CORROSION SCIENCE AND TECHNOLOGY, Vol.7, No.1(2008), pp.6~12

Case Study of Non-Metallic Repair Systems for Metallic Piping

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Non-metallic composite overwrap repair methods utilize resin based fiber-reinforced composite materials, which have higher specific strength to weight ratio and stiffness, superior corrosion and fatigue resistance, and substantially reduced weight when compared to carbon steel. Non-metallic repair methods/systems can allow desired functional properties to be achieved at a respectable economic advantage. For example, non-metallic composite repair systems have at least a 50 year design stress of 20 ksi and approximately 25% of the short term tensile strength of fiberglass. For these systems, the contribution of the repaired steel to the load carrying capability need not be considered, as the strength of the repair itself is sufficient to carry the internal pressure. Worldwide experience in the Oil & Gas industry confirms the integrity, durability, inherent permanency, and cost-effectiveness of non-metallic composite repair or rehabilitation systems. A case study of a recent application of a composite repair system in Saudi Aramco resulted in savings of 37% for offshore subsea line and 75% for onshore above grade pipeline job. Maintaining a pipeline can be costly but it is very small in comparison to the cost of a failure. Pipeline proponents must balance maintenance costs with pipeline integrity. The purpose is not just to save money but also to attain a level of safety that is acceptable. This technology involves the use of an epoxy polymer resin based, fiber-reinforced composite sleeve system for rehabilitation and /or repair pipelines.

Keywords *: non-metallic, composite, subsea line, sleeves, rehabilitation.*

1. Introduction

In the United States alone, there are over 400,000 miles of high-pressure gas gathering and transmission pipelines. Maintaining the structural integrity of such a vast network represents a significant part of the operating budget of the pipeline industry. This was the driving force for the Gas Research Institute (GRI) which, in 1987, initiated a research program that eventually resulted in the development of a unique composite repair system, called Clock Spring (Stephens, et al. 1994). Since then, other fiberglass composite repair systems have been developed in different parts of the world that enable rapid repair, without the need for cutting and re-welding, of pipelines and other metallic components that have been weakened by mechanical damage or corrosion. Table 1 represents a cursory comparison of the application scale of the non-metallic versus the traditional metallic repair techniques.

The first Saudi Aramco experience of using composite material to repair carbon steel pipe involved the use of Clock Spring system on a 20" high-pressure header line in October 1996. However, it was not until the year 2000 that Engineering Services Technology Program funded a technology item to facilitate joining the Composites Workgroup, an industry-wide consortium, which was established with the primary objective of delivering a documentation framework within which composite repairs can be specified and implemented with confidence. The consortium consisted of users, namely, Shell, BP-Amoco, Saudi Aramco, Amerada Hess, Petrobras, Statoil and BG-Hydrocarbon Resources Limited and material suppliers, namely: Walker Technical Resources, Devonport Management Ltd, Clockspring, Vosper Thorneycroft, SP Offshore and Industrial Maintenance Group).

This paper represents the summary of the consortium's work demonstrating that composite overwraps are an engineered solution for pipework and pipelines. The paper discusses a suite of documents produced by the forum that address the qualification, specification, design, installation and inspection for using external reinforcement to repair pipelines where the following damage or defects may be present:

- External damage such as dents, gouges, fretting (at supports) where structural integrity needs to be restored
- The need for structural strengthening to allow for an

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increase in pressure rating or other loads in local areas
- Internal and/or external corrosion, which may or may not be leaking, and there is a need to restore structural integrity

When leaks are present, they must be stopped and suitably plugged prior to the application of composite system. Although, there are resin systems for which it is possible to achieve an acceptable bonded connection when surfaces are wet, a dry and clean situation is preferred where possible. Repairs to live pipe systems are possible provided that the associated hazards are fully considered in the risk assessment for the operation. This should include any hazards to surrounding live equipment in addition to that being repaired. Live repairs may normally be carried out with some reduction in line pressure. The repaired pipe may be returned to full service after full cure has been achieved.

There are basically two types of composite repair systems, namely: pre-packed (Type A) and designed (Type B). Pre-packed composite repair systems may be held in stock. Installation may be performed by trained and certified personnel in accordance with the suppliers' instructions. Designed composite repair systems that are specified on a project-by-project basis must be reviewed by Engineering Services on a case by case basis. If approved, the supplier or specialist contractor will be responsible for the installation, inspection and approval of the serviceability of the installed repair.

