Testing of composite repairs according to ISO and ASME standards and beyond

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ABSTRACT

MAINTAINING PIPELINES IS A top priority for every operator to ensure safety, efficiency and sustainability. Composite wrap repairs are an alternative repair method which is less expensive and less time-consuming, but which enables an extension in lifetime of up to 20 years. It is particularly suitable for live repairs to avoid unplanned shutdowns. Although it has been used in the field for more than two decades and is described in the standards ISO 24817 and ASME PCC-2, the technology is still not always applied, or even considered as a solution in situations where it would be of advantage.

Based on its expertise in adhesive technology, Henkel Loctite has developed a composite repair system, which meets the standards ISO 24817 and ASME PCC-2. Furthermore, in order to increase the level of confidence, the Loctite composite-repair system for pipes underwent several years of certification processes defined and fully audited by independent inspection authorities, namely DNV GL, Lloyd’s Register, and TUEV Rheinland. Henkel operates with its standard repair system up to 80°C and with a newly developed high-temperature system up to 130°C. Both these systems have been approved and certified according to the standards.

In addition to the testing programme required by ISO and ASME, a range of further experimental investigations, exceeding the requirements of the repair standards, has been carried out to show the performance and robustness achievable by composite repairs. Important topics covered include tests on cyclic pressure loads, the fatigue strength of the composite, and permeation resistance vs gaseous hydrocarbons. Furthermore, a FE model has been developed that specifically enables the design of repair cases, which are not usually described in detail by the repair standards, like the repair of dents. The combination of these methods clarifies further details and improves our understanding of composite repair reliability.

1. Introduction

Maintaining pipelines is a top priority for every operator in the oil and gas industry to ensure safety, efficiency, and sustainably. By this time, there are approx. 3.5 million km of pipelines on the planet constantly exposed to the combined corrosive effects of climate factors, mechanical stress, and chemical attack [1,2], which might be added possible initial material and construction defects, consequences of ground movement, as well as third-party damage.

Estimations consider most - at least more than 60% - of existing pipelines to be older than
45 years [3, 4]. Already in 2002 according to the large-scale two-year study Corrosion costs and preventive strategies in the United States the annual costs alone in the US was estimated to approx. $7 billion dollars to monitor, replace, and maintain gas and liquid transmission pipelines [5]. Subsequently operators habitually have to deal with performance losses respectively even more avoiding them.

In the past, it was common practice to remove the complete pipe or the affected sections of pipework and replace it completely [6]. Besides material and labour for the removal and welding works, this leads above all to significant costs generated by taking the pipeline out of service. Therefore, it is essential for operators to keep such downtime to a minimum.

By this time, a wide range of rehabilitation techniques is available for both onshore and offshore piping systems. Frequently used repair techniques capable of being carried out under pressure are installing a steel sleeve or a steel clamp either welded or bolted to the outside surface of the pipes [7]. These methods are suitable for straight pipe sections and generally have limited application for complex geometries like joints or bends [6].

The use of welded steel sleeves for pipeline repair was developed during work led by Kiefner et al. in the early 1970s [9, 10, 11]. Two general types of full-encirclement steel sleeves are distinguished between, type A and type B. Type A sleeves consist of two steel half-shells welded longitudinally to create a steel sleeve around the corroded pipe and serve as structural reinforcement only. Type B sleeves are additionally welded in circumferential direction to the carrier pipe, creating a tightly closed outer shell being also able to stop leakages.

Although in-service welding is an established, frequently carried out repair method and its risks are minimized by well-investigated process parameters those risks cannot be avoided completely. Some important concerns are named in regard to the welding process control [12]:

- **HAZ**: Due to the high cooling rate of the weld as a consequence of the medium flow on the pipe’s inner wall the formation of heat-affected zones (HAZ) can be promoted, leading to material properties susceptible to hydrogen cracking and, potentially, sulphide-stress cracking.

