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DELIVERING A COMPLIANT COMPOSITE SOLUTION IN A NONCOMPLIANT SITUATION

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Summary:

This paper discusses about two-part composite systems consisting of thermoset epoxy resins reinforced by carbon and glass fiber for applications onto pipeline, pipework, piping systems, and vessels in pressurized service. The document presents details related to qualification and testing of such systems in compliance with internationally accepted standards. It also covers key components of a composite repair from the application standpoint and describes what is required to deliver a compliant solution from inception to final inspection.

1 INTRODUCTION

Composite repairs have been gaining greater acceptance among asset owners and equipment operators not only because these repairs provide an engineered, durable, and affordable solution but also because they comply with international engineering standards. Two-part component composite repair systems are typically composed of resin material and reinforcement sheet and can be designed for application onto pipeline, pipework, and pressurized vessels.

Pipeline is the pipe or components, including bends, flanges, valves, and reducers among others, used to transport fluids between plants. Hence, pipelines are generally long and of larger diameters. Piping is the pipe or plurality of pipes, joints, valves, gaskets, fittings, etc., used for transporting fluids within a plant, and they can be above or below ground. Other pieces of equipment where two-part component composite repairs can be used include pressurized vessels and tanks, and/or some of their components such as saddles, main body connections, supports, nozzles, and tees among others.

As the composite repair system must form a bond with the substrate to be repaired, it relies upon the adhesive quality of the resin for its strength. Epoxy based resins can be used as base material for two-component composite repairs based upon their excellent adhesion, mechanical properties, and erosion-corrosion resistance when compared to other nonmetallic systems such as polyurethane, methacrylate, alkyd, vinyl, and polyester-based resins. The resin can also be used for wetting the reinforcing sheet with the intention of eliminating wicking / capillary failure modes along the fiber strands of the reinforcing sheet.

The reinforcement sheet will provide strength to the repair and hoop strength where required. These sheets are typically made of carbon, glass fibers, or a combination of both. Carbon reinforcement sheets are costly, more rigid, and difficult to cut, design, and apply in comparison with glass fiber reinforcement. A combination of glass fiber and carbon reinforcement though provides mechanical strength whilst delivering a certain degree of flexibility for better long term thermal cycling performance.

2 STANDARDS

As aforementioned, the growth in acceptance and usage of composite repair systems is inherently related to the availability of standardizing documentation. Two of these standards, ASME PCC-2 and ISO /TS 24817, are detailed as follows:

- *ASME PCC-2 "Repair of Pressure Equipment and Piping" (ASME PCC-2)*

Article 4.1 of this standard provides the requirements for the repair of pipework and pipelines using a qualified nonmetallic repair system. It defines repair systems as those fabricated of a thermoset resin used in conjunction with glass or carbon fiber reinforcement among other allowed materials. Likewise, it provides guidance in assessing defects stemming from external corrosion involving structural integrity damage or not, internal corrosion, and leaks. Furthermore, it covers all the methodology to follow for designing such repair systems, along with some other design considerations such as external loads, cycling loading, fire performance, electrical conductivity, cathodic disbondment, and environmental compatibility [1].

- *ISO/TS 24817 "Petroleum, Petrochemical and Natural Gas Industries- Composite Repairs for Pipework- Qualification and Design, Installation, Testing and Inspection" (ISO 24817)*

This standard displays all the requirements and recommendations for the qualification, design, installation, testing, and inspection of external applications of composite repairs to pipework suffering from corrosion or other source of damage, most commonly presented in the oil and gas industry. This standard defines composite repair laminates as those with carbon, glass, polyester, or any other similar sort of reinforcement material in a polyester, vinyl ester, epoxy, or polyurethane matrix. The standard also provides mathematical guidance in assessing external and internal corrosion problems with or without structural integrity damage [2].

While both standards supply extensive information and guidance on how to design, apply, test, and inspect composite repairs systems, there are certain differences in calculation engines and considerations. ISO/TS 24817 Standard for instance, allows for the design of repairs onto more complex geometries such as damaged clamped surfaces, bends, T-shaped piping, reducers, flanges, and cylindrical vessels among others. ASME, on the other hand, does not explicitly consider the repair expected lifetime in the design equations.

