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Developing a Composite Repair System for High Temperature Pipe Repairs

by

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Abstract

Composite repair systems are routinely being utilized by the refinery and chemical plant industry for the repair and rehabilitation of their piping systems. With many of the lines needing repair being process lines which run at elevated temperatures, new composite repair systems are being developed to meet the demands of the industry to make safe and effective composite repair systems which can handle the continuous high operating temperatures of the piping systems. Numerous industry organizations are now recognizing composite repair systems as a reliable and effective means to mitigate corrosion concerns and keep critical piping systems in production. Since 2006, several industry standards and regulations have been published which help to insure composite repair systems meet the requirements of the operating systems and continue to provide a safe and effective maintenance solution. This paper discusses the testing completed on the practical usage aspects and the various results for one of these high temperature composite repair systems and some comparative samples of other trials during initial development.

Industry Introduction to Composites as Pipe Repair

As early as the mid-1980's, companies were beginning to recognize the tremendous advantages of using composite materials to repair steel pipe. The aging infrastructure of most pipelines and processing plants around the world helped to lead many into exploring these new opportunities for implementing suitable repair technologies, which would allow production to continue during and after the repair procedure. They were also beginning to realize that in order for this to be an effective repair methodology as well as maintaining a safe working environment, it would require much more than a simple "duct tape and bailing wire" wire fix. Initial testing and qualifications were performed by the Gas Research Institute (now Gas Technology Institute) and was focused on the repair of high pressure transmission pipelines. (1)

A very similar requirement is prevalent in the refinery and chemical plant market, but due to the environment, the aggressive nature of chemicals used, and much higher operating temperatures, piping networks suffer from much more severe and frequent wall loss. The operating pressures are not always as high as transmission pipelines, but the chemicals used and the elevated temperatures of some of the process piping accelerate corrosion, both internal and external. In most cases, the wall loss is more severe than is typically allowed in transmission pipelines. Complete wall loss and pinhole leaking is a regular occurrence within many facilities, and in order to repair these types of defects, a composite system must meet the minimum requirements and perform at the expected level under extreme conditions.

With some of the initial testing being complete on the pipeline side of the industry, there was then a precedence to proceed with evaluations of using composite repairs for some of these higher risk repairs within processing plants.

Using Composites for Repairing Corroded or Otherwise Damaged Pipe

The use of composite technologies for repairing steel pipe has gained a large amount of support and acceptance as a viable option for owners/operators. This acceptance has come to fruition as a result of several composite repair system manufacturers completing thorough testing programs to qualify and validate the composite repair systems. Originally much of this work was completed by the manufacturers of the various systems independently as there was no governing standard specific to this type of repair system, as there was for other repair techniques such as welded sleeves, engineered clamps, or simply replacing the damaged section. While this was effective in gaining knowledge of the individual system's characteristics, it was still lacking as a general qualification rule that all plant maintenance teams could utilize as a regulatory standard. In an effort to assist with qualifying and quantifying of composite repairs, the ASME and ISO organizations both introduced standards specifically for the qualification testing, validation, application, inspection, and certification of composites as used in the repair of high risk piping.

The ASME PCC-2 document, containing the article specific to composite repairs (Article 4.1 – Nonmetallic Composite Repair Systems for Piping and Pipework: High Risk Applications) was originally released in 2006. It has since published a revised document in 2008, and is expected to release a new revision in 2010 or early 2011. The ISO/TS 24817 (Technical Specification for Petroleum, petrochemical and natural gas industries — Composite repairs for pipework — Qualification and design, installation, testing and inspection) was also released in 2006. It has not yet released a revision, but is expected to have the first revision publish in 2010 or 2011. Each of these documents outlines all requirements for a composite system to be qualified, as well as the installation technician to be properly trained and certified, in great detail. These documents have allowed plant maintenance departments all over the world to have a defined industry guideline on which to base their decisions and, in essence, judge whether a composite repair system has been properly tested and validated as suitable for their piping networks.