- **Burnthrough**: Induced by the weld arc and localized heating the remaining material strength at the inner surface might be insufficient to stand the internal pressure. The resulting wall burst, ‘burnthrough’ or ‘blowout’, typically occurs at a pinhole, allowing the content to escape.

- **Unstable decomposition**: When unsaturated hydrocarbon products (e.g. ethylene) are heated while under pressure, they can exothermically decompose (i.e. explode). For these cases, special precautions must be taken to prevent the inside surface of the pipe from exceeding a critical temperature.

Obviously, the second concern of a wall burst and possible leakage of the content while carrying out welding might involve consequential damages. In general every welding process involves hot work in close range to hydrocarbons and coming with it the potential risk fire and explosion scenarios [6]. Steel-clamp repairs are another alternative for repairing corroded steel pipes, which are generally assembled from two half-shelves via mechanical fastening. Besides structural reinforcement the sealing of leakages is possible. These methods are known to require heavy machinery, which can lead to a difficult process especially in limited workspace such as underground conditions [13].

Composite wrap repairs have emerged as an alternative to pipework replacement and those
traditional repair practices described, without the need of welding or pre-premachined parts. According to industry analysis, composite repairs can be considered to be less expensive and less time-consuming. It was shown that repair using fibre-reinforced polymer (FRP) wraps systems are on average 24% cheaper than welded steel sleeve repairs and 73% cheaper than the complete replacement of the damaged steel pipe section [5].

One important driver for the increased use of composite repairs is the possibility to be carried out on an operating pipeline without taking it out of service – and without hot work. Since the initial industrial research project in the early 1990s by the Gas Research Institute (GRI), they are being constantly developed [13]. Although being used in the field for more than two decades by now and having its technical core described in the well-developed standards ISO 24817 and ASME PCC-2 the technology still is not always applied and often not even considered as a solution where feasible.

2. Technical background

For the assessment of repair methods and their capability by maintenance departments it is crucial to understand the overall relevant technical behaviour under the given circumstances. The term ‘composite repair’ refers to the rehabilitation resp. reinforcement of pressurized metal pipework by adding a hull of FRP as an additional structural component. The joining of the two components is taken out by adhesive bonding, either by bonding composite layers (impregnated and cured in advance) or by impregnating and instantly bonding the technical textiles in a ‘wet-in-wet’ process.

Additionally, due to the enclosed cross-section geometry of the FRP and the pipe, the mechanism of mechanical interlocking is created.

The overall design is a hybrid structure, combined of different materials on a macroscale level. The FRP itself consists - as per definition a ‘composite’ - of multiple components combined to an anisotropic structure on a microscale level. The given situation implies from an engineering point of view a range of technical properties and correlations, the most relevant for an epoxy-based wet-in-wet system are shown in Fig.1. For reasons of clarity not everything is shown.
2.1. Technical textile

The technical textiles like E-glass or carbon-fibres of different types are the most prominent and obvious components of the repair system. They are also the main influence for the mechanical properties of the overall FRP composite part like strength and stiffness. Furthermore, due to their mechanical dominance, they also dictate the range of the thermal expansion. As pipes are in most cases exposed to temperature cycles, the coefficient of thermal expansion, and especially its difference vs the substrate, are of interest because of the potential thermal stresses induced, often referred to as the topic of delta or CTE mismatch.

2.2. Polymer matrix

The polymer of a ‘wet-in-wet’ system works in two ways for the integrity of the repair. First of all, it is used as the composite matrix to keep the fibres in position, support and protect them. The main loads transmitted by the matrix are part-internally between the fibres and externally for non-fibre-directions like transverse forces, between laminate layers as well as shear and compression. Furthermore, the polymer is responsible for the long-term tightness of the overall repair - in case of leakage obviously vs the pipe content - but as well in the other direction vs humidity and oxygen penetration and permeation to protect the bondline. Often epoxy systems are used due to the high chemical and thermal resistance achievable.