3 COMPOSITE SYSTEM QUALIFICATION

The system to be qualified consisted of fluid grade epoxy resin and a reinforcement sheet in compliance with the definition of composite laminates/repairs provided by ASME PCC 2 and ISO 24817 standards. Resins were engineered to be a two-component polymeric 100% solids system consisting of an epoxy phenol Novolac base and an amine solidifier. Such a combination provided superior adhesion and mechanical strength when compared to other functional polymeric groups such as polyurethane, methacrylate, alkyd, vinyl, and polyesters. Epoxy phenol Novolac resins also form highly cross-linked matrices that display high temperature and chemical resistance.

As epoxy-based resins tend to cure slowly or very quickly at low and high temperature levels respectively, two types of resins were designed as shown in Table 1. The use of two types of resin facilitates application of the composite system in different environmental conditions.

1. Low Temperature Resin (LT): This resin was engineered for applications at ambient temperature levels above 5ºC with quicker cure rates than traditional epoxy-based systems. LT reinforced resin, for instance, cures in 48 hours for full service if applied at 5ºC. LT resins are recommended for equipment working at temperature levels up to 60ºC.

2. Higher Temperature Resin (HT): This resin was engineered for applications at ambient temperature levels above 20ºC with extended working life. HT resins, for instance, display working lifetimes up to 25 min at 40ºC. HT resins are recommended for equipment operating at temperature levels up to 80ºC.

Resin Type	Application Temperature Level (ºC)	Maximum Service Temperature (ºC)
Low Temperature (LT)	Above 5	60
Higher Temperature (HT)	Above 20	80

Table 1: Low & Higher Temperature Resins

The selection of the appropriate reinforcement sheet was based on mechanical strength, degree of elasticity, and ease of use (wetting, cutting, and wrapping among others). Several reinforcement fabric types including glass, carbon, polyester, Kevlar, and Dyneema were considered. Polyester was found to be very flexible and of low density but had the lowest tensile strength and modulus of all the aforementioned fibers. Kevlar is a registered trademark for a specific type of aramid synthetic fibers. When Kevlar is spun the resulting fiber has a tensile strength of about 3,620 MPa and a relative density of 1.44 [3]. Kevlar requires specialist cutting tools though and it was found not to be as strong as carbon fibers.

Dyneema has yield strengths as high as 2.4 GPa and specific gravity as low as 0.97 but low compressive strength and is very costly. Carbon has the highest tensile modulus of all above fabric types [4], but it was found to be the least elastic and has poor performance against compression loads. Glass, on the other hand, is easy to cut, transparent, and fairly inexpensive. The transparency of glass fibers would allow for the applicator to readily identify those fabric areas with insufficient resin, but glass was found to have the lowest tensile strength and modulus when compared to Kevnar fibers.

After carefully considering the benefits and drawbacks of each fabric, it was decided to use a hybrid of carbon and glass reinforcement fibers woven together. The percentage by weight and orientation of the glass/carbon weave must be designed to maximize the benefits of each fiber type, combining physical and mechanical properties with application ease. Furthermore, the reinforcement sheet would be available in three different sizes to facilitate application for the repair of piping elements exhibiting complex geometries such as tees, flanges, and reducers among others. By using this reinforcement sheet in conjunction with HLT and HT resins, it was expected to yield an optimized balance of mechanical strength, optimum adhesion, and flexibility.

As such systems required to be qualified for compliant application onto pipework, a rigorous series of external and in-house tests were carried against ISO, EN, and ASTM standards. For some tests, composite slabs were prepared using LT and HT resins reinforced with three wraps of resin-wetted reinforcement. For others, actual Carbon steel spools of known dimensions and specific defects were repaired in accordance to ISO 24817 requirements. Testing details are summarized below.

Property	Details	Test Methods
Tensile Properties	Tensile Strength, Tensile Modulus, Poisson’s Ratio, Strain to Failure	ASTM D3039 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
Thermal Expansion	Coefficient of Thermal Expansion	ISO 11359 – Plastics – Thermomechanical Analysis
Material Glass Transition	Glass Transition Temperature of resin	ISO 11357-2 – Plastics – Differential scanning calorimetry– Determination of-glass transition temperature and glass transition step height
Lap Shear Adhesion Strength	Shear strength of resin bonded to substrate	EN 1465 – Lap Shear Strength, Adhesives, Rigid to Rigid Bonded Assemblies
Structural Integrity	Wrapped pipe with defect to survive short-term pressure test	ISO 24817 – Annex C Short-term Pipe Spool Survival Test
Impact Performance	Low velocity 5 J impact performance	ISO 24817 – Annex F – Measurement of impact performance
In-Plane Shear Modulus	Shear Modulus by V-Notched Beam Method	ASTM D 5379 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
Energy Release Rate	Toughness parameter for the repair/substrate interface	ISO 24817 – Annex D -Measurement of γ_{LCL} for through-wall defect calculation
Long-Term Strength	Long-term (creep rupture) strength of the composite repair	ISO 14692 – Annex E – Measurement of performance test data
Long-Term Lap Shear Performance	Measurement of lap shear adhesion strength of resin after 1000 hours of heat exposure (at 40ºC)	EN 1465 – Lap Shear Strength, Adhesives, Rigid to Rigid Bonded Assemblies