The testing requirements for a composite repair system in the ASME PCC-2 document are summarized in Table 1 included in Article 4.1. (2)(Figure 1) These are the general requirement that each composite system must complete in order to be considered for use on pipes which are operating under high risk circumstances. However, this is simply the minimum, and in order to fully understand how a composite system will withstand the intended use, additional testing should be done to fully validate the operating characteristics.

Justification for Development

With regards to composite repair systems being utilized on high temperature piping, of great concern is degradation of tensile strength and lap shear bonding to the pipe surface. While most epoxies perform admirably under room temperature conditions, when applied to elevated temperature, there is a tendency of the material to lose some or all of its original design characteristics. In order to fully justify design requirements as stated in the industry standard, a composite repair system has undergone several stages of testing in order to develop an appropriate blend of design characteristics and field use. In order to fully understand the impact of temperature degradation, two high temperature epoxy systems were used to saturate a woven, bi-directional fiberglass fabric. Each of the systems was tested under ambient conditions as well as exposure to high temperatures to determine if the systems would be suitable for high temperature applications.

A target temperature of 300° F (149° C) was used as a guideline for the desired upper limit for the repair system. With this in mind, the testing completed on each of the systems was done at 300° F (149° C) to gauge the suitability of the repair system at this upper operating limit. Four different mechanical characteristics of the systems were evaluated as a part of the development process to determine the appropriate final system.

- Tensile Strength
- Tensile Modulus
- Lap Shear Strength
- Direct Pull-Off Bond Strength

By looking at the degradation values based on the drop in each of these strengths, one can more accurately estimate the effectiveness and suitability for this system to be utilized for the repair of high temperature piping. This is also an important consideration when designing a composite repair system, as the tensile strength which is used in the design of the system should account for the value that it will be when exposed to the elevated temperatures. This is a critical factor in the required thickness as determined by Equation 11 in Article 4.1 of the ASME PCC-2 document. (2)

$$t_{repair} = \left(\frac{PD}{2} - t_s s\right) \cdot \left(\frac{1}{f s_{lt}}\right)$$

Where:

t_{repair}= design repair thickness
P= internal design pressure
D= external pipe diameter
t_s = minimum remaining wall thickness of the pipe
s = SMYS (Specified Minimum Yield Strength) of pipe
f= service factor based on testing completed on composite
s_{lt} = 95% lower confidence limit of the long term tensile strength of the composite

As is shown by the equation above, the tensile strength (s_{lt}) is inversely proportional to the calculated thickness of the repair system. Therefore, any degradation which occurs due to the higher operating temperatures will only serve to increase the required thickness of the repair system. For this reason, the intent for high temperature repairs is to maintain the high tensile strength for the composite material.

In addition to tensile strength, the effect of the elevated temperature on the bonding characteristics of the composite system is equally important; especially due to the nature of the majority of plant applications: leak repairs. The bonding of the repair system is critical for leak repairs in order to maintain an adequate seal to the pipe when subjected to elevated temperatures. Some testing has recently been completed by the Gas Technology Institute on several composite repair systems for the long term testing of the adhesive between layers of composite material, which indicates that there is a certain amount of degradation and loss of strength when fully submerged and subjected to temperatures between 60° to 140° F (15° to 60° C) and can vary significantly from one system to the next. (3)

Test Specimen Creation

The tensile coupons were created by saturating the fiberglass fabric with the epoxy systems and laying them up into 4 layer panels approximately 6” wide by 12” long. Each layer was saturated with the epoxy system by using a flexible spatula spreader to insure that the fabric was completely saturated with no dry spots. Once the 4 layers were in place, the panel was placed into a hydraulic press between two steel plates covered with a release film and separated by spacers to insure that the proper thickness was acquired and the panel was not overly compressed resulting in an unrealistic fiber volume fraction. Each tensile panel was allowed to cure overnight at room temperature before being removed from the press. The panels were then removed from the press and either placed into the oven to begin the heat saturation process or sent to be cut into tensile strips using a water-jet cutting process.

