

An Overview of Corroded Pipe Repair Techniques Using Composite Materials

K. S. Lim, S. N. A. Azraai, N. M. Noor, N. Yahaya

Abstract—Polymeric composites are being increasingly used as repair material for repairing critical infrastructures such as building, bridge, pressure vessel, piping and pipeline. Technique in repairing damaged pipes is one of the major concerns of pipeline owners. Considerable researches have been carried out on the repair of corroded pipes using composite materials. This article attempts a short review of the subject matter to provide insight into various techniques used in repairing corroded pipes, focusing on a wide range of composite repair systems. These systems including pre-cured layered, flexible wet lay-up, pre-impregnated, split composite sleeve and flexible tape systems. Both advantages and limitations of these repair systems were highlighted. Critical technical aspects have been discussed through the current standards and practices. Research gaps and future study scopes in achieving more effective design philosophy are also presented.

Keywords—Composite materials, pipeline, repair technique, polymers.

I. INTRODUCTION

POLYMERIC composites are being increasingly used as repair material for repairing critical infrastructures such as buildings, bridges, pressure vessels, piping and pipelines. Steel pipelines are the most effective and safest way for oil and gas transportation over a long distance [1]-[4]. There are over one million kilometers of pipelines laid around the world to transport products such as oil and natural gas, and there are more new pipelines expected to be installed in the near future [5]. These pipelines are subjected to deterioration due to several factors, including third party damage, material and construction defects, natural forces and corrosion [6]-[10]. The deterioration of steel pipelines is a common and serious problem, involving considerable cost and inconvenience to industry and to the public [11]. According to the United States Department of Transport, the average annual corrosion-related cost is estimated at \$7 billion to monitor, replace and maintain gas and liquid transmission pipelines. About 80% of the cost is related to maintenance and operation of corrosion related problems [12]. Recently an explosion of underground pipeline in Kaohsiung, Taiwan killed at least 27 people and injured

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286. Initial investigation showed that the cause of this incident was likely triggered by a leaky underground pipeline owned by a local chemical producer that operates a 4-inch propene pipeline [13]. Hence, corrosion and metal loss cause failures in pipelines and their repair techniques is one of the primary interests of researchers all around the world [10], [14].

According to a guidance document published by AEA Technology Consulting [15], corroded pipe defects can be grouped into the three main categories: (i) pipe subjected to external metal loss, (ii) pipe subjected to internal metal loss, and (iii) piping components that are leaking. If defects are found, the pipeline operators will assess the pipeline condition and decide if repair is necessary to keep the safe operation of the pipeline. When repairs are needed, there are a variety of repair techniques available to pipeline operators for a given repair situation. Prior to the repair, the operators have to check a list of parameters including pipeline operating characteristic, geometry and materials so that the best choice of repair techniques can be made [16].

II. CONVENTIONAL STEEL REPAIR TECHNIQUES

For years, the most common repair solution for a corroded steel pipe is to remove the pipe entirely or removing only a localized section and then replacing it with a new one. Alternatively, the repair can be done by installing a full-encirclement steel sleeve or steel clamp. These conventional repair techniques incorporate external steel sleeves that are either welded or bolted to the outside surface of the pipes as shown in Fig. 1.

The use of full-encirclement steel sleeve was developed in the early 1970s. There are two basic types of full-encirclement steel sleeves; type A and type B. Type A sleeves function as reinforcement for the corroded area by welding two pieces of steel sleeves longitudinally. Type B sleeves are also welded in the same manner as type A sleeve, except that the sleeve ends are welded circumferentially onto the carrier pipe. Type B sleeve is capable of repairing leaking defects or defects that may eventually leak because the ends are welded with fillet welds to the carrier pipe. In addition to the welded sleeves, steel clamp repair is another alternative for repairing corroded steel pipes. Instead of welding, the sleeves are joined by mechanical fastening. The operating principle of the mentioned repair steel techniques has proven to be effective by restraining the corroded section from bulging, hence the reinforcement.

