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Fibre Composites for High Pressure Pipeline Repairs, in-air and subsea – An Overview

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ABSTRACT

In 2001 it was reported that in North America alone, corrosion to the Oil & Gas pipeline distribution network costed approximately $2-3.3 billion per annum with 10% of that cost being associated with actual failure of the pipeline. In addition pipelines are also susceptible to erosion and mechanical damage producing further losses in pipe structural integrity. This results in high maintenance costs, possibility of adverse environmental consequences and the costly interruption to product transportation and distribution. The cost and technical challenges of adequately addressing repair are significant and greatly increase for underwater applications particularly with increasing water depth. It therefore induces the need of searching for alternative repair techniques involving new advanced materials for ease of installation and application against adverse environmental effects in the long run. Fibre composite materials provide excellent advantages over conventional metals in engineering practices for many decades. These advantages make fibre composite suitable candidate for effective repair technology. This paper provides a comprehensive review on the recent development and future prospect of using these materials for in-air and underwater pipeline external repairs. Various aspects of technical knowhow; benefits and shortcomings of the repair considerations are also presented.

KEYWORDS

Composite, pipeline, underwater, repair.

1. INTRODUCTION

Advancement of human civilization and scarcity of natural resources like oil and natural gases are forcing to explore deeper into the earth's crust; eventually increasing high pressure ashore and subsea drilling depth. Oil and gas reserve possesses the major share of fossil fuels; dominant source of energy of the world [1, 2]. Pipelines are the most efficient and the safest ways to transport oil and gases over long distances. In Australia, the subsea drilling activity totalled to a depth of about 150000 m; 3 times the onshore drilling activity in year 2009 [3]. Total petroleum exploration cost was $3494 million for the period 2009-10. About 78.6% of this cost was committed to subsea exploration [4]. A disruption of such transportation may be caused by structural failure due to the loss of containment, that is, pipe leakage or rupture. Pipelines can experience corrosion, surface reduction or distortion due to accidental loads, external environmental adversity, internal water-mixed hydrocarbon and other chemicals and eventually reduce service life. Thus, pipelines are being repaired to keep them operational at service conditions. United States alone losses between $2 and $3.3 billion dollars every year due to only corrosion in gas and petroleum pipelines that need to be repaired or replaced [5]. Researchers, all over the world, through their persistent effort, have carried out numerous studies to find out suitable materials for pipeline repair over the last decades. Repair and re-strengthening of defected pipelines demand prior knowledge, considerable technical expertise, application machinery and advanced material resources. The intention of the paper is to provide information on the use of fibre composites as alternative materials being used for the subsea pipeline external repair along with insight of suitable application techniques.

2. EXISTING REPAIR SYSTEMS

Most of the underwater pipeline systems consist of metal pipes due to their high strength, relative simplicity of joints and low cost. Steel and its alloys cover the major share of pipe materials. However, metal pipes have some drawbacks, namely low corrosion resistance, incomplete utilization of strength characteristics, formation of different sediments on the inner surface of pipes, etc. [6-9]. The pipe defects are grouped into the three main categories considered in the guidance document published by AEA Technology Consulting [10]. According to this guideline, possible damage scenarios of a steel pipe can be (i) the pipe subjected to external metal loss, (ii) the pipe subject to internal metal loss, and (iii) piping components that are leaking. For years, the only traditional credible solutions to damaged pipe works are to cut out the section and replace it with new or welded sections, usually stopping production. Conventional repair techniques incorporate external steel clamps that are either welded or bolted to the outside surface of the pipes as shown in Fig. 1 [11]. Welding or clamping of pipelines underwater itself is a cumbersome process involving drawbacks like ensuring dry and gaseous environment, sophisticated surface preparation, diving facility, skilled manpower and heavyweight application requirement [12]. The cost and technical challenges of these maintenance strategies increase significantly with water depth. Unlike onshore pipelines, underwater pipelines are typically designed for gravity, internal pressure, external pressure, effect of pipe lowering [13-15]. Repair in subsea conditions demand special application technique other than that of onshore repair. Service and safety concerns are dominantly much critical for underwater cases where inspection and maintenance are bulky, costly and time consuming. Thus researchers searched for alternative materials that are relatively lightweight, easily applicable and can be an effective repair solution.