The lap shear test pieces were created by obtaining 1” by 3” steel coupons and grit blasting each piece to prepare the surface for application of the epoxy. The coupons were then marked to insure that the overlap would be 1” resulting in a one square inch area of bonding. The epoxy was applied to both surfaces, and then the coupons were placed together and overlapped as previously measured and allowed to cure overnight at room temperature. (Figure 2) Once cured, any excess epoxy which may have run over was removed by a light sanding to insure the bonded surface was isolated.

The direct pull-off specimens were created using a steel plate, which had been grit blasted, and standard 20 mm aluminum dollies. Two scenarios were evaluated for this test: a wet surface and a dry service. A length of grit blasted carbon steel plate was used to apply the aluminum dollies with the epoxy system as the bonding agent. (Figure 3) The surface of the steel was sprayed with water in pre-determined strips prior to the application of the dollies to represent a wet environment during the installation of the system.

Tensile Testing

Tensile testing was completed at three different stages of the temperature vs. time process in order to determine what effect that extended usage of the material at the elevated temperatures would have on the strength of the system. Once created, two of the three panels were then placed into an oven to be temperature saturated for a period of seven days and for a period of 30 days. All panels were initially cured at room temperature. Prior to testing (but after removal from oven environment), each panel was then cut into the individual tensile coupons using a water jet cutting technique. By using the water jet technology, this creates a cleaner cut with less induced edge stress than using a different cutting method (such as traditional metal saw blades). (Figure 4) Initial tensile testing involved two different epoxy systems (Gen. A and Gen. B), and each were used for the initial layup at the room temperature cure panels. Subsequent testing in the high temperature environment focused only on the Gen. B epoxy system. All coupons were tested on a 10 ksi tensile testing machine to determine tensile strength, tensile modulus, and elongation. (Figure 5)

Lap Shear Testing

Lap shear testing was completed at three different stages of the temperature vs. time process in order to determine what effect that extended usage of the material at the elevated temperatures would have on the bonding characteristics of the epoxy system. Only the Gen. B epoxy was used during this phase of the testing as the Gen. A epoxy had previously been ruled out for continued testing. Lap shear coupons were created to be tested at the same time-temperature intervals as the tensile coupons. Testing was completed on specimens cured at room temperature for 24 hours, after 7 days at 300° F, and after 30 days at 300° F.

Once the coupons had completed the required time-temperature cycle, any excess epoxy on the edges of the overlapped section was gently removed by a wire wheel to remove any additional coverage area of the epoxy. Each coupon was then tested on the same tensile machine as the tensile coupons to determine the lap shear strength of the epoxy system to grit blasted steel. (Figure 6)

Direct Pull-Off Testing

Direct pull-off bond testing was completed at three different stages of the temperature vs. time process in order to determine what effect that extended usage of the material at the elevated temperatures would have on the bonding characteristics of the epoxy system and also to determine the percentage of bond strength lost when applied to a damp substrate. As with the lap shear testing, only the Gen B epoxy system was considered during the direct pull-off testing. Testing was completed on specimens cured at room temperature for 24 hours, after 7 days at 300° F, and after 30 days at 300° F. Each of these time-temperature points had specimens created on a dry surface and a wet surface. The testing was done using standard 20 mm aluminum dollies and a digital pull-off adhesion tester to determine the direct bond strength in each scenario. (Figure 7)

Test Results

Tensile Test Results:

After the initial tensile testing evaluation between the Gen A and Gen B epoxy systems (using the same fiberglass fabric for all coupons throughout the testing program), the tensile results were relatively similar. (Figure 8) Even though the results indicate a slightly higher tensile strength, the Gen B resin system was chosen as the epoxy to move forward with.