Despite the discussed advantages of steel sleeve/clamp, these methods are generally suitable for straight pipe section only and have limited application for joints or bends. Welding

or clamping of pipelines itself can be a difficult process especially in limited workspace such as underground conditions. Sometimes, heavy machinery is required to perform this cumbersome job [17]. Moreover, welding involves hot-work that poses potential risk of fire and explosion. Thus, researchers have sought alternative materials that are relatively lightweight, easily applicable and can be an effective repair solution.



Fig. 1 Full-encirclement steel sleeve (a) and steel repair clamp (b)

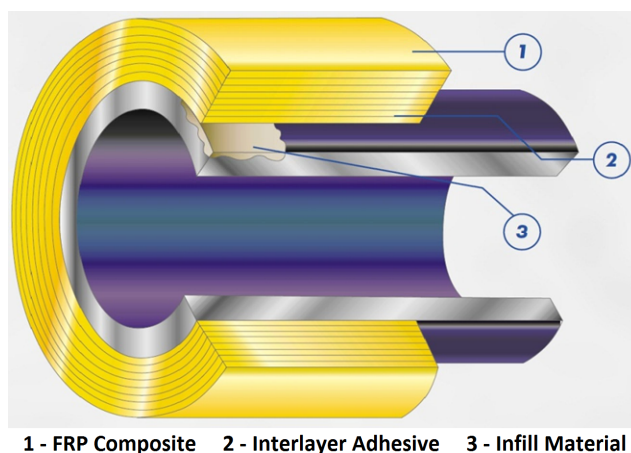
III. EMERGING OF COMPOSITE REPAIR SYSTEMS

Recently, fiber reinforced polymer (FRP) composite based materials have emerged as a popular alternative repair system for damaged steel pipeline [18]-[21]. In fact, the use of fiber-reinforced polymer (FRP) composite materials in pipeline repair began in the late 1980s. Since then, continuous efforts have been made by numerous institutions and companies to develop their own research and development (R&D) and commercial composite repair products and the trend is likely to accelerate. Repairs made with FRP materials offer numerous advantages over traditional, welded repairs and reduce overall repair cost. Because of FRP composite repair technology's construction safety, convenience and constancy, no need of welding, and its advantages such as designability and durability, it has been widely applied in the repair for steel pipeline [22]. Furthermore, the acceptance of composite based materials as an alternative to conventional repair materials is indicated through the recent development of several codes and standards, including ASME PCC-2 [23] and ISO/TS 24817 [24]. Both standards recognized composites as a legitimate repair material. Currently, a wide variety of FRP composite materials are available in pipeline repair systems. They are mainly specially engineered products consisting of high strength fiber reinforcement in a thermoset polymer resin. Repair systems using fiber-reinforced composite can be categorized as pre-cured layered, flexible wet lay-up, pre-impregnated, split composite sleeve and flexible tape systems. Although the products made by different companies and

research institutes around the world have widely different performance, its composite material repair system mainly includes three parts: (i) high strength fiber reinforcing materials; (ii) adhesive materials with high curing speed and high performance; and (iii) high compressed strength material for pipeline defect filling as load transfer medium.

A. Pre-Cured Layered System

The pre-cured layered system involves bonding of pre-cured fiber-reinforced composite materials that are held together with an adhesive applied in the field. Clock Spring[®] [25], PermaWrap[™] [26] and WeldWrap[™] [27] systems are examples of commercially available layered systems being used in pipeline repair industry. Fig. 2 shows basic components of a commercially available pre-cured layered system, Clock Spring[®] repair system: (1) composite sleeve, (2) interlayer adhesive, and (3) infill material. All these three layered systems are made of fiberglass as reinforcement and claim that it can repair defects of up to 80% metal loss. This type of repair system consists of a pre-manufactured coil of high strength composite material which allows it to wrap securely around pipes. The layers of wrap are sealed together with a strong interlayer bonding adhesive. The defect area is filled with high compressive strength infill material to assist the load transfer prior to their installation. This repair method supports defects and prevents defect failure through load transfer and restraint [28]. It is ideal for blunt-type defects.