2. Applications of composite repair (case studies)

A pre-packed (Type A) composite repair system, namely, StrongBack was used in November 2001 for the repair and rehabilitation of a subsea line at offshore and aboveground pipeline at onshore. As it was the first installation of its kind in Saudi Aramco, the repair program involved training, certification, and installations by the specialist applicator from StrongBack. The first application was carried out for the repair of 24" Subsea Trunkline at offshore in

Table 1. Composite Repair Applications Comparison in Pipelines[1]

Location	Welded Sleeve	Mechanical Clamp	Composite Sleeve
1. Onshore	Yes	Yes	Yes
2. Offshore	No	Yes	Yes
3. Defect Location			
Straight Pipe	Yes	Yes	Yes
Gradual Bend	Special Configuration	Yes	Yes
Sharp Bend	Special Configuration	No	Special Configuration
Internal Defect	Yes	Yes	Conditional
External Defect	Yes	Yes	Yes
4. Defect Type			
Leak	Yes	Yes	No
Dent	Yes	Yes	Yes
Gouge	Yes	Yes	Yes
Crack < 0.4t	Yes	Yes	Conditional
Crack > 0.4t	Yes	Yes	No
SCC	Yes	Yes	Yes
Wrinkles Bend	Special Configuration	No	No
Hard Spot	Yes	Yes	No
Arc Burns	Yes	Yes	Yes
Girth Welds/External	Yes	Yes	Yes
Blisters	Yes	Conditional	No
5. Defect Size			
Large Area > Diameter	Yes	Yes	Yes
Small Area < Diameter	Yes	Yes	Yes
Pit < 0.8t	Yes	Yes	Yes
Pit > 0.8t	Yes	Yes	No

Arabian Gulf. This line was externally damaged in two locations downstream of an elbow located at 117 ft deep. The line was operating at 1,350 psi and 94°C. The flexible composite repair system was applied by Saudi Aramco local diver's contractor using one diving boat. The application was monitored remotely by a StrongBack consultant from a TV monitor on the diving boat surface deck.

The pipe section was first cleaned from marine growth and grit blasted to a Sa 2½ cleaning standard one day before StrongBack application. The epoxy polymer GS 561 compound was mixed on the boat deck surface, delivered and hand applied by to two divers who made the underwater repair using one roll of 10" X 90 ft Kevlar fiber StrongBack wrap to rehabilitate the 1st gouged area. After the wraping was completed, a stretch shrink transparent wrap was applied on the area to hold the StrongBack sleeve tight on the pipe body during the curing process and squeeze out any air entrapment between layers or gases resulting from the chemical curing reaction. After 3 to 4 hours, the stretch wrap was removed and the Kevlar fiber wrap was topcoated with epoxy resin GS 561 by hand with overlap of 1 to 2 inch on both sides of the StrongBack sleeve. A similar procedure was carried out for the second damage location. The repair was done in one day and the only alternative repair would have been the use of a mechanical sleeve, but this would have required the pipeline to be shut down, purge, and lift from the seabed to allow hot welding work to take place, with a lifting barge in addition to the diving boat.

The second application of StrongBack repair system was carried out for the repair of the 10" aboveground crude line at onshore. The application was carried out on a selected internally corroded section of the pipeline with the aim of rehabilitating the pipeline on account of the wall thickness loss so as to avoid leaking. The application procedure was similar to the undersea application procedure except that the topcoat GS 561 used contained UV protection system. The two applications were solely a case study item and it resulted in savings of 37% for offshore and 75% for onshore jobs.

In late 2000 early 2001, Clock Spring repair system was used for rehabilitating few pipelines characterized by a serious external corrosion, due to surface breaking laminations on 26", 32" and 48" pipeline. Using the "Coil-Pass" method; and because it's rigged and has limited width, 14 Clock Spring units were installed on the pipeline, applied on either side of the valves with a 'cosmetic' (i.e. no pressure reinforcement) single wrap around the pipe at the valve position. Each repair was completed within five hours, using local labors without the need to shut down the pipeline. The only alternative repair would have been to use a carbon steel welded sleeve but this would have required the pipeline to be shut down and purged to allow hot welding work to take place.

On December 2002, a third flexible composite materials, namely, Armor Plate repair system was applied to two locations a 24" NGL pipeline above ground at onshore. It was applied at the end of a metallic sleeve as an alternative to welding to hold the sleeve in place. Welding was not recommended because the associated hot work is a potential safety hazard for the hydrocarbon gas pipeline. This application represents the first time in Saudi Aramco when a non-metallic repair system was used in conjunction with a metallic repair sleeve in order to exploit some of the unique characteristics of the principal repair systems in repairing corroded pipelines. This alternative combination is more cost effective than the use of the metallic repair sleeve alone but less cost-effective than the use of non-metallic repair system alone.