Table 2: Testing Details

Several results worth mentioning are displayed as follows:

Measured Properties	**LT Reinforced Resin**	**HT Reinforced Resin**
Poisson's Ratio	0.26	0.26
Tensile Modulus (MPa)	38,800	38,600
Thermal Expansion Coefficient (mm/mm°C)	0.00000944	0.00001126
Lap Shear Strength (MPa)	15.5	15.0
Energy Release Rate (J/m^2)	68.57	76.53

Table 3: Testing Results

Poisson's ratio is the negative ratio of transverse to axial strain derived when a material is compressed in one direction and as a result, it expands in the other two perpendicular directions to the original load direction. Poisson's effect has a considerable influence in pipeline systems under pressure. Internally generated circumferential stresses tend to cause the pipe to slightly increase in diameter while becoming shorter. Hence, any composite repair used to restore mechanical strength to a pressurized pipe system must be able to cope with these stresses in the same or similar to the pipe itself. Reported Poisson's values for the two-component resin/glass-carbon reinforcement composite systems were close to Carbon steel's Poisson's ratio, commonly calculated in the 0.27-0.3 range [5]. This means that such a composite repair will react similarly to the Carbon steel substrate onto which it is applied upon compression or tension loads.

Tensile or Young's Modulus is a measure of the stiffness of a certain material. Reported Young's Modulus for the two-component resin/glass-carbon reinforcement composite system is a high value, implying that the repair will retain an extremely high level of stiffness and bending moments. Also, experience has shown that elastic modulus of at least 6,895 MPa is a good benchmark for predicting the in situ performance of a composite repair [6].

The thermal expansion coefficient in solid materials describes how the size of a material changes with a change in temperature while the pressure is held constant. Thermal stresses cause metals to expand and contract when exposed to high and low temperature levels respectively. Hence, any composite repair used to restore mechanical strength to metallic substrates must be able to cope with thermal stresses in the same or similar way to the substrate itself. Reported coefficients for the two-component resin/glass-carbon reinforcement composite system were very similar to that of steel, approximately 0.00001 mm/mm˚C [5]. This means that the repair and the substrate will expand and contract at a similar rate, minimizing the mechanical stresses to the repair/substrate bond line caused by differential thermal expansion or contraction.

Energy Release Rate is a measure of the toughness of a composite repair and it is related to the amount of energy required to cause failure at the composite repair/substrate bond line when repairing a through wall defect. This value is then used to characterize the adhesion between the composite repair and the substrate. Mathematically, the value is also utilized for determining minimum composite repair thickness required for applications onto through walled substrates.

During short-term pressure survival test, Carbon steel spools with a defect of known dimensions were rebuilt by using a composite repair designed to provide the original yield strength. The yield pressure of the undamaged spool was calculated to be 39.2 MPa. A repair was then engineered to restore the pipe to this original pressure. The repair was applied to specification and the pipe was pressurized up to 39.2 MPa without failure. This demonstrated that the two-part composite repair had performed as designed. Pressure was then increased to determine where a yielding would occur, whether in the repair or in the original pipe. At around 42 MPa, the pipe clearly yielded, outside of the repair area. This is factual evidence that not only had the composite repair returned the pipe to its original strength, but it had also made the defect area stronger than the original pipe section.

4 DELIVERING THE COMPLIANT SOLUTION

All the above properties and survival testing results must be quantitatively provided for the composite systems to be in compliance with ISO and ASTM standards. Not only do these compliant composite repairs rely on a pre-qualified material and pre-defined mathematical design but also on competent application craftsmanship. Hence, once such systems are qualified and calculated, the next question is how to deliver the solution.

Training is the answer. All personnel in charge of the execution, inspection, and design of such repairs shall be properly trained and validated by the composite repair manufacturer. The validation process is addressed to train and certify installers, supervisors, and designers of composite repair systems.