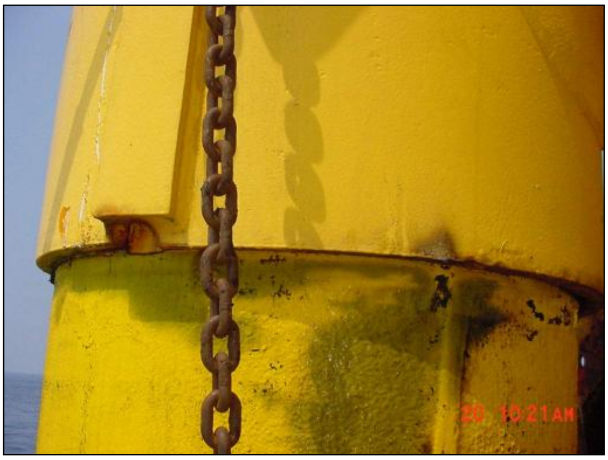

Fig. 1 Traditional welded metal clamp repair [11]

3. FIBRE COMPOSITE REPAIR OPTIONS

Fibre composites provide excellent advantages in terms of weight, cost, moisture and chemical resistance, toughness, abrasive resistance, strength, appearance, thermal and electrical insulation and machinability properties that are important in structural repair [16]. The acceptance of composite as alternate of conventional repair materials is indicated through the recent development of codes and standards. ASTM D 2992 [17] specifies standard practice for designing fibreglass pipe and fittings. However the most significant advance to the repair of high pressure and high risk pipelines is the development ASME PCC-2–2006 (Part 4) [18] which is dedicated to applicability of composite overwrap repairs to pipelines. This code allows any ASME compliant metallic pipeline to be repaired with a composite overwrap for all the possible repair scenarios of hoop, axial and leak proofing, the codes also includes the ASME metallic pipe plastic (yielding) philosophy into the repair. ISO 24817 [19] provides a similar methodology to ASME PCC-2 however does not allow pipe yielding and therefore is suitable for non-metallic and/or brittle pipes.

Investigation by Lukács et al. [20] have suggested that composite reinforcing materials and the external reinforcing technology can be used for wide variety of pipe diameters and length for both quasi-static and cyclic loaded pipeline sections or pipelines. In recent years, numerical analysis and experimental studies on sandwich and layered composite applications have been carried out to serve improved performances in pipeline repair [21-22]. Generally, two types of repair systems - 'Pre-cured layered system' and 'Flexible wet lay-up system' are applied in repair of defective pipelines [23]. Both repair methods encircle the pipe by sleeve either flexibly or through stiffer bonded connections.

3.1 Flexible Wet Lay-up System

Flexible bandage application is intensively utilized by pipe repair industry in the form of overwrapping for onshore repair cases even angles or bents of pipes [24]. This application utilizes resin matrix that is usually uncured during application and finally creates stiff shell after curing. However, underwater repair using fibre composites is common only for shallow or low pressure applications [25-26]. A typical subsea spiral wrapping application is shown in Fig. 2 [27]. In situ curing and washout of resin make this system difficult to install in under subsea conditions. Peck et al. [28] studied composite pipe repair using UV cured glass fibre wrapping in vinylester system. Results suggested that because of under-curing and non-uniform curing, the capacity for the adhesive to transfer load is reduced and therefore the overall strength of the joint and composite piping system is compromised. Application of underwater UV curing is a complicated process. Similar to standard heat curing applied onshore, resin curable in underwater condition is also available commercially. Curing of CFRP wrapped repair was simulated in saltwater conditions by Seica & Packer [29]. Due to complicacy of wet lay-up system in underwater scenario, it is often found desirable to use pre-cured spiral sleeve or half shell sleeve.

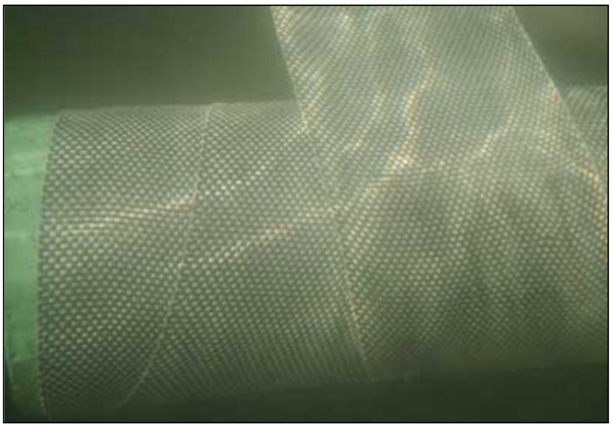

Fig. 2 Flexible composite wrapping repair of subsea pipeline [27]

3.2 Pre-cured Layered System

Layered systems involve bonding of a pre-cured system that is held together with an adhesive applied in the field. The Clock Spring® and PermaWrap™ systems are examples of layered systems. Fig. 3 shows the intensively used Clock Spring® repair system [30]. Repair using these systems is generally limited to straight sections of pipe. This repair technique has the potential to be applied in subsea applications. Bonding of layers and installation are major drawbacks of this repair system.