3. Scope for repair methodology

The scope of the composite repair methodology covers the repair of carbon steel pipelines, pipework, and pipework components, originally designed in accordance with a variety of pipe codes and standards including ISO 15649/13623, ASME B31.1; B31.3; B31.4; B31.8 and BS 8010. These design codes and standards for pressurized equipment provide rules for the design, fabrication, inspection and testing of new piping and pipeline systems. They do not address the fact that equipment degrades in service or may have to be up-rated due to a change in duty, nor do they consider options for remedial actions should such events occur. Indeed, there are standards, such as API 579 and BS7910 that do address fitness for service of degraded equipment, but, again, these standards do not specify or give guidance on possible repair options.

Ageing pipework and pipelines have created a market for repair methodologies that can be used as an alternative to replacement. This is particularly so as degradation is often limited to isolated areas and a local repair can offer rehabilitation rather than replacement of a significant system. A further benefit of having repair schemes available is that it potentially allows immediate action to be taken thereby minimizing any system downtime. As a result, there is a considerable demand for documentation that covers the repair situation and the desired documentation scope includes damage commonly encountered in utility, oil, and gas pipelines. The damage type includes circumstances requiring the restoration of structural integrity and the pipe services that are considered include:

- Utility fluids, diesel, seawater, air;

- Chemicals; and
- Produced fluids, including gas and gas condensate.

The applicable pressure/temperature envelope is dependent on the type of damage being repaired. For all repairs, continuous service temperatures should be limited to the range -50℃ to 100℃. For service temperatures greater than 40℃ individual laminate systems shall not be used at temperatures higher than the glass transition (T_g) less 30℃ in the case of epoxies or higher than the heat distortion temperature (HDT) less 20℃ in the case of polyesters and vinyl esters. For repairs where the pipe is not leaking or the repair is denoted as temporary, the temperature limit can be relaxed to T_g less 20℃. T_g or HDT shall be measured in accordance with ISO 113572 or ISO 75 (or equivalent) respectively.

Where the pipe being repaired is leaking, the upper limit for continuous service pressure should be 50 bar due to the fact that in leaking circumstances, the repair material is in direct contact with the process fluid, and subject to loadings that are more severe than in the non-leaking case. For the non-leaking case there is considerable successful experience at high pressures especially for pipeline applications. The 50 bar limit also applies for repairs where it is assessed that any continuing degradation of the steel pipe (e.g. through internal corrosion) will result in a through wall defect at some point during the remaining design life. Where leaking of the pipe being repaired is not a design factor, there is, in principle, no upper limit to continuous service pressure, although all repairs will be subject to a risk assessment and internal pressure will be an important consideration.

4. Composite repair documents

Because of the variety of composite repair systems that are currently available, the desired documentation is performance-based, so as to cover all available product forms. A prescriptive approach that, for example, gives specific information regarding constituent materials or laminate lay-up cannot be sufficiently inclusive and would almost certainly hinder general applicability. The vendor and the field proponent are the primary sources of required data for the performance-based documentation and the following illustrates the inter-play between these primary sources.

4.1 Repair design

The key stages of design and the sources of data illustrate the layout of the design process. The role of the owner/proponent in the provision of information that specifies the functional requirement of the repair is highlighted. The design document provides details on the information that is necessary to specify a repair situation in the first place. The information is then used as input to the calculation. In this regard, each load condition should be carefully considered. (For example, specifying a design pressure well in excess of operation could prejudice the viability of composites as an option). Hence, the required laminate thickness may be determined by mathematical equations, which is not included in this paper.

4.2 Qualification

It is a fundamental premise behind performance based design methods that the materials and processes that are used to produce test samples for qualification are identical to those to be used in the delivered product or service. It is also important that testing replicates the conditions to be seen in service. Of necessity, qualification always represents a compromise between testing rigor and practical limitations. If the testing requirement is too limited, its value will be minimal and the uncertainty that this would represent would need to be catered for through the imposition of large safety factors. Too extensive a test program would cause the document to fall into disrepute – it might not be used, might hinder the uptake of the product and inhibit development. In the repair documentation,[2] procedures for product qualification are defined. These include the following:

- Specification of tests for basic material properties of the repair laminate, e.g. modulus and strength values. Wherever possible, existing test methods are specified;
- Description of simple tests to demonstrate a minimum level of durability. For example, there is a requirement to carry out simple lap shear testing after a period of exposure; a minimum level of residual strength need be achieved;
- Description of tests to determine the toughness design parameter and the energy release of the rate of toughness, needed for leaking repairs. Essentially this entails pressure testing a series of specimens with flaws of different geometry and then determining the toughness empirically by reference to the relevant Equations.