Potential installers and supervisors shall undertake off-job training and initial validation in a training environment, where they will receive theoretical and practical instructions in the installation and supervision of composite repair systems. Installers shall complete a test piece repair that shall then be inspected and destructively hydro- tested to ascertain quantitative data on that application performance. In addition, supervisors will attain full validation on a live application project after a prudent time agreed upon by the composite repair system manufacturer. Each installer is issued a certificate and identification card valid for a period of one year. Installers are expected to provide records of at least ten repairs in any one year after validation to wave recertification. Otherwise, installers will require a revalidation of their competency.

At least one repair system manufacturer also requires that potential designers shall undertake training and validation in a training environment where they will receive theoretical instructions on the design methodology for each defect type and geometry. Designers will be assessed by the composite repair system manufacturer. Installers, supervisors, and designers shall be issued a certificate and identification card by the composite repair system manufacturer.

5 KEY COMPONENTS OF COMPOSITE REPAIR

The repair flow diagram typically consists of three main components represented as follows:

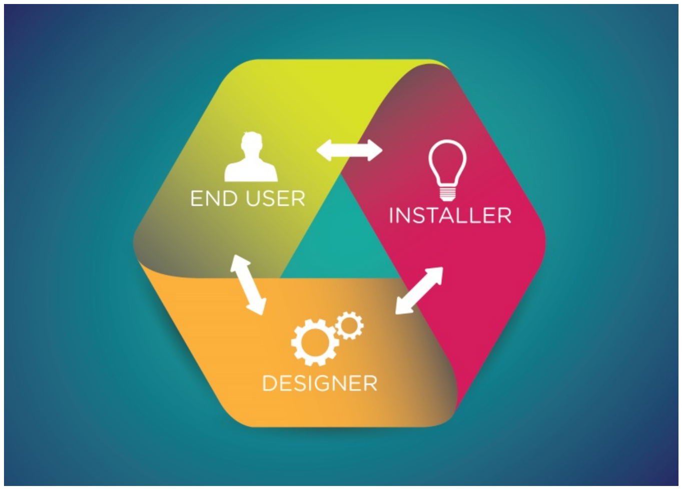

Figure 1: Key Components of Composite Repair

Once the damage is assessed by the end user or client, he or she should contact the composite repair supplier. The composite repair supplier is often the validated application company who contacts an approved design company (Designer) who will in turn submit a design data sheet to the client. This report is intended to collect all the information pertaining to such damage and potential repair and shall be completed by the client. A good communication between the client and the designer is paramount in fully understanding the nature of the problem and possible repair.

The information provided in the design data sheet will be used by the designer to initially confirm the type of repair based upon the nature of the defect and the geometry of the repair. Some of the data to be supplied by the end user and gathered by the designer includes, but is not limited to the following:

- Original equipment design variables consisting of process design and operating conditions, mechanical loads, and a detailed description of the damaged area. Any complementary information such as isometric drawings, pictures, or schematics is deemed necessary.
- Maintenance and operational history including documentation of any significant changes in service conditions, past repairs, and any inspection reports detailing the nature of the area to be repaired.
- Service condition data including expected repair lifetime, required design and operating variables, expected future service conditions, and required time scale for the application.
- End user service detailing all the facilities to be provided by the end user during implementation of the repair.

Composite repairs can be designed for type A and B defects. Type A defects are those within the substrate, not through-wall and not expected to become through-wall within the lifetime of the repair system. This type of repair is considered to be relatively easy as it only requires structural reinforcement. Type B defects, on the other hand, do compromise the structural integrity of the piece of equipment and require through-wall sealing as well as reinforcement. This is why these repairs are considered to be more complex repairs. The geometry of the repair can range from a straight pipe section, bend, tee, flange, or reducer to a cylindrical vessel. The level of complexity in the repair will increase in the same order.

Once the type of defect and geometry of the repair are confirmed, the designer will calculate the repair parameters, thickness of the composite repair, axial extent of the repair, and number of required wraps. The designer shall contact the end user to formally authorize or reject the composite repair application. If the application is authorized, the repair parameters should be shared with the end user. The Installer will be carrying out the application, and as explained earlier, he or she shall possess proper validation issued by the composite repair manufacturer.

Execution is the next step and it is for the installer to carry. It is relatively easy and can deliver a compliant repair to a damaged substrate. An example of a procedure for a compliant solution is detailed as follows.

