthened struc­
tures exist, but they are neglected in this paper because 
only the most representative typologies of intervention 
are presented.

3.1 Hythe bridge

Hythe bridge is a cast iron girder structure crossing 
the river Thames with two spans of 7.8 m constructed 
in 1874 (Fig. 10). It is composed of eight inverted 
T section cast iron beams and two edge beams with 
a channel section supporting a decorative parapet. 
Transverse brick jack arches span between the bottom 
flanges and support the carriageway.

The objective of the restoration was to elevate 
the carrying ability of this bridge up to 40 t assess­
ment load. Mouchel Consulting used pre-stressed 
CFRP plates. The degree of pre-stress was designed to 

Figure 10. Hythe bridge in England (1874).
the same coloration of the bridge, that has allowed this intervention to be invisible.

3.3 Slattocks Canal bridge

Slattocks Canal bridge is a girder structure spanning over the Rochdale channel in England.

It is characterized of twelve steel beams with a I section and a 7.6 m span supporting a concrete deck. The FRP strengthening consisted in the application of carbon fiber plates of 4 mm depth and 100 mm width, bonded to the tension flange of the twelve girders. The reinforcement reached a 8 mm depth because two layers of CFRP plates were used (Fig. 11). The cost of FRP intervention allowed to economize about 40% in comparison to a traditional repair method, that asked for the installing of traffic lights to control vehicle flow.

3.4 King Street bridge

King Street bridge at first was a railway bridge while currently it is serving a vehicular road. Tony Gee & Partners was commissioned to examine it. The bridge is characterized by six cast iron beams of 56 mm thickness, which sustain transverse masonry arches spanning 2 m. It has suffered an important intervention in the middle of 1900th when its single clear span was reduced from 8.9 m to 5.9 m creating a new steel support. The application of FRP materials has allowed to restore the original aspect since they permitted the elimination of the steel reinforcement. The cast iron beams have been strengthened through the application of two laminates of 170 mm width and 33 mm thickness to the bottom tension flanges. Carbon pre-preg laminates were disposed longitudinally while glass laminates provided transverse strength and prevented the galvanic corrosion. The reinforcement has been applied introducing a permanent stress into the FRP strengthening system. The application of the composite was realized after the girder had been unloaded temporarily, jacking the deck structure upwards. Once the adhesive has cured, the jacks have distressed so that the reinforcement participated in resisting to dead loads.

3.5 Acton bridge

Acton bridge on the London underground is a steel girder structure with timber deck. It has been strengthened with the bonding of carbon fiber polymers plates to the tension flange of the girders. The objective of this design was to reduce living load stresses by about 25%. Once obtained this result the fatigue life of the bridge would be notably increased. The bridge was subjected to the cycling load because of the passage of the train that caused severe fatigue loading to the girders. The intervention was evaluated through monitoring and the results showed that the strengthening was successfully.

3.6 Corona bridge

Corona bridge is a 4 m span, cast iron arch bridge over rio del Rimedio in Venice (Italy). The bridge was cast at the Collalto foundry in Mestre in 1852 (Fig. 12). It is characterized of three cast iron ribs connected to each other, at the time of its construction, by transverse cast iron beams. The lower part of the rib is moulded to form a flat arch. Each rib is formed of rectangular openings diminishing in size towards the middle. In 2001 it was restored with the aims to arrest the cracks and to reduce the structure's vulnerability to impacts by boats. The arches were reinforced with aramid multiaxial and interlaced fabric while the rectangular openings were coated with aramid tape. Lateral arches were reinforced only in the internal parts, because the external aspect of the bridge had to be preserved. The central rib, instead, was strengthened in both sides. The resin used was pigmented with grey colour. After the composite application the bridge was entirely repainted, also the composite layers (Fig. 13).

In the laboratory of the University of Architecture in Venice, Charpy tests have been conducted to determine

![Figure 11. Slattocks Canal bridge in England.](image1)

![Figure 12. Outer rib of the Corona bridge before the intervention with FRP.](image2)
the increase of ductility due to this type of strengthening. The specimens were notched in the middle and, on some of them, was applied primer before the application of AFRP that covered the length of the test unit. Results from the experimental research showed an increase of ductility between the 20% and 25%. Among the test units strengthened with composite, and those strengthened with composite and primer an improvement in the adhesion between two materials was noticed in the second case.