1 - FRP Composite 2 - Interlayer Adhesive 3 - Infill Material

Fig. 2 Clock Spring[®] FRP composite repair system

Since the composite wrap is pre-manufactured under control environment (normally in factory), it often offers better quality control. Similar to steel sleeve/clamp repair, the drawback of the repair using these systems is that it is generally limited to straight sections of pipe, hence limited application for repairing other components such as bends and joints.

B. Flexible Wet Lay-Up System

Flexible wet lay-up system is intensively utilized by pipeline industry in repairing onshore and underwater including angles or bends of pipes [29]. Aquawrap[®] [30], RES-Q Composite Wrap [31] and Armor Plate[®] [32] system

are examples of commercially available wet lay-up technology. Flexible wet lay-up utilizes resin matrix that is usually uncured during application and finally creates a stiff shell after curing. Finally, composite cloth will be used to wrap the repaired area to strengthen the loading capacity. A typical installation of flexible wet lay-up system including these steps: (1) cleaning the damaged section; (2) applying infill material to damaged section; (3) applying matrix resin to pipe surface; (4) preparing the composite cloths; and (5 and 6) wrapping the composite cloth on the section to be repaired. Fig. 3 illustrates the installation steps.

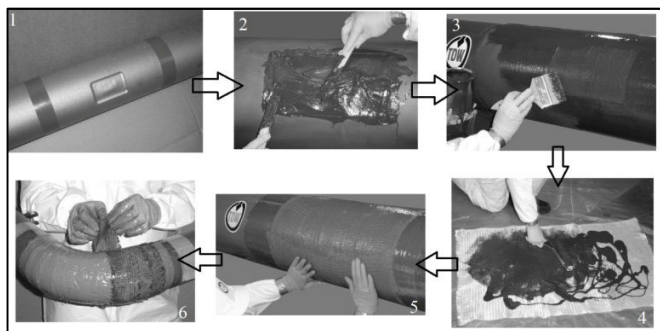


Fig. 3 Typical installation steps on flexible wet lay-up system

Aquawrap[®] repair system is comprised of a proprietary polyurethane formula and custom-woven biaxial glass fiber composite. Worth published a report that presented a research output to validate Aquawrap[®] repair system [33]. Detailed material characterizations on composite wrap and different repair scenarios such as external metal loss, gout and dent have been carried out to determine the effectiveness of the product. Through laboratory and field testing, the author concluded that this repair system is easy to use, reliable and efficient in repairing piping that has been subjected to various types of damage. Armor Plate[®] system is an E-glass/epoxy material that is impregnated with different resin systems to cater to various environmental conditions such as underwater condition, wide range of operating temperature (-51°C to 91°C). Alexander and Wilson have reported the test result and field experience of Armor Plate[®] system [34]. Similar to work done by Worth [33], detailed material testing on composite wrap have been done. Repair on gouged and corroded pipes have been carried out and repaired pipes were tested under cyclic loading conditions. Test results confirmed that this repair system is a viable means for repairing mechanically damaged pipes and increasing the fatigue life of the repaired pipes. In an article written by Morton, the use of RES-Q Composite Wrap was discussed [35]. This product is comprised of carbon fabric and unique blend epoxy resin. The thermoset resin and hardener contains no volatile solvent and does not shrink and expand during curing process. The RES-Q Composite Wrap system was designed to be used on a variety of pipe conditions. These conditions include both buried and above-ground pipelines; pipelines that cross rivers and pipelines adjacent to bridges and overpasses; and also piping systems within refineries, process plants, and hydrocarbon

processing facilities.

