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# Application of FRP wraps in arresting Corrosion of Steel Structures (Review Paper)

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***ABSTRACT*-Steel is used as a construction material in many ways. Industrial buildings, bridges and docks are important examples of the type of structure in which steel is used. Steel can be used as a structural material above ground, or below ground or water in the form of piles. However it has a drawback of corrosion in saltwater environment which can reduce the strength and life of the structures. A number of investigations have been carried out in search for strong, durable and cost effective materials for rehabilitating steel structures laid underwater. This leads to development of many advanced construction materials like Fibre Reinforced Polymers (FRP). FRP have a high potential for repairing metallic components and tubular piles. This paper provides information on the current practices and applications of fibre-reinforced composite materials for external repair of steel pipelines and steel piles. The lightweight, high strength and corrosion resistance of fibre reinforced polymers (FRP) make them ideally suited for quick and effective structural repairs. This paper provides information on the corrosion mechanism of steel in sea water, use of FRP in strengthening of steel structures, in repair of steel pipelines and steel piles.**

***Keywords:* Steel; Fibre reinforced polymers (FRP); Corrosion protection; Strengthening; Carbon Fibres; Glass Fibres**

## I. INTRODUCTION

Corrosion is the destruction of metals and alloys by the chemical reaction with the environment. During corrosion, the metals are converted to metallic compounds at the surface and these compounds wears away as corrosion product. Hence, corrosion may be regarded as the reverse process of extraction of metals from ore.

Corrosion and in particular corrosion of metal structures, is a problem that must regularly be addressed in a wide variety of areas, for example, in the automotive industry, metal parts are often plated or coated to protect them from road salt and moisture in hopes of increasing their longevity. Indeed, many traditional metal parts are currently being used with polymeric components, which are not only lighter but also more cost effective to produce.

But these are generally impervious to electrochemical corrosion often experienced by metals. Even with the proper selection of base metals and well-designed systems or structures, there is no absolute way to eliminate all corrosion. Therefore, corrosion protection methods are used to additionally mitigate and control the effects of corrosion. Corrosion protection can be in a number of different forms/strategies with perhaps multiple methods applied in severe environments. Forms of corrosion protection include the use of inhibitors, surface treatments, coatings, sealants, cathodic protection and anodic protection. In many situations, a better solution can be achieved by using modern FRP materials. Applications made using FRP are safe and reliable solutions able to face harsh conditions in many different corrosive environments and outperform traditional materials. With more than 50 years of field experience, FRP is now a proven material technology.

Engineered composites like FRP have properties and capabilities that metals lack and they usually cost less than their metals counterparts: austenitic stainless steels, high nickel content alloys, or titanium. FRP is one-fourth the density of steel, which means that in many instances, equipment can be handled manually instead of renting a crane. FRP is easy to repair and does not necessitate arc welding in hazardous areas. The dielectric properties of FRP means that it can be used safely where electrical conductivity cannot be tolerated. The anisotropic nature of FRP (different physical properties in different directions) enables the engineer to align the fiber reinforcement with the principal strain field, thus making the equipment stronger and lighter than a corresponding steel fabrication. Whether it is the material itself or its corrosion resistance, all of these advantages translate into better engineered systems that perform better, last longer, and cost less. This may be in new build systems or refurbishment and replacement of corrosion damaged metals or other materials.

FRP material consists of a mix of fibre reinforcements and a polymer system. The combination equals an engineered material system resulting in unique attributes replacing traditional materials such as stainless or coated steel, wood and alloys. An estimated 25 to 30 percent of the annual cost of corrosion-related damage can now be avoided if optimum corrosion management practices are employed.

## II. CORRECTION MECHANISM OF STEEL IN SEA WATER

On steel piling in seawater, the more chemically active surface areas (anodes) are metallically coupled through the piling itself to the less chemically active surface areas (cathodes) resulting in a flow of electricity and corrosion of the anodic areas. General surface roughening occurs when these local anodic and cathodic areas continually shift about randomly during the corrosion process. Sometimes these active local areas do not shift position end, therefore, the metal suffers localized attack and pitting occurs. In general, the depth of pitting is related to the ratio of the anodic sites to the area of cathodic site in contact with the electrolyte (seawater). The smaller the anode area relative to the cathode area, the deeper the pitting corrosion occurs.

