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Assessing the state of composite repair systems

With improved innovations and technology, the pipeline industry will benefit from the continued development of composite materials.

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For almost 20 years, composite materials have been used to repair and reinforce transmission pipelines. This effort has been accompanied by an extensive array of engineering analysis and testing programs funded by pipeline companies, research organizations, and composite manufacturers.

The original use of composite materials was for repairing corroded pipelines where the intent was to restore strength to the damaged section of the pipeline. In addition to repairing corrosion, composite materials have successfully been used to repair dents, wrinkle bends, induction bends, and pipe fittings including elbows and tees.

Composite materials have managed to provide the pipeline industry with a safe, reliable, and economic alternative to repair using conventional options such as steel sleeves. This trend is expected to continue with the aging international infrastructure, coupled with greater demands for pipeline systems to meet the needs of a global energy market. Twenty years ago, one was hard-pressed to find a pipeline company that used composite materials on a routine basis. However, today most pipeline companies use composite materials as part of their rehabilitation programs and at the present time there are at least fifteen companies actively marketing composite repair systems. One of the challenges that confronts the industry is determining when composite materials can be used and what systems are best-suited for repairing a given damage mechanism.

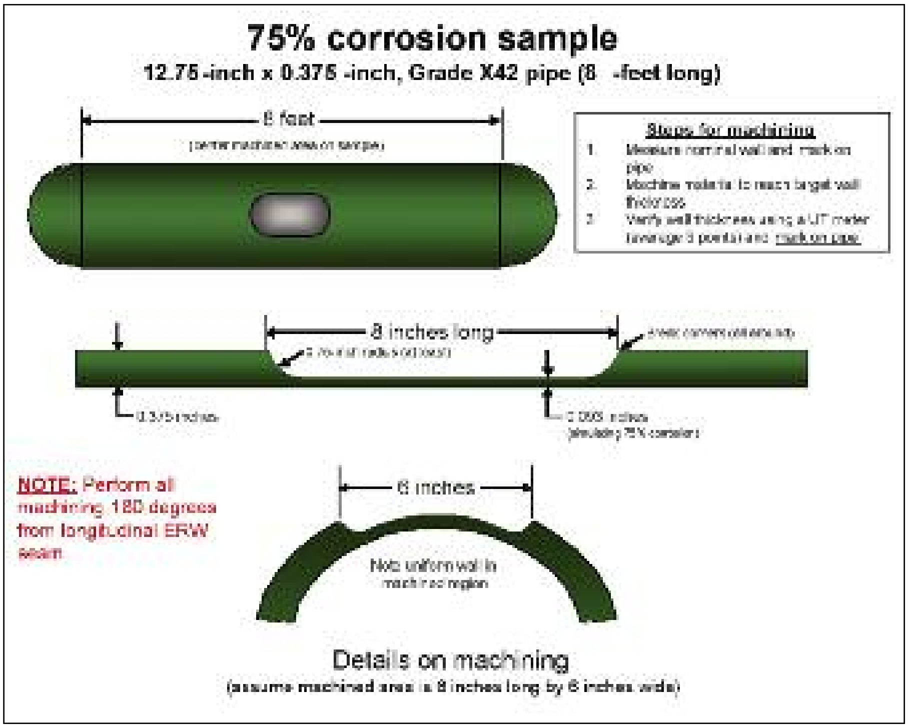


Figure 1. Sketch of simulated corrosion.

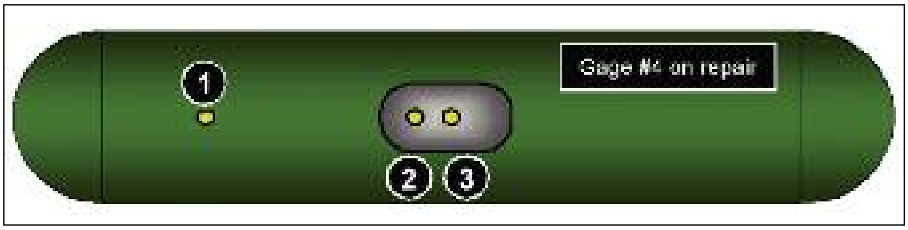


Figure 2. Diagram of strain gage locations.