4.REPAIR CONSIDERATIONS

Polymers and composites provide a wide range of performances in the engineering world [29, 31]. Earlier studies suggested that fibre composites have a high potential for repairing underwater steel pipes. However, several repair factors should be taken into consideration to use fibre composite in high pressure subsea scenario.

4.1 Fibre

Fibre provides the muscle for the composites. Fibre orientation determines the directional strength and stiffness for any particular application. The most commonly used reinforcing fibres for composites are glass, carbon, aramid, polyethylene, boron, polyester, nylon, natural fibres etc. Glass fibres are low cost, easily available and more compatible with resin systems whereas have low modulus and more susceptible to fatigue, creep and stress rapture. Carbon fibres exhibit high strength, and stiffness, low density and superior fatigue performance. However, the cost, availability and compatibility are some of the disadvantages in their applications. Aramid fibres absorb water and degrade in underwater conditions. The suitability of these fibres is decided on the performance requirement of engineering application and desired physical properties. Numerous studies have been carried out to determine the behaviour of glass and carbon fibres for composite applications [32-33]. Both Glass and carbon fibre absorbs water and exhibits lower strength under immerged condition than that of dry condition but this adversity is more dominant in glass fibre at elevated temperature [34-35]. Carbon fibre can withstand higher internal pressure than that of glass and aramid fibres as demonstrated in Fig. 4 [36]. Natural fibre or hybrids of natural fibre reinforced composites are often found environmentally superior. In consideration to strength and water absorption issues, the prospects of natural fibres in underwater scenario are yet to be investigated.

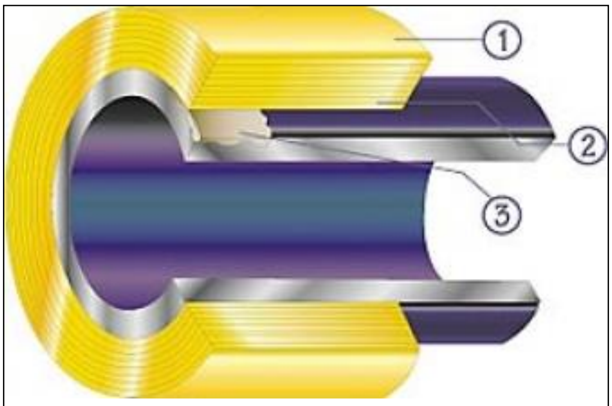

Fig. 3 Clock Spring™ repair system [30]

4.2 Resin

Resin acts as matrix for the fibres. It accommodates the fibres and play significant role in composite performances. Commonly used resins are: epoxy, polyester, vinyl ester, phenolic, polyurethane etc. Study by Ray [35] suggested the interfacial adhesion in the carbon/epoxy and glass/epoxy composites is affected by hygrothermal ageing at higher conditioning temperature and for more exposure time. However, epoxy resins are intensively used in underwater application than other resins for its anti-corrosive performance and durability [29]. Water activated and water repelling in site-cured resins demand further research to be applied for high pressure subsea conditions.

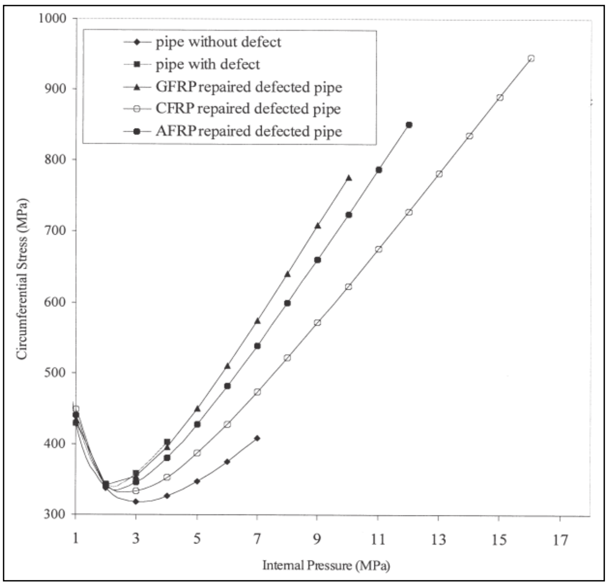

Fig. 4 Stress comparison for various repair scenarios [36]

4.3 Simulation of Defects

Naturally occurring corrosion or gouge is difficult to analyse. Researchers often use controlled mechanical gouge or metal loss to replicate the natural scenario [37-38]. Determination of remaining strength and test pressure requirement can be determined from ASME B31G [39]. One typical mechanically gouged pipe wall used by Duel et al. is shown in Fig. 5 [37]. Thus, geometry of gouge chosen to simulate specific repair conditions is often arbitrary and case specific. Experimental and numerical simulations often required to compare and design effective repair application.