A general corrosion mechanism and initiation of corrosion in a pipe surface in the presence of salt water are given in Fig. 1. It can be seen from the Fig. 1 that the hydroxide and chloride ions are contributing to the accelerated corrosion in submerged and sea water conditions. Fig.2 shows degradation of the protective coating and formation of hydroxide of iron as a result of the corrosion (Md Shamsuddoha et al, 2013).

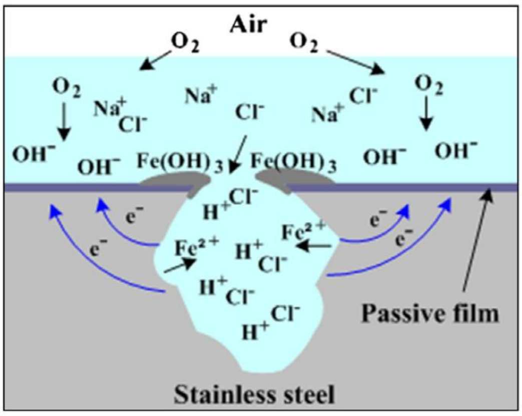

**Fig.1.** Corrosion of Steel in seawater (Md Shamsuddoha et al, 2013).

**Fig.2**. Corrosion on steel surface (Md Shamsuddoha et al, 2013).

## III. USE OF FRP IN THE STRENGTHENING OF STEEL STRUCTURES

Since steel is also a material of high elastic modulus and strength, the use of FRP in strengthening steel structures calls for innovative exploitations of the advantages of FRP. The main advantage of FRP over steel in the strengthening of steel structures is its high strength-to-weight ratio, leading to ease, speed of transportation and installation, thus reducing disturbance to services and traffic. Another significant advantage of FRP, which applies only to FRP laminates formed via the wet lay-up process, is the ability of such FRP laminates to follow curved and irregular surfaces of a structure. This is difficult to achieve using steel plates. A third advantage of FRP is that its material properties in different directions can be tailored for a particular application. As a result of the second and third advantages, FRP jackets with fibers oriented only or predominantly in the circumferential direction can be used to confine steel tubes/shells or concrete-filled steel tubes to delay or eliminate local buckling problems in steel tubes/shells, thereby enhancing the strength and/or seismic resistance of such structures. The method of FRP confinement is attractive not only in the strengthening of steel tubular structures, but also in the construction of new tubular columns.

The combination of adhesive bonding with shape flexibility makes bonded wet lay-up FRP laminates an attractive strengthening method in a number of applications. Needless to say, steel plates can also be adhesively-bonded but bonding is less attractive for steel plates due to their heavy weight and inflexibility in shape. Furthermore, for the same tensile capacity, a steel plate has a much larger bending stiffness than an FRP laminate so a steel plate leads to higher peeling stresses at the interface between the steel plate and the steel substrate. It is also easier to anchor FRP laminates to a steel member by wrapping FRP jackets around the steel member.

Steel plates can also be attached by welding to strengthen existing steel structures, but the bonding of FRP laminates is superior to the welding of steel plates in the following situations:

i). Bonding of FRP laminates for enhanced fatigue resistance has the advantage that the strengthening process does not introduce new residual stresses;

ii). In certain applications (e.g. oil storage tanks and chemical plants) where fire risks must be minimized, welding needs to be avoided when strengthening a structure and bonding of FRP laminates is then a very attractive alternative;

iii). High-strength steels suffer significant local strength reductions in heat-affected zones of welds, so bonded FRP laminates offer an ideal strength compensation method.

The use of both CFRP and GFRP to strengthen steel structures has been explored. The three types of CFRP plates supplied by SIKA are referred to herein as high strength, intermediate modulus and high modulus plates respectively and their stress–strain curves are illustrated in Fig. 3.

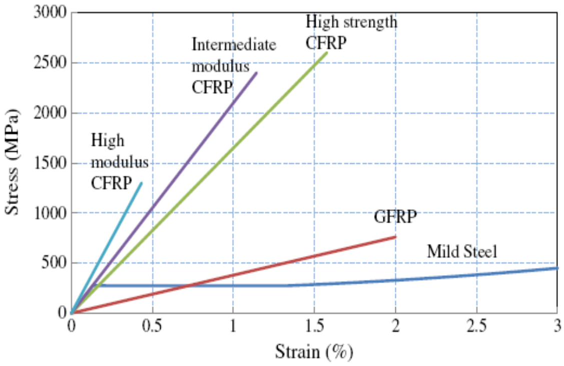

**Fig.3.** Typical FRP and mild steel stress-strain curves (Teng J.G. et al, 2012).

Since FRP composites, particularly CFRP composites are an expensive material, in all applications, the amount of FRP material required should be minimized. For this reason, where the amount of FRP material required is small by nature of the problem (e.g. local strengthening under a concentrated force), FRP strengthening is more likely to be attractive (Teng J.G. et al, 2012).