Once this decision was in place, the next step was to test the panels after they had been through the temperature period. (Figure 9) As is evident from the table, there is no significant loss in strength (approximately 2%) after submersion in the high temperature environment for a period of 30 days. We do see a slight increase in the modulus of the system (approximately 5%) over the time exposed to the high temperature.

Lap Shear Test Results:

Results from the lap shear testing show a very promising retention of properties. (Figure 10) You can see that after 7 days in the high temperature environment, there is no loss of lap shear strength. It is only in the 30 day samples that we begin to see the beginnings of any loss in value. Even with this loss, which is only approximately 20% of the initial value, the end result is almost 5 times stronger than the minimum value as stated in the ASME PCC-2 as the requirement for a composite system. This is of great importance to the intended use of the composite system, as it shows that the material can be used at continuous high temperatures and maintain the lap shear design strengths of the composite.

Direct Pull-Off Adhesion Results:

The direct pull-off adhesion results are also very promising. (Figure 11) There is a definite increase in adhesive properties based on the testing completed to date. The test machine used has a maximum pressure capacity of approximately 3,400 psi, and this value was reached during the adhesion tests being completed. Because there was need to get some usable data on the effect of the temperature, it was decided that the pressure should be cycled from 0 psi to the machine maximum and the number of cycles would be recorded and used in the evaluation process. In addition, by applying to both wet and dry surfaces, we can gauge the effectiveness in "wet" conditions. There is a small effect on the adhesion when applied to wet surface as opposed to when applied to a dry surface, although, this seems to be increased after time in the high temperature as the results after only 7 days are equal to that of the dry specimens. This is further reinforced by the 30 day "wet" results which show only a 7% difference between the same specimen applied to a dry surface. Again, this further confirms that the system will be suitable for sustained usage at these elevated temperatures.

Discussion

The evaluation process for the development of this system began with two different epoxy systems. It is important to note that the end result of the materials should be usable and installation friendly for field use. With this in mind, the Gen A epoxy system was dismissed after the first round of tensile testing for two main reasons.

1. It was too viscous, and
2. The hardener had a very strong odor and hazardous materials.

Because of these two issues, the Gen A epoxy was dismissed from continued testing. Because of the viscosity, it made the saturation of the fiberglass fabric more difficult and allowed more chance for improper saturation in the field. The hazardous materials, and strong odor, from the hardener were also a deterrent as this would be difficult to approve and would require additional safety steps making the application more involved and less "field-friendly."

It should be noted that as the epoxy was "aged" in the high temperature environment, it underwent a color change. (Figure 12) This phenomenon is normal and expected as a general characteristic of the system. It should also be noted that the observation was made that the ingress of the color change was limited to the outer edges of the coupons and the interior of the coupon did not seem to be affected, even after the prolonged submersion in the high temperature environment. (Figure 13) This leads to the theory that the material has some insulating qualities which protect a large portion of the interior strength of the system. This seems to be supported due to the fact that while the tensile strength shows no significant reduction, the lap shear strength value did slightly decrease.

Conclusion

Based on the information gathered in this preliminary testing program, it has been concluded that the characteristics and performance of the composite system has been deemed acceptable for continued testing. The tests chosen to be performed in this initial evaluation were based on "real world" requirements to insure that the properties could be retained when exposed to these elevated temperatures. Now that the properties and their retention values have been confirmed, the product will further undergo all of the full-scale testing as outlined in the ASME PCC-2 and shown in Figure 1 of this paper. By completing these tests, the system will then be qualified for use in the field according the guidelines given in these standards.