2.3. Adhesive layer and interface

Another main function taken by the polymer is to create the adhesive joint, more precisely both the adhesive bulk layer and the adhesive interface vs the substrate. The joining of FRP parts, especially with metals such as steel, is one of the most challenging topics in FRP composite technologies and therefore, for some years, has been the focus international research efforts [among others, Refs 15-21].

The main reasons for the technological challenges of the joint are [22, 23]:

• dissimilar materials (e.g. thermal expansion, melt points)
• high-strength, concentrated loads within the fibres and limited (re)formability
• material-adapted load introduction (fibre joint, low strength in resin-rich layer)
• additional corrosion effects (high differences in electrochemical potential)
• surface conditions (e.g. risk of mitigating polymer contents, residues of release agents)

For the repair of pipes with a wet-in-wet system, the creation of the FRP structure and of the joint are made in one and the same process step, sometimes referred to as the technologies of ‘intrinsic joining’ or also ‘co-curing’ in the aerospace industry [24, 25]. A major advantage of this process is the homogenous material transition of matrix to adhesive zone and, thus, that only one adhesive interface exists, which is usually a hot-spot in terms of performance, quality control, and for environmental exposure.

2.4. Filler system

The purpose of the filler is in first place to fill-up the pipe wall where there is reduced wall thickness so that fibres can be positioned without performance losses in regard to the introduction of load complexes. Secondly, the loads must be transmitted from the damaged steel zone while allowing as little steel deformation as possible. Thus, the compression strength, and especially compression modulus, of the filler are most relevant properties, giving consideration also to elevated temperatures.
2.5. Steel substrate

Both major repair codes for composite repairs, the ASME PCC-2 (Scope, 1.1) and the ISO 24817 (Definitions, 3.39) define the term ‘repair system’ to comprise among others the substrate [26, 27]. The steel substrate is to be considered a part of the repair system because of the interconnection and interference on the overall mechanical behaviour of the hybrid cross section and the importance of the chemical and topographic condition of the surface for the development of intermolecular covalent forces within the adhesive interface.

<table>
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<th>Chapter (ISO/ ASME)</th>
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</tr>
<tr>
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<td>3.4.10.4</td>
</tr>
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<td>ASME Table 1</td>
</tr>
</tbody>
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3. Testing and engineering

The assessment of the overall technical performance and design guidelines has been driven during the last decades, and the successive editions of ISO 24817 and the chapter 4.1 (and 4.2) of the ASME PCC-2 are significant milestones of the development of engineering models and design rules, as well as the setting-up of testing procedures for composite repairs. The fundamental targets of the design are to ensure that strains in the repaired steel section, on the one hand, and in the composite reinforcement, on the other hand, do not reach unacceptable
levels, under all given circumstances and during the designated repair lifetime. In Table 1 an overview is given regarding the explicit test methods of the two repair standards.

Based on its expertise in both general polymer and specifically adhesive and sealing technology, Henkel Loctite developed a composite repair system qualified according to ISO 24817 and ASME PCC-2 codes. Furthermore, in order to increase the level of confidence and reliability the Loctite composite-repair system had to undergo several years of qualification and certification process. The testing programme covered both the ISO and the ASME standards and all required tests were audited by inspection authorities, namely DNV GL (former Det Norske Veritas and Germanischer Lloyd), Lloyd’s Register, and TUEV Rheinland.

On the one hand, the level of confidence and trust towards third parties is enhanced by auditing and approval of inspection authorities. On the other hand, the extensive co-operation and the ongoing input of independent expert groups during the years of development and qualification led to a range of insights in regard to the details of the codes and the requirements for testing procedures. Based on the discussion, some requirements and comments were added for the test programme and a range of additional tests was carried out.

3.1. Composite material properties

A basic, nevertheless essential, requirement refers in first place, but not exclusively, to the coupon tests dictated by the two codes to evaluate the material properties of the composite. Fibre-reinforced components - their quality, performance, the ratio of fibres and polymer resin - are strongly influenced by the way they are manufactured. For laboratory analysis it is in general preferred and common practice to achieve a reproducible outcome, for example by using a hot press or autoclave, etc., and set the final thickness of the specimen via the machine control.