This four-article series has been prepared to provide industry with an overview of the current state of the art in composite repair technology and how the integrity of pipeline systems are being restored using composite materials. Subsequent articles will address topics that include the repair of mechanical damage (dents with gouges), wrinkle bends, repair of offshore risers, and finally, international markets and insights from pipeline companies using composite materials.

The aim of the current article is several-fold. First, the intent is to provide the reader with a brief history of composite materials and the companies that have brought them to market. A second aim is to discuss a 10-year study, sponsored by the Pipeline Research Council International and twelve composite repair companies, focused on evaluating the long-term performance of composite repair systems.

Background and history

Even though composite materials have been used to structurally repair piping and other facilities for many years, there is a specific history that accompanies the repair of high-pressure gas and transmission pipelines.

Originally, the Office of Pipeline Safety (OPS) required the use of waivers before installations could take place using composite materials to repair transmission pipelines. However, the U.S. Department of Transportation's new pipeline repair rule went into effect on January 13, 2000 that permitted the repair of pipelines using composite materials as long as reliable engineering tests and analyses show permanent restoration of the serviceability of the pipe. Prior to this rule, pipeline companies had to obtain a waiver from the DOT to use Clock Spring, and no other composite repair methods were officially permitted.

From a standards standpoint, in the U.S., ASME PCC-2-2006 Repair of Pressure Equipment and Piping has emerged as the reference document as Part 4 Nonmetallic and Bonded Repairs specifically provides guidance in repairing pipelines and piping using composite materials. The ongoing development of ASME PCC-2 will meet the expanding demands of the pipeline industry, including developing guidelines for repairing defects such as dents and wrinkle bends.

In many regards, Clock Spring set the standard in terms of market expectations associated with the development of composite repairs. The Gas Research Institute (GRI, now known as the Gas Technology Institute) was instrumental in gathering both industry and research partners for evaluating the repair system. Some of these efforts involved the following activities:

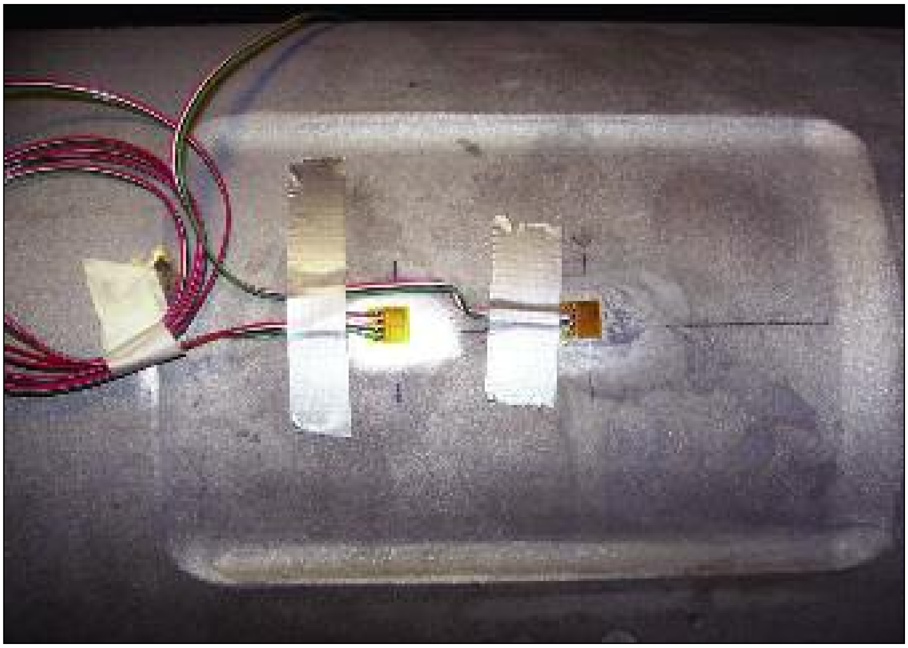


Figure 3. Strain gages in simulated corrosion.

- Composite material testing and analysis, including short and long-term stress-rupture testing;
- Adhesive testing to assess lap shear strengths;
- Burst testing considering general defects, circumferential defects, long axial defects, and repair of dents, gouges, and mechanical damage;
- Field exposure assessment of Clock Springs installed in 1989 (coupon testing and inspection of installed wraps); and
- Development of GRIWrap to provide a general procedure for the safe application of Clock Spring.