## IV. USE OF FRP IN REPAIR OF STEEL PIPELINES

Traditionally, the most reliable repair solution for a damaged pipe is to remove the entire pipe or just a localized damaged section and replace it with a new one or cover with a welded steel patch. Welding or clamping of pipelines itself is a cumbersome process especially in underwater and underground conditions. Conventional repair techniques incorporate external steel clamps that are either welded or bolted to the outside surface of the pipes.

Generally, there are three types of repair systems - Flexible ‘wet lay-up system’, Pre-cured ‘layered system’ and Stand-off sleeve system that are applied in the repair of defective pipelines (Alexander .C and Francini.B, 2006).

Pipeline repair/rehabilitation systems can be considered under four broad categories. They are:

i). systems that prevent the future progression of corrosion,
ii). repairs that are intended to reinstate the strength of the pipe containing a part wall defect like gouging,
iii). repairs that are designed to enclose the fluid in case of the failure
iv). repairs that will restore the strength of the pipe and contain the transported fluid in case of any failure incidence.

These requirements for pipeline repair need to be considered in the selection of the appropriate composite repair system (Palmer-Jones.R and Paisley.D, 2000).

### A. *Flexible wet lay-up system*

Flexible overwrap repair system is intensively utilized by pipe repair industry for onshore repair in the form of overwrapping the steel pipes even at angles or bends for a wide range of pressure applications. This application utilizes resin matrix that is usually uncured during the application and finally creates a stiff shell after curing. The flexible wet lay-up system is suitable for both internal and external repairs. This repair is generally designed for future progression of corrosion and to reinstate the strength of the pipe containing a part wall defect. However, pressure containment is one of the shortcomings of the system. This system is also suitable for underground conditions for relatively low to medium pressure applications.

### B. *Pre-cured layered system*

The pre-cured layered system involves bonding of pre-cured fibre-reinforced composite materials that is held together with an adhesive applied in the field. Clock Spring® repair system and WeldWrap™ system are examples of commercially available layered systems. This type of repair system is a coil of high strength composite material with a structure that allows it to wrap securely around pipes. The layers of wrap are sealed together with a strong bonding agent. The defect is filled with adhesive filler to assist with support and load transfer prior to their installation. This method of repair is ideal for blunt-type defects. Most of the medium duty repair technologies are based on this principle. This group of repair supports defect and prevents defect failure through load transfer and restraint. However, the repair using these systems is generally limited to straight sections of pipe. It requires a large space to apply the layered system on the defected pipe.

### C. *Stand-off sleeve system*

Stand-off sleeve systems provide higher structural integrity than both flexible lay-up system and pre-cured layered systems. Most of the heavy duty repair technologies are based on this principle. This system can restore the original strength, is permanent, contains leaks and supports axial loads. The advantage of this system is that it can carry internal pressure, axial tension and bending loads. This repair technique has the potential to be applied in both underground and underwater applications. The concept is to provide a continuous support by the introduced infill layer that can minimize the radial deformation and transfer the load from pipe to the outer shell. At the same time, the possible leak can be contained (Md Shamsuddoha et al, 2013).

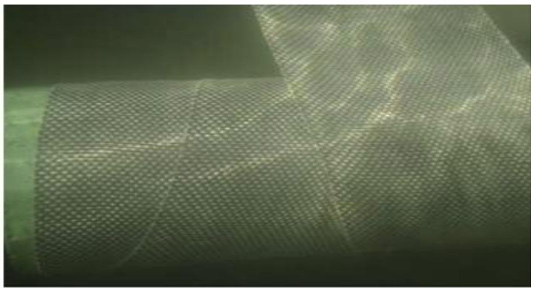

**Fig.4.** Flexible composite wrapping for underwater repair (Md Shamsuddoha et al, 2013).

## V. EXPERIMENTAL PROGRAM

### A. *Tubular Steel Structures:*

Round hollow sections were used in this investigation because offshore structures are mainly constructed with circular steel elements. Round HSS168 X 4.8 tubes (168.5 mm X 4.9 mm measured dimensions) conforming to Grade 350W Class C were provided by IPSCO Inc. The fibres used in the present study were provided by Sika Canada Inc. (Sika) and Fyfe Co. (Fyfe). The epoxy resins supplied by Sika were Sikadur® Hex 330 and Sikadur® Hex 306. A thixotropic material was selected from Fyfe, the Tyfo SW-1 Underwater Epoxy Coating.