Future Work

As has been mentioned in this paper, this testing is only the first step in the full testing program which should be completed on this composite repair system. It is recommended that all testing required by the ASME PCC-2 and ISO/TS 24817 standard documents be completed in order to gain full regulatory compliance. In addition, many of the industrial uses that this product will be subjected to will undergo routine outages and shutdowns. It is recommended that the effect of temperature cycling on the properties of this system be examined as well to insure that the change in temperature does not negatively effect these values, or that it is at least a known effect that can be designed for. And finally, it is recommended that the possibility of the product providing some insulating quality should be explored to further examine the system benefits for high temperature usage.

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1. C. Alexander and B. Francini, “STATE OF THE ART ASSESSMENT OF COMPOSITE SYSTEMS USED TO REPAIR TRANSMISSION PIPELINES,” IPC2006-10484, Proceedings of the 6th International Pipeline Conference (2006)
2. Post Construction Committee, “ASME PCC-2-2008 Repair of Pressure Equipment and Piping,” ASME, New York, 2009, pp. 134
3. D. Germata, K. Stutenberg, and K. Farrag, “Composite Pipe Repair Systems Interim Report: Long-Term Shear Test Results,” GTI, (April 2010)

Figures:

Table 1 Repair System Required Material and Performance Properties

	Material Property	International Test Method	ASTM Test Method
Mechanical properties	Young's modulus	ISO 527	ASTM D 3039
	Poisson's ratio	ISO 527	ASTM D 3039
	Shear modulus (in-plane)	. . .	ASTM D 5379
	Thermal expansion coefficients	ISO 11359-2	ASTM E 831
	Glass transition temperature of resin, T_g, or HDT	ISO 11357-2 or ISO 75	ASTM D 6604, ASTM E 1640, or ASTM E 831
	Barcol or Shore hardness	BS EN 59, ISO 868	ASTM D 2583
	Bending modulus	ISO 178	ASTM D 790
Adhesion strength	Lap shear	BS EN 1465	ASTM D 3165
Performance data	Long-term strength (optional)	Appendix V	. . .
	Energy release rate (optional)	Appendix IV	. . .
	Structural strengthening (optional)	Appendix III	. . .