A final report for GRI, "Development of Fiberglass Systems for Natural Gas Pipeline Service," was prepared by NCF Industries. This document spanned a period of time from January 1987 to March 1994, and covered the basic history and development of Clock Spring. During the 1990s, GRI continued numerous research efforts that included field validation efforts, long-term-reliability efforts, and repair of non-straight pipe geometries such as elbows.

In the mid-1990s, industry began using wet lay-up systems. The first system on the market was a private label product known as StrongBack manufactured by Air Logistics Corp. StrongBack is a composite reinforcement product that is water-activated, resin impregnated, and uses glass fiber remediation materials. In the past several years, Air Logistics has also brought to industry an additional water-activated system, Aquawrap. This system has undergone extensive testing, including full-scale testing to address its use in repairing mechanical damage.

In 1997, Armor Plate, Inc. started a research program to develop the Armor Plate Pipe Wrap system. This system employs a fiberglass material that is field-impregnated with unique epoxy systems to withstand specific environmental conditions, including underwater applications, high temperatures, and cold weather.

Once the 2000-edition of the OPS ruling came out, use of composite materials in repairing pipelines increased significantly. Consequently, the number of manufacturers interested in this repair technology also increased.

In 2000, WrapMaster, Inc. started a testing program to assess the capabilities of PermaWrap, which is a system similar to Clock Spring in that it employs a hard shell with an adhesive installed between layers.

Citadel Technologies developed the Black-Diamond Composite Wrap. Although similar in nature to Armor Plate's Pipe Wrap in its use of epoxy products, this system has the added strength advantage of using carbon fibers, which on average have an elastic modulus that is on the order of two times that of conventional E-glass.

Numerous other companies are continuing to pursue the development of products of this repair genre. Listed below are several companies, not specifically addressed in this article, that have developed composite systems for repairing high-pressure transmission pipelines:

- EMS Group
- Pipe Wrap, LLC
- T.D. Williamson, Inc.
- Walker Technical Resources Ltd.
- 3X Engineering
- Furmanite
- Neptune Research, Inc.
- Comptek Structural Composites.

With improved innovations and technology, along with proper use of engineering evaluation methods and testing, the pipeline industry will benefit from continued development of composite materials. The focus must remain on the requirement that composite repair systems provide reinforcement to ensure long-term integrity of pipelines.

Long term performance

A question often posed regarding the use of composite materials concerns long-term performance. Composite materials have been used in the aircraft industry for decades; however, the fundamental difference when repairing pipelines concerns the issue of sustained loading. When a composite repair is installed on the outside surface of a pipe, the composite is under load as long as the pipeline is pressurized. For this reason, composite repair systems are typically designed so that operating stresses in the composite remain below a predetermined design level. This is achieved by selecting appropriate composite thicknesses and strengths.

There are two significant bodies of work that have been undertaken over the past several years concerning the long-term performance of composite materials.

- Composite materials are used to repair significant levels of corrosion. Most manufacturers state that they can repair corrosion depths up to 80%. Although there is no doubt that most composite materials can repair corrosion depth of this magnitude, there was minimal evidence in the open literature to demonstrate that, when subjected to cyclic loading, composite materials can repair corrosion levels of this magnitude. Consequently, a series of tests at Stress Engineering Services, Inc. were conducted to address this issue on five different competing composite repair systems.
- A research program was undertaken to evaluate the performance of buried pipe samples having simulated (machined) corrosion repaired using composite materials. A total of 180 12-in. nominal diameter pipe samples were prepared. Thirty-six of these samples were burst at Year 0 to establish a baseline dataset, while the remaining 144 were buried for burst testing at a future date. This program was funded by the Pipeline Research Council International, Inc. (PRCI) and twelve composite repair companies from around the world. The buried test samples will be removed at specific time periods over a 10-year period and burst tested to evaluate long-term performance.

The results of both of these programs are critical to understanding what limitations exist in terms of long-term performance of composite repair systems in repairing corroded pipelines.