3.7 Struts in a vent shaft on the London Underground

Ultra high modulus carbon fibers have been used to strengthen cruciform cast iron struts in a vent shaft on the London Underground, East London Tube line. Twenty six layers were applied to the four flanges of the eighteen compression struts. The carbon composites were applied using DML’s patented resin infusion under Flexible Tooling (RIFT) method whereby a dry carbon fiber stack is placed onto the member to be reinforced and is infused with resin under a vacuum. Large scale tests were conducted before the restoration to demonstrate the efficiency of the reinforcement. Three pairs of struts were cast in various slenderness ratio and tested using different thickness of carbon fiber reinforcement. To simulate the real condition in the vent shaft, the load was applied eccentrically at both ends of the struts and, before the application of FRP strengthening, one strut from each pair was preloaded up to 50% of the predicted buckling load. These tests showed that the FRP strengthening system increased the load carrying capacity of about 40%, the axial and bending stiffness.

3.8 Christina creek bridge I-704

A steel slab-on-girder bridge I-704 has been reinforced with CFRP plates by the Department of Transportation of the University of Delaware. This bridge was chosen from this University with the objective not to reinforce a deteriorated structure but to analyze the efficiency of the FRP strengthening system. The bridge selected represents the most common type in the country. They intended to verify the fatigue durability and bond durability to environment of the CFRP/steel. The bridge consists of three simple spans with a total length of 35 m. The main span acting compositely with deck was 19 m long. Only a single girder was chosen to demonstrate the efficiency of the system. They selected the girder subjected to the most stress cycles and largest stress ranges. The rehabilitation consisted of bonding one layer of CFRP plates to the outer surface of the tension flange. Six cover plates of 1.5 m length, were placed side-by-side to cover the entire wide flange. The plates had a staggered joint in the final parts for easier installation and were beveled at a 45° angle to form a scarf joint. This detail minimizes the peel stresses and permits an increased force transfer through the bonded plate-to-plate surface. For the operation of bonding of the plates a two parts structural adhesive was applied using a compressed air gun with a mixing nozzle. This toll eliminated the need to measure and mix adhesive components. To avoid the phenomenon of galvanic corrosion a layer of glass fabric was placed between the CFRP plate and the tension flange. It was, also, pressed to avoid the presence of air pockets. The plates were attached using clamps that were positioned on wood blocks (Fig. 14).

After all the plates were attached, the clamps were tightened to allow the resin to fill all the spaces in order to eliminate the penetration of air and moisture. The excess adhesive, squeezed out, was cleaned from
the plates after the clamping. The time necessary for curing depends on the environment temperature and on the characteristics of the adhesives used. In this case the temperature was 21°C so that eight hours was enough for adhesives to reach their sufficient strength. The traffic was allowed to back over the reinforced girder passed this period of time.

The results from this field implementation verified that the application of CFRP plates determine an increase in stiffness of 11.6% and a strain decrease of 10%.

4 CONCLUSIONS

Research work and practical experiences have demonstrated that the use of FRP materials for strengthening steel structures is gradually increasing. The following conclusions can be drawn:

- the effectiveness of the FRP strengthening system largely depends on the surface preparation and on the application procedure that allow the resin to fill all the voids;

- failure of metal flexural members can happen through different mechanisms: FRP rupture, FRP debonding. In the design progress of the type of strengthening, it is necessary to investigate each of these failure modes and to verify the adhesive properties of the resin;

- to prevent the initiation of galvanic corrosion a glass fiber layer can be effectively placed between steel and carbon fiber plates;

- FRP strengthening systems can be used as repair techniques to restore the lost capacity of a metallic section and are also effective in strengthening of existing steel structures to resist higher loads;

- the use of CFRP sheets permitted to increase the live load carrying capacity of historical bridge by reducing the tensile stresses in the original material;

- the application of prestressed CFRP plates to steel structures prevents further cracking due to fatigue loads by promoting crack closure effect;

- the use of AFRP fabric is efficient in improving the cast iron brittle behaviour owed to shock and impacts by heavy bodies.

REFERENCES