In-situ curing of resin makes this system difficult to install especially in areas with high ground water table, thus leading to the possibility of under-curing and non-uniform curing. These can cause reduction in the capacity of the adhesive to transfer load and therefore the overall strength of the repair is compromised as reported in these works [36], [37]. In addition, the application of wrap system in a confined space such as underground is very difficult. Pressure containment is another shortcoming of this system.

C. Pre-Impregnated System

ProAssure[™] Wrap Extreme [38], Syntho-Glass[®] XT and Viper-Skin[™] [39] are examples of pre-impregnated systems available in the pipeline repair industry. ProAssure[™] Wrap Extreme is a novel pre-impregnated composite resin system for onshore and offshore pipeline repair. This system is developed by a team of researchers from Commonwealth Scientific and Industrial Research Organization (CSIRO) and Petroliaam Nasional Berhad (PETRONAS), Malaysia's national oil and gas company. Consisting of E-glass fiber with a proprietary underwater epoxy resin formulation with effective corrosion protection and pipe reinforcement properties, ProAssure[™] Wrap Extreme is curable underwater and is capable of withstanding wet environments with minimal loss of adhesion and mechanical properties. Syntho-Glass[®] XT and Viper-Skin[™] are both products of Neptune Research Inc. (NRI). The former consists of bi-directional fiberglass while the latter is a bi-axial hybrid of carbon and glass fibers. Both are pre-impregnated with polyurethane resin. Fig. 4 shows the factory impregnation process of ProAssure[™] Wrap Extreme.



Fig. 4 ProAssure[™] Wrap Extreme

In contrast to flexible wet lay-up system, the pre-impregnation process of fibers uses a factory-controlled, wet-out process. As a result, consistent resin content and maximum, repeatable strength properties are attainable. However, the fiber is pre-impregnated with resin and needs to be stored in specific environment (normally sub-zero degree Celsius) prior to repair. This makes the logistic and handling of this repair system more challenging especially for offshore application.

D. Split Composite Sleeve System

Split composite sleeve system provides higher structural integrity than pre-impregnated, flexible lay-up 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. A team of researchers from the Centre of Excellence in Engineered Fiber Composite (CEEFC), at the University of Southern Queensland, Australia have developed a split composite repair sleeve. This sleeve was successfully used in rehabilitating underwater piles at the Missingham Bridge in Northern New South Wales, Australia in 2005 [40]. This success gives an insight into the opportunity to extend split composite sleeve in repairing damaged pipeline. Alexander found that carbon half-shell split sleeve can be effectively used for high pressure pipe repairs [41]. Fig. 5 shows the world's first pipeline repair clamp made of advanced composite material: ProAssure™ Clamp, as claimed by the manufacturer [42]. The manufacturer also claimed that it is an effective leak containment solution. According to a PETRONAS custodian engineer, Mr. Mohd Nazmi bin Mohd Ali Napiah, this product is currently undergoing field trial.



Fig. 5 ProAssure™ Clamp

The repair concept is similar to that of metal PLIDCO split-sleeve concept developed by Pipe Line Development Company [43]. In case of material loss either by corrosion or gouging, infill or cushion is used to ensure a smooth bed for the composite clamp. 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, possible leaks can be contained.

The principle of this concept largely depends on the performance of the infill. However, the potential benefits and contribution provided by infill materials is not yet fully explored. Joining method of split sleeves is one of the challenges of this repair especially in underwater and restricted spaces. Similar to the pre-cured system, the application of stand-off sleeve is limited to straight section only.