All pipelines experience some level of pressure cycling. It is recognized that liquid pipelines experience a greater number of pressure cycles than gas pipelines; however, it is a mistake to state that gas pipeline are never subjected to cyclic pressures. Figure 5 provides typical pressure-cycle data for gas pipelines based on work presented by Kiefner et al. As noted, severity conditions are provided that range from "light" to "very aggressive." While the total accumulated number of cycles is of interest, a more meaningful presentation is achieved by summing the pressure

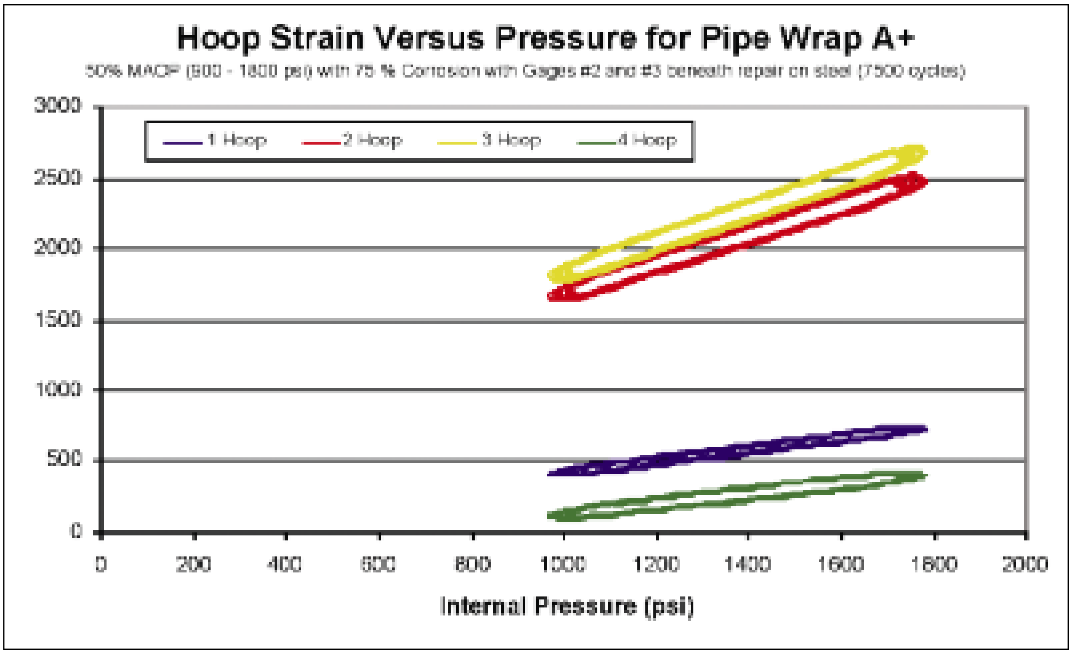
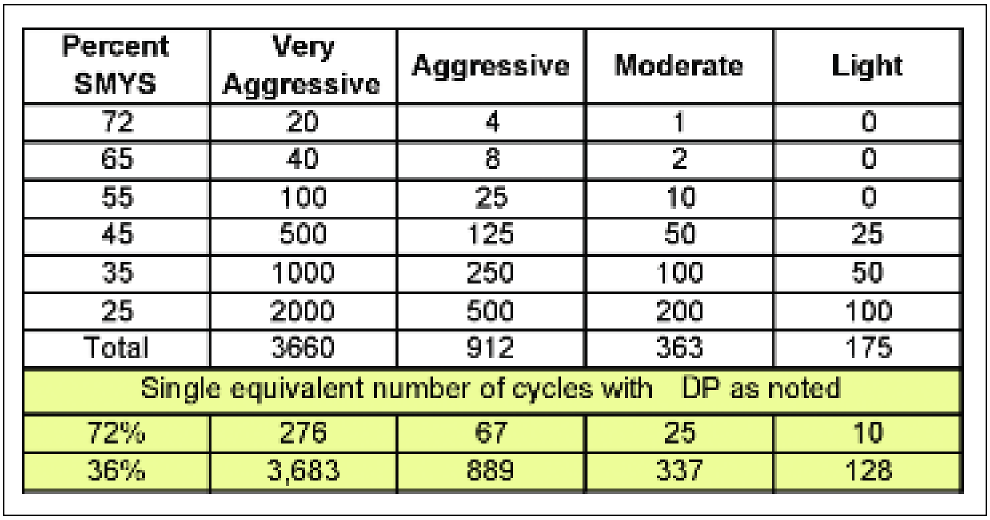


Figure 4. Hoop strains at 7,500 cycles for system #3.

ranges and applied cycles into a single equivalent cycle count using Miner's Rule and a fourth-order relationship between stress and cycle range. The last two rows included in Figure 5 have been included by the author and are equivalent cycles for pressures ranges equal to 36% and 72% of the specified minimum yield strength (SMYS).