Figure 1 - Table 1 from ASME PCC-2

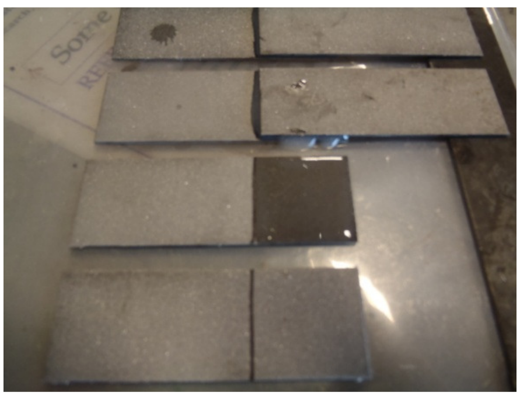

Figure 2 - Creating the Lap Shear Test Pieces

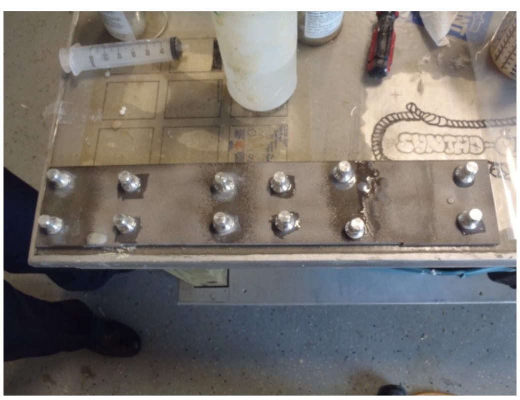

Figure 3 - Creating the Pull-Off Test Pieces

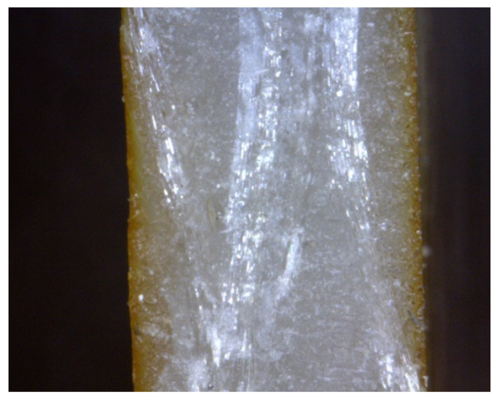

Figure 4 - Cross Section of Tensile Coupon

Figure 5 - Tensile Coupon Test Setup

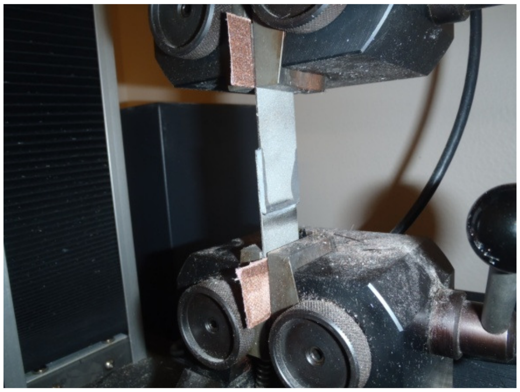

Figure 6 - Testing of Lap Shear Specimen

Figure 7 - Testing of Direct Pull-Off Adhesion

Product Sample	Elongation (%)	Modulus (ksi)	Tensile Strength (psi)
Gen A	2.46	4.282	87,100
Gen B	2.08	4.385	85,800

Figure 8 - Tensile Comparison (Gen A vs. Gen B)

Time	Temp.	Elonga-tion (%)	Modulus (ksi)	Tensile Strength (psi)
24 Hrs	Room Temp.	2.08	4.385	85,800
7 Days	300° F	2.28	4.259	85,400
30 Days	300° F	2.26	4.610	84,500

Figure 9 - Tensile Testing: Time vs. Temp

Time	Temperature	Lap Shear Strength (psi)
24 Hrs	Room Temp.	3,150
7 Days	300° F	3,180
30 Days	300° F	2,493

Figure 10 - Lap Shear: Time vs. Temp

Time	Condition	Temp.	Adhesion (psi)	# Cycles
24 Hrs	Dry	Room Temp.	>3,400	8
7 Days	Dry	300° F	>3,400	>20
30 Days	Dry	300° F	3,354	16
24 Hrs	Wet	Room Temp.	2,635	NA
7 Days	Wet	300° F	>3,400	>20
30 Days	Wet	300° F	3,149	18

Figure 11 - Direct Pull-Off: Time vs. Temp

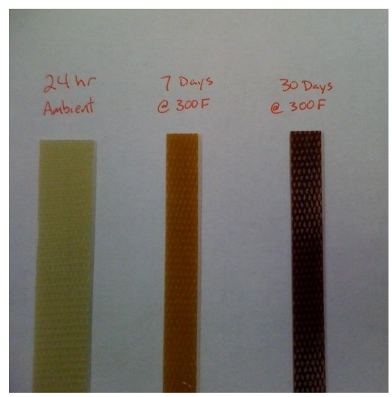

Figure 12 - Color Change Over Time @ 300 F

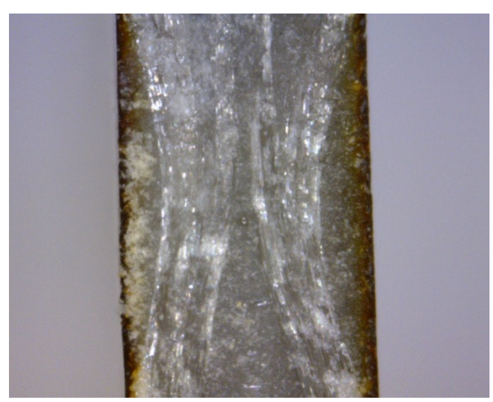

Figure 13 - 30 Day @ 300 F Tensile Coupon