In general all properties of the composite strongly depend on the fibre-volume ratio, especially the stiffness, strength, thermal expansion, humidity absorption, and the long-term behaviour. Consequently the fibre-volume ratio (also known as the fibre-volume fraction, sometime also given in mass ratios) is a major parameter to describe a composite and is generally in FRP technology strongly advised to be documented for every experiment carried out [22].

To give an example for clarification of the impact of different processing methods: this value can be increased for a given textile-matrix-combination between approx. 20% -30% for a hand-laminated composite up to 80% by adding the process step of vacuum bagging afterwards [25, 26].

The large part of loads is taken by the fibres and properties like strength and stiffness moduli are always standardized, i.e. referenced to the full cross-section area including the polymer part. Thus at the same time the structural material properties increase by a comparable factor as the fibre-volume-ratio changes, see also Fig.2:

• in first place because of less ‘waste matrix material’ in regard to the overall strength and stiffness and by reaching similar force levels with less cross-sectional area;
• secondly because of the increasing uniformity of fibre distribution and orientation coming along with higher fibre-volume fractions [22].

Both standards require generally the repair laminate to be ‘the same’ within the qualification tests, but neither refer to the impregnation and consolidation process despite its strong importance for the results. Nor do they refer to the fibre-volume fraction as a significant material parameter in terms of documentation and also quality control - although the thickness measured might help to reconstruct and compare in general [25, 26].
Thus, one focus point set jointly with the inspection authorities for the certification process of the Loctite composite-repair system was the method to manufacture the specimens to be kept absolutely the same as in a field process. The fibre-volume ratio was measured and documented accompanying the tests and is furthermore given as a reference for quality control in field applications.

It is a suggestion for future revisions of the codes to add stronger guidelines in regard to the manufacturing method of all specimens, and to control and document the outcome in terms of the fibre-volume fraction.

3.2. Gas permeation

The repair of pipework containing gaseous hydrocarbons is part of the scope of both repair codes and through-wall, leaking defects. For liquid media in general it might be sufficient to measure the burst-pressure performance and conclude, up to a certain confidence level, ideal leak-tightness.

In regard to contents in gaseous condition, though, the gas traverse through the layers of a polymer-based composite should be considered. Especially for gases of small molecule weight, the diffusion rate might be at a significant level either for material losses or for risks because of uncontained hazardous substances.

Thus, the permeation resistance of the Loctite composite-repair system vs relevant small molecule weight gas was determined in a series of tests in addition to the codes’ requirements. The results had to meet a range of limits from the field of gas pipe works, and were found to deliver satisfying results for the according codes of practice and regulations to prove the applicability for gas piping systems.

3.3. Cyclic loading

The topic of cyclic loading is covered by both standards via sophisticated design rules, which take into account standardized de-rating factors for the allowable strain of the composite, independent of the number of cycles and the ratio of upper and lower pressure [25, 26]. In regard to the assessment of the specific performance of a certain repair system there is no explicit testing programme included in ISO 24817, while ASME PCC-2 gives two reference for testing: in first place it is refers to ISO 24817 (where the reason is not clear), and secondly ISO 14692 for glass-reinforced plastic (GRP) piping.

The design factors of ISO 24817 are largely based on the design rules of ISO 14692 in regard to cyclic loading, i.e. on de-rating factors for the fatigue behaviour of GRP pipes. ASME gives different formulas, but as well for the de-rating the allowable strain of the composite.

Thus, both standards base the assessment of fatigue degradation solely on the composite behaviour in a standardized way - without a material-specific test base. As the adhesive bond
is a crucial, functional, element of the repair system, it seems critical to completely keep it out of sight. Especially for repairs of leaking components, the adhesive bond is clearly of major importance and directly exposed to any cycles loading via internal pressure variations.