E. Flexible Tape System

The original 3X Engineering, REINFORCEKit® 4D concepts is a combination of Kevlar 49 tape and specific epoxy resin [44]. In the application of this system, layers of

Kevlar tape are bonded using ceramic reinforced resin to form a rigid composite sleeve after curing. According to manufacturer, this composite repair system is strong but not rigid, thus providing considerable strength and flexibility. Furthermore, the repair can be designed to last at least 20 years. Kevlar has a range of advantages including relative low weight, high strength and stiffness. Laminated Kevlar is very stable at high temperatures and it is impact and scratch resistant. Despite the advantages, Kevlar is normally expensive due to the demands of the manufacturing process and the need for specialized equipment. It also tends to absorb moisture. It must be combined with moisture resistant materials if there is a need for moisture resistance as a physical property. Another principle disadvantage of Kevlar is low compressive and bending strength [45].



Fig. 6 Wrapping process of Kevlar tape repair system

TABLE I
GUIDE TO GENERIC DEFECT TYPES

Type of defects	ASME PCC-2	ISO/TS 24817
General wall thinning	Y	Y
Local wall thinning	Y	Y
Pitting	Y	Y
Gouges	R	R
Blisters	Y	Y
Laminations	Y	Y
Circumferential cracks	R	Y
Longitudinal cracks	R	R
Through wall penetration	Y	Y

*Y implies generally appropriate

*R implies can be used, but requires extra caution

IV. CURRENT CODES AND PRACTICES

The acceptance of composite based materials as an alternative to conventional repair materials is indicated through the recent development of several codes and standards. The most remarkable advancement in the composite repair standards is the development of ASME PCC-2- Part 4, Nonmetallic and Bonded Repairs [46] and ISO/TS 24817, Composite Repairs for Pipework [24]. ASME PCC-2 was revised in 2008, 2011 and 2015 while ISO/TS 24817 2006 still remains relevant without any revision. Procedures in both technical specifications cover the repair of metallic pipework, pipework components, pipelines originally designed with a variety of standards. As a general guide, Table I summarizes the types of defects that can be repaired using composite

repair systems.

In designing the composite repair of type A (non-leak) and type B (leaking) cases, both standards provide very similar design approach. For example, in the calculation of minimum repair thickness of composite wrap, both standards consider three options for type A defect: (i) substrate allowable stress, (ii) composite wrap allowable strain, and (iii) composite wrap allowable stress by long-term performance test data. The options (i) include the load carrying capacity of substrate pipe that may or may not yield. When the yield strength of the substrate is the criterion for determining the thickness of the repair, the minimum remaining wall thickness (t_s) in hoop direction of the steel substrate when un-reinforced is defined as:

$$t_s = \frac{P_s D}{2s} \quad (1)$$

where P_s is the Maximum Allowable Operating Pressure (MAOP), D is the pipe diameter and s is the Specific Minimum Yield Strength (SMYS) of the pipe. The maximum strain (ε) of the substrate and composite combination is given by:

$$\varepsilon = \frac{PD}{2(E_c t_{min} + E_s t_s)} \quad (2)$$

where P is the internal design pressure, E_c is the tensile modulus of the composite laminate in the circumferential direction, E_s is the tensile modulus of the pipe material, and t_{min} is the minimum repair thickness. Accordingly, the yield strength (s) in the pipe substrate is:

$$s = \frac{P D E_s}{2 E_c t_{min} + E_s t_s} \quad (3)$$

Substituting for t_s from (1) into (3) gives:

$$PD = 2s \left(\frac{E_c}{E_s} t_{min} + \frac{P_s D}{2s} \right) \quad (4)$$

Rearranging the equation gives:

$$t_{min} = \frac{D}{2s} \left(\frac{E_s}{E_c} \right) \cdot (P - P_s) \quad (5)$$

Equation (5) is the minimum repair thickness for the hoop stress due to the internal pressure as defined in Section 3.4.3.1 of the ASME PCC-2.