4.4 CFRP and Seawater Issue

Coupling of dissimilar metals in conductive corrosive solutions, such as sea water, can lead to the accelerated corrosion of one metal and deposition of other metal [40]. Carbon is a very good cathode; hence it is likely to stimulate galvanic corrosion attack on high alloy metals. Galvanic corrosion results from electrochemical coupling of carbon fibres with steel alloys, which is another mechanism where design of interfaces, treatment technology, and environmental conditions are needed to be carefully characterized. Tavakkolizadeh & Saadatmanesh [41] studied Carbon Fibre Reinforced Polymer (CFRP) for galvanic corrosion when carbon and steel are bonded together under a series of conditions. The results suggested the existence of the galvanic corrosion when there is a direct contact between a CFRP laminate and steel substrate. Since the galvanic corrosion only initiates when there is direct contact between two dissimilar metals in the presence of an electrolyte, measures can be taken to eliminate one or both of these parameters and to eliminate this problem by introducing anothertype composite with highly resistance to seawater corrosion.

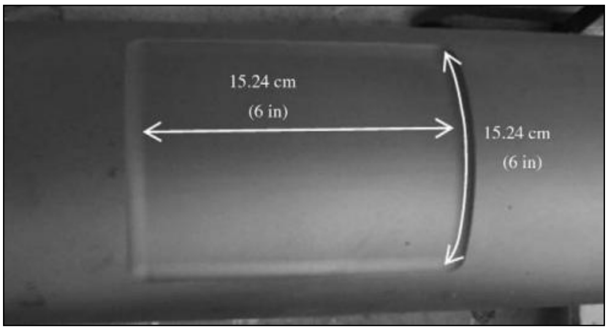

Fig. 5 Pipe test vessels with machined flaws [37]

4.5 Hybrid Composites

Hybrid composite system often utilized to eliminate galvanic corrosion along with to serve high pressure performance requirements. Multilayered hybrid composite sleeve design applied by Alexander is shown in Fig. 6 [11], where inner and outer layers of E-glass are introduced to cover carbon fibres in the reinforcement to eliminate galvanic corrosion. The inner layer acted to protect the pipe from potential corrosion due to carbon interaction with steel, while the outer layers protect the carbon fibres against potential impact and wear. Sleeve layout orientation was reported to be found both longitudinally and circumferentially to gain strength against hoop and flexural loading [11, 29].

4.6 Surface Preparation

The effectiveness of fibre composite repair systems lies on the bonding strength of the resin between steel and composites. Surface treatment is required to increase the surface energy of the adherents as much as possible to improve bonding. Subsequently, a relationship exists between good adhesion and bond durability [42]. Application of sand paper and final rinse with solvent are useful to provide an oil, grease and dirt free surface. Grinding and sandblasting the steel substrate surface, instead of simply hand-sanding the surface, was found to increase the average shear strength by at least 40 percent [43]. Since offshore repairs are done in close to hydrocarbon atmospheres, any method to mechanically rough up the surface (sandblasting, cutting, grinding) that may produce heat and sparkling; thus to be applied with caution [44]. Surface preparation technique that promotes good adhesion between steel and composite needs to be investigated for subsea application.

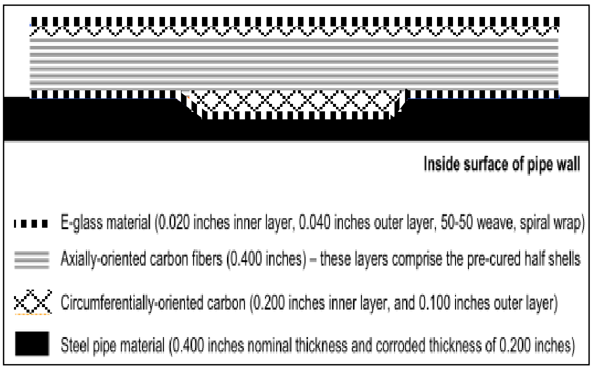

Fig. 6 Composite wrapping repair of subsea pipeline [11]