A key point when considering qualification data is that the achievement of a high toughness should not necessarily be seen as an objective. What is more important is that the value that is used can be replicated with confidence under site conditions. Arguably, a lower value that has with it an associated reduced degree of scatter could be a preferred arrangement. Essentially, if the 95% lower confidence bound is accepted as the data fit curve, then the design curve can be obtained through dividing this data fit curve by the service factor.

4.3 Installation

Inevitably, each repair product will have its own installation requirements. The repair documentation[3] provides guidance for each step of the process and advises on what should be included within an installation manual. The fundamental issue is that the site installation should mirror those processes that were applied in the preparation of samples for qualification testing. This is especially the case for surface preparation as this is the single most important task to be performed. It is also likely that failure to execute this operation correctly is the root cause of many of the examples of disappointing performance. In many respects the challenges of achieving adequate surface preparation are similar to those encountered during painting so they are not unduly onerous. To assist in the achievement of the necessary level of control, the installation document advises on the contents of method statements including the definition of hold points. These include simple on-site tests that are helpful in checking surface preparation. What the document does not specify is what the surface preparation should be or how to achieve it. There is guidance on good practice for given circumstances, but the detail is for the supplier to state following the qualification process. Installer qualification also includes guidance on what constitutes a minimum level of training. This applies where the repair is being executed by local maintenance personnel as, regardless of who is carrying out the repair, they need to be trained.

4.4 Inspection

The Inspection/Non Destructive Test (NDT) document[4] is written as a guidance note as opposed to specification form in recognition of the fact that this area is still in development. In essence, there are three inspection challenges for composite repairs:

- Inspection of the repair laminate;
- Inspection of the interface between the repair and the substrate;
- Inspection of the underlying pipe in service after repair.

Of these, the third is of most concern to the proponents, especially if the pipe is subject to internal corrosion. Indeed, this issue is perhaps the most significant with regard to the potential use of composites for the more demanding applications. For hydrocarbon service, the ability to inspect the status of the pipe, post repair, is a prerequisite.

The document provides information on the aspects of the inspection issue related to allowable defects and the inspection methods that can be used. In reality, the inspection of the repair laminate itself is of limited value and the main means of assuring quality is to employ effective process control during application. This is similar to the practice adopted for the construction of composite process equipment.

For detection of defects within the substrate, electromagnetic techniques are currently used. They are able to see through both carbon and glass based composites and therefore the repair does not need to be removed. Both low frequency and pulsed eddy current techniques have been successfully used.

For the detection of delamination within the interface, currently no techniques are used. However, laser shearography is one potential method which may offer some chance of success. The technique measures the surface deflection of the laminate. For the detection of defects within the composite laminate, visual inspection is the best available technique at present.

5. Generic issues

5.1 Repair classification

At the outset of a repair activity, a risk assessment is carried out to determine the details of the design route to be taken as well as the need for appropriate supporting technical documentation. The risk assessment will also determine the safety margin or safety factor to be used in the design. Following completion of the risk assessment, any specific repair is then allocated to a particular class. There are basically five Repair Classes illustrated in Table 2 and they are defined as follows:

- Class 1: Repairs that are intended to include those remedial actions where the service conditions are not onerous and the risks associated with the system do not impinge directly on personnel safety or plant integrity.
- Class 2: Repairs that cover pressure ratings up to 20 bar and are appropriate to the majority of the utility service systems on any offshore facility. This Class is intended for those systems that do not relate directly to personnel safety.
- Class 3: Repairs that cover similar operating conditions as Class 2, but this designation is intended to cover those systems that have specific safety related functions.
- Class 4: Repairs that cover pressure ratings up to 50 bar. This Class is appropriate for many of the systems transporting produced fluids on an offshore facility. Hazards for these systems derive primarily from the

Table 2. Repair Classification.