Alternatively, when the design of the composite is carried out with the assumption that the underlying pipe substrate does not yield, the substrate pipe carries no further load after yield and any further load is assumed to be carried solely by the composite. Therefore the extra strain, ($\varepsilon_{plastic}$) carried by the composite after yield is given by:

$$\varepsilon_{plastic} = \frac{(P - P_{yield})D}{2E_c t_{min}} \quad (6)$$

where P_{yield} is the internal pressure of the pipe substrate at yield. The elastic strain, ($\varepsilon_{elastic}$) within the composite laminate

is given by:

$$\varepsilon_{elastic} = \frac{(P - P_{live})D}{2(E_c t_{min} + E_s t_s)} \quad (7)$$

where P_{live} is the pipe internal pressure during repair. Equating the total strain, the sum of (6) and (7) to the design allowable strain of the composite (ε_c), the thickness of the repair can be derived from:

$$\varepsilon_c = \frac{PD}{2E_c t_{min}} - s \frac{t_s}{E_c t_{min}} - \frac{P_{live} D}{2(E_c t_{min} + E_s t_s)} \quad (8)$$

Assuming the repair is done at zero pressure ($P_{live} = 0$), the repair thickness is given by:

$$t_{min} = \frac{1}{E_c \varepsilon_c} \left(\frac{PD}{2} - s t_s \right) \quad (9)$$

As can be seen in (9), the repair design does not account for the defect geometry (i.e.: width and length), only minimum remaining wall thickness (of the substrate) is considered. The remaining strength of corroded section depends not only on the material but also flow geometry [47]. Likewise, the presence of infill material is not considered in close-form solution. The load transfer between the substrate and the composite largely depends on the compressive strength of the filler material [10], [48], however no strength contribution is assumed. This may lead to a conservative calculation of minimum repair thickness [49].

V. FUTURE SCOPE OF STUDY

The available literature has shown that FRP composite can be effective in repairing defective pipes. Benefits associated with composite repair systems include: (i) the short amount of time needed to complete a repair, (ii) the undisrupted product transmission in the piping system while the repair is made, and (iii) explosion potential is eliminated since no welding or cutting of the pipeline is required. Industry analysis shows that composite repair systems are, on average, 73% cheaper than replacing the damaged section of the steel pipe completely and 24% cheaper than welded steel sleeve repairs [50]. Despite having these advantages, the long-term performance is one of the main concerns for composite repair system. In response, an extensive research program sponsored by Pipeline Research Council International, Inc. and twelve (12) composite manufacturers from around the world was conducted to better understand the long-term performance of composite repair systems [51]. In addition, the effect of defect geometry on the load transfer mechanism needs to be identified for better understanding of the system behavior.

The role of infill materials is very significant to ensure satisfactory repair performances [10], [14], [48]. However, detailed attention to infill materials is often omitted. In a report published by Farrage, the author mentioned that if the compressive modulus of the filler material is relatively low, large deformations of the pipe substrate may occur before the load is transferred to the composite [48]. This large deformation phenomenon required further attention to

evaluate its effect on overall repair system. In the same report, a parametric study using Design-of-Experiment (DoE) methodology was performed to model the pipe-composite repair at various material properties and loading conditions. The results of the study provided an understanding of the influencing properties which is further investigated in the experimental program. The most significant parameters which affect the performance of the repair are the pipe size, applied pressure, and repair tensile modulus. Recently, Sekunowo et al. provided a short review of the effect of nanoparticles in enhancing mechanical properties of composite [52]. This article presented the idea of enhancing the compressive and tensile modulus of infill material. The former may possibly address the concern of large deformation prior to load transfer to composite wrap while the latter could potentially contribute in load carrying capacity, thus reducing the usage of composite wrap. Several parties have conveyed their interest in reducing the usage of composite wrap since it can directly reduce the repair cost of repair material. If the contribution can be identified, the inclusion of infill material in the close-form solution may result in a more effective repair philosophy. Moreover, it may also potentially serve as second stage of protection in case of composite wrap failure due to unexpected reasons such as third party damage, ultraviolet deterioration, creeping, and fatigue, just to name few. These are the gaps that demands further investigation in advancing the subject matter.

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