4.7 Infill

Subsea metal sleeve repair system often uses thixotropic infill materials that are viscous enough to replace water and hardens over time providing a leak proof layer. This layer fills the irregularities or dents of pipe surface and act as smooth bed for the encircling sleeve. The use of infill materials in the leaks or void between pipe and sleeve is observed in the studies by Duell et al. [37] & Fraire et al. [38]. Mattos et al. [44] studied the sole epoxy repair systems for metallic pipelines undergoing elastic or inelastic deformations with localized corrosion damage that impair the serviceability. The authors suggested applying the epoxy resin and then applying a composite material sleeve, with the normalized thickness, to restrain the plastic strain and to assure a satisfactory level of structural integrity. Underwater curing, flowablity and strength degradation issues demand additional investigation for better understanding of infill performance.

4.8 Contribution of Repair Elements

Repair of defected pipeline usually involves metal pipe with reduced thickness or distorted surface, with or without filler and fibre composite laminate sleeve. One of the prime concerns of the researchers in the field of pipeline repair is the stress and strain contribution provided by the elements. Analytical and experimental behaviours of pipe material, filler and composite for damaged pipeline were investigated by a number of researchers [29, 37-38, 44, 45-47]. Based on prior research using strain gauges installed in between different layers, it is clear that variations in strain exist between the different layers [11, 38]. A typical analytical distribution of stress and strain curve is shown in Fig. 7 [37]. ASME PCC-2 and ISO 24817 adopt conservative repair approaches. Further research is required to enhance the effective potential of the repair elements that involve not only a complex set of loading conditions, but also an aggressive subsea corrosive environment.

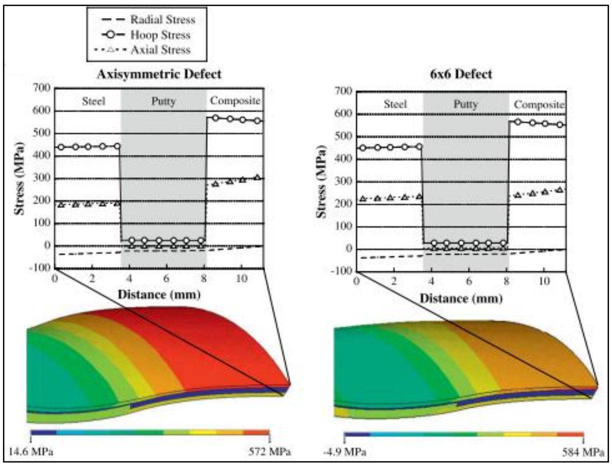

Fig. 7 Strain and stress distributions among repair components [37]

5. DISCUSSION

This paper has shown that composite overwrap repairs are an important contribution in reducing cost and increasing repair durability of some pipelines. They provide an excellent option in the repair of live pipes due to the lack of hot work required for their installation, however are not overly suited where the pipe temperature exceeds 100°C. With respect to the composite structural properties, carbon fibres and its hybrids with glass are most appropriate for repair along with epoxy resin as matrix. Both engineered overwrap and half shell made of composites are suitable to sustain the operating pressure and external adversities. Orientation of fibres in the repair is subject to application requirements and loading conditions that may vary on defect type and geometry. Infill grout provides a smooth bed and transfers the loads to increase the efficiency of the repair. Existing code of practices only considers the conservative contributions of pipe substrate and laminate layers. However, infill material can also keep an important role provided that it possesses sufficient stiffness. Contribution of high strength infill to transfer load in between pipeline surface and repair laminate under subsea conditions demands future research for better understanding. Appropriate choice of composite components is expected to provide a successful repair that can serve desired performances.

6. CONCLUDING REMARKS

The deterioration of metal pipelines in adverse in-air and underwater conditions results in the development of fibre composite pipeline repair systems to maintain the utility of pipelines. Researchers have shown that the fibre composite alternatives for pipeline repair have the potential to compete successfully with available conventional metal options. Besides, ease of handling and faster installation make composites ideal for underwater repair. However, further repair investigation on consideration especially stress contribution of repair elements along with infill need to be investigated in detail with respect to underwater compatibility and applicability issues. Subsea adversity demands more rigorous research and development to build up the confidence in using fibre composites. Adhesive bonding of stiffer or flexible layers, subsea washout, diver requirement and quality control in installation are some of the issues that are yet to be investigated to make subsea composite repair attractive.

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