1. Prior to the application

    a) The materials to be used shall be in their right amounts and in good condition, reinforcement shall be free of contaminants or damage
    b) The environmental conditions, dew point, ambient temperature, substrate temperature, shall be monitored
    c) The application area shall be properly identified as per design
    d) The surface to be repaired shall be prepared as per NACE No. 2/SSPC-SP 10 “Near White Metal” and freed from contaminants as per SSPC-SP 1. Surface angular profile shall be at least 3 mills (75 micron) confirmed by Testex® Replica Tape QA QC measurements as per NACE RP0287.

2. Application should commence as soon as the surface preparation activity has been completed. In the event that the substrate is suffering from metal loss, the original thickness of the substrate can be rebuilt by using compatible epoxy grade paste materials prior to application of the composite system.

3. Once the resin is selected, HD or LT, it is then applied onto the substrate. The resin should be pushed deep into the substrate profile to minimize the risk of air entrapment and in the process, achieve an optimum bond with the substrate. The glass fiber/carbon reinforcement sheet should then be wetted with the same resin.

4. The wetted reinforcement sheet should be wrapped over the first layer of resin maintaining a pre-fixed degree of overlapping throughout the axial extent of the repair. In order to achieve intimate contact between layers, firm hand-pressure should be exerted in every wrap. The angle at which the reinforcement sheet is laid should be alternated in every wrap to make the fabric fibers as multidirectional as possible, hence ensuring that the repair is strong in all directions.

The same procedure should be repeated until the required number of wraps has been achieved. Repair shall be then consolidated by tightly wrapping a release plastic film, ensuring a high quality laminate, with no air entrapment or voids.

5. The system must be allowed to cure and only returned to service after full cure has been achieved.

Tangible evidence of proper application standards shall be provided by the supervisor upon completion of the repair, including but not limited to the following details.

Item	Specifics
Repair Location	Details of the pipe/vessel location where the repair took place
Design	Designed outputs including ▪ Minimum repair thickness ▪ Axial extent of the repair ▪ Required number of reinforcement wraps
Materials	▪ Repair system supplied ▪ Type of resin (LT or HT) and amounts ▪ Batch numbers of all materials used
Repair	▪ Surface preparation procedure, method of application, equipment used, inspection and testing methodology ▪ Environmental conditions including relative humidity, dew point, substrate temperature, ambient temperature ▪ Details of surface preparation procedure, including method of application, equipment used and inspection and testing method; ▪ Mixing ▪ Lay-up reinforcement procedure, orientation of individual layers and overlapping percentage ▪ details of time limitations between stages of the repair, e.g. between surface ▪ Curing schedule
Quality Control	▪ Visual identification of personnel conducting and supervising the repair ▪ Surface preparation records ▪ Visual inspection records ▪ Measurement of actual thickness per wrap application and total thickness ▪ Measurement of actual axial extent ▪ Curing temperature and time ▪ Records of additional testing (hardness, bond strength measurement, cathodic disbondment, fire resistance, NDT results), if carried out
Service Inspection	▪ Details on service inspection internals ▪ Expected repair procedure if premature failure ▪ Actions upon arrival to repair lifetime (extension or revalidation)

Table 4 – Application Documentation Package

6 CONCLUSIONS

1. Two-component composite repair systems allow the asset owner and/or equipment operators to restore weakened and/or damaged metallic substrates by means of an engineered and compliant solution.

2. These systems must be previously qualified against recognized international standards ISO/TS 24817 and ASME PCC-2 for compliance.

3. These repairs are designed to extend the lifetime of piping systems and substitute temporary repairs.

4. Personnel responsible for the design and execution of composite repairs shall be trained by the composite repair system manufacturer.

5. Good communication among all personnel involved in the composite repair process is fundamental in bringing the repair to fruition.

6. Compliant composite repairs are indeed the right solution for extending the lifetime of equipment in an efficient and reliable manner.

REFERENCES

[1] ASME PCC-2 Repair of Pressure Equipment and Piping, 2015.

[2] ISO/TS 24817 Petroleum, petrochemical and natural gas industries-composite repairs for pipework-qualification and design, installation, testing and inspection, 2006.

[3] Quintanilla, J. (1990). Microstructure and properties of random heterogeneous materials: a review of theoretical results", *Polymer engineering and science*: 559–585.

[4] Kopeliovich, Dmitri, *Carbon Fiber Reinforced Polymer Composites.*

[5] The Engineering Toolbox, www.engineeringtoolbox.com

[6] Alexander Chris, Fancini Bob; *State of the Art Assessment of Composite Systems Used to Repair Transmission Pipelines,* Proceeding of IPC 2006, 2006