In one conclusion it was decided to carry out fatigue tests in regard to the fatigue behaviour of the specific composite of the Loctite system - manufactured according to the field-hand lamination process (see also the section on composite material properties). The test was carried out according to ISO 14125, see Table 2.

The result of 2,000,000 cycles passed at a very conservative maximum deformation of 2.5 mm showed a high fatigue performance for the composite - as property of the material alone.

In regard to the overall performance of the repair system under inclusion of the adhesive bond, it was decided also to carry out cyclic pressure-fatigue tests on the complete Loctite repair system under real conditions. Besides other tests, including the structural reinforcement of type A repairs, tests were carried out on type B leakage defects. The test parameters and results are given in Table 3.

In regard to the fatigue behaviour - and essentially the adhesive bond in this case - a decent robustness and reliability of the Loctite repair system could be shown and also proven to certification authority.

3.4. Temperature performance

As a major point the performance of repair systems and the assessment of the same, especially at elevated temperature, will now be discussed, as the dependency of polymer’s behaviour on temperature is a complex topic.

3.4.1. Glass-transition temperature measurement

Both codes require the measurement of the glass-transition temperature (Tg), or the ‘heat-deflection temperature’ (HDT), in order to define the maximum application temperature of the repair system. The values are reduced in dependency on the kind of defect and service parameters.

The HDT is in generally accepted to be related to mechanical properties, and the glass-transition
The temperature may be a quite close value [28]. The Tg is allowed to be measured by the most common methods via differential scanning calorimetry (DSC) or thermomechanical analysis (TMA). While all these methods are accepted to characterize the temperature behaviour of polymers, values might differ as much as by more than 30°C [29].

From the methods named above to determine the Tg, the DMA is typically accepted as the most sensitive way to measure subtle transitions in polymer’s characteristics [30]. In regard to the background of composite-pipe repairs, it is described that the Tg of highly cross-linked thermoset resins are often only measurable by DMA, because DSC and TMA may not be sensitive enough [31]. Furthermore, it has to be said that a DSC won’t give any empirical insight in regard to the mechanical performance of a certain system. Goertzen and Kessler have already discussed the use of DMA for the assessment of composite repair systems for pipes and have shown the feasibility [32].

Considering this background, the DMA method was chosen for the certification of the Loctite composite-repair system. It should be pointed out that even with the measurement method fixed, a range of parameters can be chosen. The test parameters, such as heating rate and frequency, will

### Table 3. Cyclic fatigue-pressure test series, type B

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Pipe diameter</td>
<td>150 mm</td>
</tr>
<tr>
<td>Pipe wall thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Defect type</td>
<td>Through wall defect (“Type B”), hole diameter 10 mm</td>
</tr>
<tr>
<td>Cycling load</td>
<td>Full load cycles (w. medium water)</td>
</tr>
<tr>
<td></td>
<td>Upper pressure limit 113 bar</td>
</tr>
<tr>
<td></td>
<td>Lower pressure limit 0 bar (0 - 10 bar due to system regulation)</td>
</tr>
<tr>
<td>Pressure Frequency</td>
<td>Approx. 10 min</td>
</tr>
<tr>
<td>Repair design</td>
<td>Specimens were designed only for static pressure</td>
</tr>
<tr>
<td></td>
<td>Repair was calculated for no cyclic load at all</td>
</tr>
<tr>
<td>Approval Requirement</td>
<td>7,000 cycles</td>
</tr>
<tr>
<td>All type B specimens passed</td>
<td><strong>minimum</strong></td>
</tr>
<tr>
<td></td>
<td>&gt; 70,000 cycles</td>
</tr>
</tbody>
</table>