Percent SMYS	Very Aggressive	Aggressive	Moderate	Light
72	20	4	1	0
65	40	8	2	0
55	100	25	10	0
45	500	125	50	25
35	1000	250	100	50
25	2000	500	200	100
Total	3660	912	363	175
Single equivalent number of cycles with DP as noted				
72%	276	67	25	10
36%	3,683	889	337	128

Figure 5. Typical pressure cycle data for gas pipelines.

Using the data in Figure 5, it is possible to estimate the years of service in a gas transmission pipeline to which the experimental fatigue life (i.e. cycles to failure) corresponds. To evaluate performance of pipelines having corrosion depths of 75%, test samples were prepared by machining simulated corrosion in 8-ft long test samples fabricated using 12.75-in. x 0.375-in., Grade X42 pipe. Weld caps were welded to the ends of the samples, and then simulated corrosion equivalent to 75% loss in wall thickness was machined in the wall of the pipe. A diagram of the simulated corrosion is shown in Figure 1. Bi-axial strain gages were installed in the machined area prior to the repair as shown in Figure 2, with a photograph of the installed gages shown in Figure 3. During testing each sample was cycled to failure at a pressure range from 890 psi to 1,780 psi (36% to 72% SMYS).

Five different composite repair systems were tested in this study. Each system was unique and involved different composite materials and thicknesses. Listed below are the systems that were used in this study, along with a brief description of material type and thickness.

- #1 (E-glass 0.50 inches thickness): 43,090 cycles
- #2 (E-glass 0.688 inches thickness): 72,920 cycles
- #3 (E-glass 0.50 inches thickness): 140,160 cycles
- #4 (E-glass 1.00 inches thickness): 165,120 cycles
- #5 (Carbon 0.660 inches thickness): 532,776+ cycles (no failure).

As observed in the above data, there is a wide discrepancy that exists in the number of cycles to failure for the five different repair systems.

Figure 4 plots the strain gages results recorded at 7,500 cycles for System #3. Figure 6 provides the maximum – minimum range (i.e. delta = maximum – minimum), and mean strain values at this same cycle count. Note the following in relation to the specific strain-gage results (cf. Figure 2 for gage locations):

- Gage #1: The strain range on the base pipe was 360 microstrain (stress of 10,800 psi).
- Gage #2: The strain range on the corroded pipe beneath the repair was 900 microstrain (elastic stress of 27,000 psi).
- Gage #4: The strain range on the outside surface of the composite repair was 339 microstrain (an estimated elastic stress of 1,000 psi assumed a composite modulus of 3 Msi).

The number of design cycles is calculated by dividing the cycles to failure by 20 (based on the methods of the ASME Boiler & Pressure Vessel Code). This calculation generates a design fatigue life for a given pressure range. The Kiefner data in Figure 5 is then used to estimate the years of remaining life for the given repaired defect.

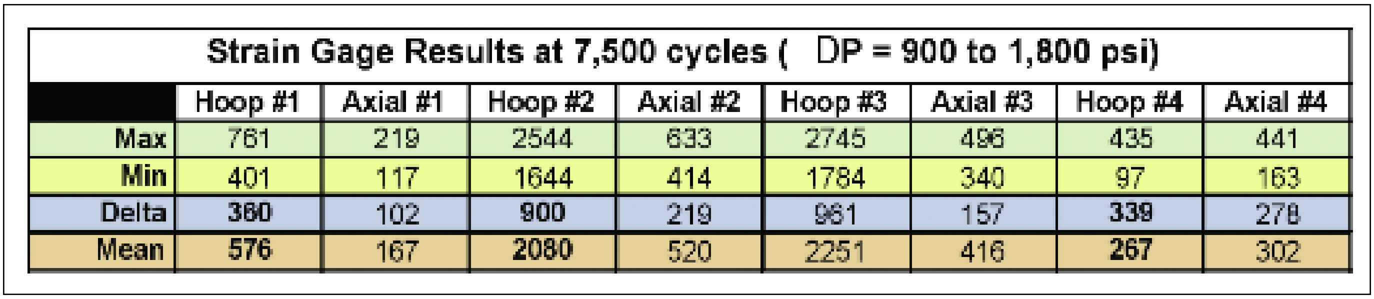
Consider the following example using the cycles to failure for System #3:

- The number of experimental cycles to failure is calculated by dividing 140,164 cycles by 20.
- This previous calculation corresponds to a design life of 7,008 cycles assuming a cyclic pressure range of 36% SMYS.
- Using the Kiefner data with a stress range of 36%, a moderately aggressive gas transmission pipeline will cycle annually 337 times. Correspondingly, the 7,008 design cycles corresponds to 21 years of service (7,008 design cycles divided by 337 cycles per year). For the "Light" condition, the period of service increases to 55 years (128 cycles per year).