Repair Class	Typical Service	Pressure	Temperature
Class 1	Low specification duties, e.g. static head, drains	Up to 5 bar	-20℃ to 40℃
Class 2	Cooling medium, sea (service) water, utility hydrocarbons	Up to 20 bar (150 pressure class)	-20℃ to 100℃
Class 3	Fire water/deluge systems	Up to 20 bar	-20℃ to 100℃
Class 4	Produced water and hydrocarbons, flammable fluids, gas systems	Up to 50 bar (300 pressure class)	-20℃ to 100℃
Class 5	Intended to cover operating conditions more onerous than Class 4		

nature of the fluids they convey.

- Class 5: Repairs that cover applications not included in the above.

The derivation of the definitions for the repair classes involves the consideration of typical repair situations and the repair options currently available. The intention is to ensure that these procedure allow the use of simple repair procedures and techniques for straightforward scenarios (Class 1), whilst establishing a means of increasing the level of conservatism for the higher risk duties (Classes 2 to 5). The selection of Class is governed by the risk level of the intended repair job.

The definitions for Class 1 to 5 cover the majority of composite repairs carried out at the present time. It is not intended that the data presented in Table 1 should preclude the use of composites for other duties. For the more onerous applications (Class 5), detailed deliberation between the owner/user and supplier is mandatory.

5.2 Repair type

Repair materials that are commercially available fall into two generic types denoted as Type A (pre-packed) and Type B (designed or engineered). Broadly, the principles governing the installation of Type A and Type B are similar and the documented procedures[2)-4)] are appropriate to both types, although the timing of certain of the qualification and design activities may vary. It must be emphasized, however, that training and qualification of any personnel carrying out repairs is a pre-requisite for the success of composite overwrap repairs.

Type A represents those repair systems that are supplied in a pre-packed form and are often held as a stock item and the intent is for them to be applied by maintenance personnel on the facility.

As indicated in the timelines for Type A repair, the material suppliers will need to provide design details prior to the identification of individual repair situations. The general issues at stake are as follows:[2)-4)]

- Materials of construction;
- Applicable service conditions;
- Use for temporary or permanent applications;
- Tabular/graphical presentation of repair details, e.g. data relating to defect/pressure/ thickness envelopes;
- Specific installation guidance;
- Specific inspection guidance.

Type B repairs, detailed design is carried out in response to specific enquiries and the details would normally be presented in the form of a design document containing the necessary calculations. At the present time, it is the norm for repairs of Type B to be applied by the suppliers of the repair systems or by specialist contractors.

The fact that this type of repair is procured and designed on an on demand basis means that this is an appropriate route for many cases. The aspirations of proponents, however, are for these repair systems to become increasingly available for application by local personnel so that a wider range of repairs may be carried out without the need for the mobilization of additional resources.

5.3 Repair lifetime

Repairs are denoted as temporary or permanent and this designation may have an effect on design, materials of construction (including surface preparation) and documentation requirements. Temporary is intended to denote those situations where the repair is required to survive for a limited period, after which it shall be replaced. Each case should be the subject of an individual assessment, but in any event the repair lifetime should be limited to a period of less than 2 years. Typical of these applications will be those where immediate repair action is necessary and the pipe will be assessed further at the next scheduled inspection interval, shut down, or Testing & Inspection (T&I) period.

Permanent is intended to denote those situations where the repair is required to reinstate the pipe to its original design lifetime or to extend its design life for a specified period. The effect of the temporary/permanent designation manifests itself primarily in the qualification procedures and design factors adopted. In the context of installation, it is important that the repair method as qualified is applied with the same degree of attention regardless of whether it is temporary or permanent

6. Summary

This report has described a suite of documentation that covers the design, installation and inspection of composite repair methods for pipework systems and pipelines. The benefits of the work are that it provides a framework that allows Saudi Aramco facilities to select the composite repair option with confidence. In addition the establishment of an accepted approach to material qualification gives suppliers a firm basis on which to invest in material testing and product development program. Together, these points represent the necessary next steps in taking composite repair products forward so that they can realize their potential and use within Saudi Aramco facilities.

The most important element in composite repair is surface preparation, and failure to execute this task correctly will lead to a reduced level of performance irrespective of other issues such as the quality of the mechanical design of the repair laminate itself. As such, it is important that installation instructions are followed rigorously.

Acknowledgements

The author wishes to express his appreciation to the following Saudi Aramco members of the consortium that participated in conducting this study O. Olabisi, M. S. Mehdi, G. M. Fallatah, A. Y. Asiri, N. I. Al-Nasri and S. Frost, from UK.

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