### Table 4. DMA measurement: Tg vs frequency and heating rate

<table>
<thead>
<tr>
<th>Tg (°C)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freq. (Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.316</td>
<td>62.0</td>
<td>58.2</td>
<td>60.3</td>
<td>57.1</td>
</tr>
<tr>
<td>1.00</td>
<td>65.2</td>
<td>61.0</td>
<td>63.2</td>
<td>59.9</td>
</tr>
<tr>
<td>3.160</td>
<td>68.9</td>
<td>64.5</td>
<td>66.5</td>
<td>62.8</td>
</tr>
<tr>
<td>10.00</td>
<td>73.0</td>
<td>68.0</td>
<td>70.5</td>
<td>66.0</td>
</tr>
<tr>
<td>31.60</td>
<td>77.7</td>
<td>72.3</td>
<td>74.4</td>
<td>69.9</td>
</tr>
</tbody>
</table>
change the Tg measurement within the same DMA set-up: increasing frequencies and heating rates will shift the measured value of Tg upwards [30, 33-35]. Therefore, it is recommended to keep these parameters in a rather conservative range not to overestimate the Tg. Table 1 shows as an example an overview of comparison tests carried out [32].

3.4.2. System testing at elevated temperatures

While the ASME PCC-2 requires qualification tests to be carried out at the “maximum temperature at which the repair system is to be used in service”, ISO defines a “qualification test temperature” and dictated how to calculate two de-rating factors in regard to higher temperatures. An example is the ISO’s Annex E and ASME’s Appendix V for the optional measurement of “performance test data” to determine the design values of allowable the long-term strain and the long-term strength of the composite [26, 27]. The performance of the repair system is de-rated per design rules according to the design temperature (the service temperature of the application) in comparison to the maximum temperature of the repair system.

This opens-up the possibility of testing and qualifying composite repair systems at lower temperatures than the real application temperature.

At this point it has to be highlighted that polymers exhibit a complex mechanical behaviour dominated by their viscoelasticity in regard to further influences like the deformation condition and deformation rates, relaxation as well as other time-related parameters. The overall mechanical response of polymeric structure during loading is temperature- and time-dependent in close relationship to the real load complex [36].

It is therefore strongly advised to also consider the temperature-related characteristics of those other polymeric materials crucible for the functionality of the repair system. While still having an indication for the matrix resin in regard to the polymer’s resistance vs heat, there is no link for the adhesive (if different from matrix) nor for the filler system, which might also be of polymeric nature, as well.

The filler has to exhibit high compression performance at the same temperature as the matrix resin, and mostly under a constant long-term load. Static loads on polymers always involve the topic of creep; the combination of static loads and elevated temperatures the viscoelastic nature might lead to higher deformation than expected. While ASME requires the filler’s modulus to be tested without a reference to temperature, ISO does not require the determination of filler properties at all.

As a consequence, it was decided to carry out all tests related to the qualification test temperature of ISO 24817 at the overall maximum application temperature of the Loctite repair system. In regard to the example of the long-term performance tests (Annex E resp. the Appendix V) pipe specimens were pressurized and kept at elevated temperatures for 1000 hours:

- at 80°C for the Loctite standard repair system; and
- at 130°C for the recently introduced Loctite high-temperature repair system.

4. Conclusion

The composite-wrap repair technology merged from two ‘novel’ (or at least considered to be novel) technological fields at once: fibre-reinforced polymers and adhesive technology. While, traditionally, metals are used in construction and the design paths are well-known and accepted, new approaches first have to overcome doubts. In order to increase the confidence in reliability and long-term durability, it is crucial to assess the technical behaviour.
As the topic of composite repair involves multiple sub-topics, each of some complexity, the overall technical assessment of the multi-material system under a range of load scenarios is highly challenging. Therefore it is a required further to develop the testing and design methodology as described in ASME PCC-2 and ISO 24817 permanently, and to extend them iteratively.

Additionally to the testing procedure according to the both repair standards, the certification process of the Loctite composite-repair system was defined by the inspection authorities to include a range of further experimental investigations. These are not covered by the codes at this time, but are worth considering.

Conflicts of interest

The author has no conflicts of interest to declare.

References