The methodology presented here can also be used to estimate the remaining years of life for a given repair using actual pressure history data from a pipeline. Necessary components for this calculation including experimental cycles to failure and a cyclic pressure history for the pipeline.

Long-term burial study

An extensive research program was



Strain Gage Results at 7,500 cycles (DP = 900 to 1,800 psi)	Hoop #1	Axial #1	Hoop #2	Axial #2	Hoop #3	Axial #3	Hoop #4	Axial #4
Max	761	219	2544	633	2745	496	435	441
Min	401	117	1644	414	1784	340	97	163
Delta	**360**	102	**900**	219	961	157	**339**	278
Mean	**576**	167	**2080**	520	2251	416	**267**	302

Figure 6. Summary of strain gage results at 7,500 cycles.

undertaken (and is currently underway) in response to questions from the pipeline industry regarding the long-term performance of composite repair systems. The sponsors of this program included PRCI and twelve composite manufacturers from around the world. The basic elements of this program include the following:

- Fabrication of (180) 12.75-in. x 0.375-in., Grade X42 8-ft long test samples with welded end caps.
- Sample preparation that included corrosion depths of 40%, 60%, and 75% of the pipe's nominal wall thickness (refer to Figure 1 for geometry of machined region).
- Samples were repaired by the participating manufacturers. All manufacturers repaired samples for a three-year test period (12 total samples), while four of the manufacturers elected to participate for a 10-year study (requiring an additional nine samples).
- Burst tests were planned for all of the repaired samples at 0, 1, 2, and 3 years. The 10-year participants will have additional burst periods at 5, 7.5, and 10 years.
- While 36 samples were burst during the Year 0 test period, 144 samples were buried in the ground (cover depth of approximately 18 inches) at Stress Engineering's Waller, Texas Test Facility. Samples will be continuously pressurized at 36% SMYS (890 psi) and cycled 75 times once per month at 36% SMYS (890 – 1,780 psi) and once per quarter at 72% SMYS (0 to 1,780 psi). Burst test samples will be removed from the buried trenches at the designated test periods.
- During the testing period, strain gages will be used to monitor strain in the corroded steel beneath the composite repairs.

Listed below are the companies participating in the long-term study. Included in parentheses are their respective years of participation:

- Armor Plate, Inc. (10 years)
- Air Logistics Corp. (3 years)
- Clock Spring Co., LLC (3 years)
- Citadel Technologies (10 years)
- EMS Group (10 years)
- Pipe Wrap, LLC (3 years)
- T.D. Williamson, Inc. (10 years)
- Walker Technical Resources Ltd. (3 years)
- Wrap Master (3 years)
- 3X Engineering (3 years)
- Furmanite (3 years)
- Neptune (3 years).

Manifolds were used to connect the samples together to facilitate rapid pressurization. Over 20,000 ft of wire was used to connect the strain gages from each sample to a central data acquisition system that will collect data once per month over a 10-year period.

To keep industry up to date with ongoing activities, Stress Engineering constructed *www.compositerepairstudy.com*, a website that highlights details associated with the long-term study and provides additional information on composite repair technology development and associated documentation.

Conclusion

In following months, this article series will discuss a wide range of subjects that relate to the repair of pipelines using composite materials. Composite repair systems are going to continue to play an important role in rehabilitating the aging pipeline systems around the world. Prior research, as well as ongoing efforts, has focused on demonstrating how composite materials can restore the serviceability of pipelines using engineering analysis and testing methods. A significant body of knowledge has been accumulated over the past 20 years, and is expected to continue in the future. ■

Editor's note: *this article is the first in a four-part series highlighting the history of composite repairs, state of the art, and ongoing research programs focused on validating the use of composite materials for long-term service.*

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