Seven 2.4 m long pieces were cut from the steel tubes. The size of the specimens was chosen to suit the available equipment for a four-point bending test employing a 2.2m span length. One specimen is taken as control specimen and the remaining six were wrapped with CFRP materials. Two wrapped specimens were prepared ‘‘in-air’’ (i.e. under standard curing conditions), whereas the other four were wrapped underwater (i.e. under seawater curing conditions). Wrapping CFRP materials underwater involved an additional challenge: adhesion of the wet resin whilst the layers tended to debond from the tube under their own weight. Hence, to ensure adequate bonding of all layers, circumferential nylon ties were used for the last set of two specimens (i.e. 6 and 7) to hold the CFRP sheets in place during curing. The surface preparation of the tubes involved grinding the surface with a mechanical brush to remove minor rust formations and then, for in-air applications, a cloth impregnated with acetone was used to remove any further accumulated dust and impurities.

The testing arrangement utilized a special-purpose beam jig within a 1000 kN capacity universal testing machine equipped with a digital data acquisition system. The simply supported beams were tested in a quasi-static manner under four-point bending until the specimens reached a maximum load and their load–deflection response was on a steady decline. In addition, linear variable differential transformers (LVDTs) were provided to measure displacements (Michael V. Seica and Jeffrey A. Packer, 2007).

## VI. RESULTS AND DISCUSSIONS

1) For the strength enhancement of steel structures, CFRP is preferred over GFRP due to the much higher elastic modulus of the former.
2) In particular, when the enhancement of buckling resistance is the aim, the use of high or ultra-high modulus CFRP is very attractive.
3) For the confinement of steel tubes, particularly when ductility enhancement is the main aim, GFRP is more attractive as it is cheaper and offers a greater strain capacity (>2%).
4) An issue to note is that of galvanic corrosion when steel is in direct contact with CFRP, so a layer of GFRP has been advised to be sandwiched between them by some researchers (Teng J.G. et al, 2012).
5) The tubes wrapped with Fyfe materials display greater flexural capacity than those wrapped with Sika materials since the thickness of the Fyfe laminate, and the total volume of fibres were larger than that of Sika laminate.
6) The wrapped beams exhibited an increase in stiffness as well as ultimate strength compared to the reference beam.
7) Specimen-7 (Sika/Fyfe-U-strapped), which was wrapped underwater, achieved a higher strength than that of standard Specimen 2 (Sika-S), which was repaired ‘‘in-air’’ using all Sika materials.
8) Specimen-7 also outperformed Specimen 5 (Fyfe-U), the underwater wrapped specimen using all Fyfe materials, achieving both a higher ultimate load and a more ductile behavior. This suggests that the combination of Sika fibres with Fyfe underwater matrix may be better suited for seawater application (Michael V. Seica and Jeffrey A. Packer, 2007).

## VII. CONCLUSIONS

1) External bonding of FRP has been clearly established as a promising alternative strengthening technique for steel structures by existing research.
2) As more research is conducted and more reliable design guidelines become available, the technique is also expected to receive increasing acceptance in practice.
3) Traditional steel repairs are heavyweight, time consuming and incorporate tedious welding works which restrain their use in pipelines located underground and underwater. As an alternative, fibre-reinforced composite has proven to be an effective repair solution for corroded steel pipelines.
4) Composite split sleeve repair with infill will provide an easily applicable and long-term solution to steel pipelines.
5) Hitherto, research concerning FRP has been mainly oriented towards strengthening concrete structures and in one study, the rehabilitation of steel tubular structures with CFRP has been explored, aiming to assess experimentally the possibility of rehabilitating tubular steel flexural members, with emphasis on underwater applications.
6) The Fyfe-wrapped specimen displayed higher strength and stiffness improvements than its Sika-wrapped counterpart, mainly because of the increased thickness of the CFRP sheets from the former supplier.
7) No serious debonding problems were found in any of the specimens, suggesting that the fibres bonded adequately regardless of the application and curing conditions involved.

8) All CFRP wrapped specimens did reach the plastic moment and also exhibited increased ductility and rotation capacity. Therefore, it can be concluded that the use of CFRP composites to enhance the strength of tubular steel flexural members both in air and underwater is perfectly feasible.

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