Proceedings of IPC2006
6th International Pipeline Conference
September 25-29, 2006, Calgary, Alberta, Canada

IPC2006-10483

REINFORCING FIELD FABRICATED BRANCH CONNECTIONS USING COMPOSITE MATERIALS

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

Tony Wilson
Armor Plate, Inc.
Pasadena, Texas
twilson@armorplateonline.com

ABSTRACT
Field fabricated branch connections are manufactured in lieu of forged tee fittings. To be used in accordance with ASME B31.8, these connections are subject to the area replacement method to ensure that sufficient material is present to reinforce the opening in the run piping. If insufficient material is present in the weld itself, pads are welded into place to serve as the reinforcing mechanism. One question posed recently to Stress Engineering Services, Inc. and Armor Plate, Inc. by a gas pipeline company was the feasibility of using composite materials to reinforce previously-fabricated branch connections that did not have sufficient steel material present to satisfy the requirements of the area replacement method.

Initial evaluation of the concept involved calculating the strength required to ensure that the branch connection would have sufficient long-term strength to withstand operating condition. Elastic-plastic finite element analyses were also performed using limit analysis methods to determine the minimum composite thickness that was required. Once all analytical efforts were completed, a full-scale test was performed on an exemplar branch connection fabricated from a 24-in x 0.375-in pipe and a branch pipe fabricated from 12.75-in x 0.375-in pipe (both Grade X42). Pressure levels exceeding 2.9 times the MAOP of the 24-inch pipe (787 psi) were reached before the branch connection leaked at a maximum pressure level of 2,314 psi. This burst pressure is 1.76 times SMYS. A burst in the connection did not occur, but rather a leak developed in the weld joining the branch and the run pipes and most likely initiated in the crotch region where the highest levels of strain occurred during pressure testing.

Considering the results of the test program and the calculated results, the pipeline operator concluded that a sufficient design margin existed to warrant the use of the composite materials as a valid reinforcement method. In addition to specific elements of the evaluation program, this paper will also provide discussions on using composites materials in repairing and reinforcing high pressure pipelines.

INTRODUCTION
This paper provides details on a burst test performed on an actual branch connection that was reinforced using 12 layers of Armor Plate® Pipe Wrap. The purpose of the test program was to assess the use of composite materials in reinforcing branch connections. A burst test was performed on an exemplar branch connection fabricated from a 24-in x 0.375-in pipe and a branch pipe fabricated from 12.75-in x 0.375-in pipe (both Grade X42). The highest D.O.T. allowed design factor is 0.6 which results in a MAOP of 787 psi. Under these conditions, ASME B31.8 requires a branch connection thickness of 0.371 inches. The ultimate tensile strength for the 24-inch pipe material was measured to be 72,200 psi, which results in a calculated burst pressure of 2,256 psi for the pipe alone not considering the presence of the branch connection.

In addition to the burst test, finite element analyses of the branch connection were performed to assess the mechanical reinforcement provided by the externally-installed composite material.

This paper provides details on the methodology and test results that were used to assess the viability of using composite material to reinforce branch connections. Included in this discussion are the following:

- Geometry of the branch connection
- Finite element analysis used to estimate required number of wraps
- Burst test results
- Implications of analysis and burst test results

It should be noted that composite materials have been used extensively to repair corrosion, mechanical damage, and reinforce a variety of pipe fittings including elbows and tees. The new generation of wet lay-up composite systems is suited to repair non-straight pipe geometries. There are numerous on-going research programs being conducted by manufacturers and industry to assess the long-term viability of these repair systems.

GEOMETRY OF THE BRANCH CONNECTION
A branch connection was fabricated using 24-in x 0.375-in run pipe (10-feet in length) and a 12.75-in x 0.375-in run pipe (6-feet in length). Both pipes were of Grade X42. Figure 1 is a photograph of the branch connection prior to shipment to Armor Plate, Inc. As shown, end caps were installed on both the run and branch pipes to permit pressure testing.

The branch connection was sent to the manufacturer where 12 wraps of Armor Plate® Pipe Wrap were applied. Testing was performed at the request of the gas pipeline company planning to use this reinforcement method in the field. They conveyed that the welds had been inspected via non-destructive examination and met their corporate requirements. The intent of this program was to address the validity of this reinforcement technique using composite materials.

FINITE ELEMENT ANALYSIS OF BRANCH CONNECTION

To assist in determining the recommended number of reinforcing composite layers, a series of finite element analyses were performed. The intent was to determine the required composite thickness to achieve a certain level of reinforcement. This information was then used to define the number of wraps applied for the test program.

After discussing the ASME B31.8 area reinforcement calculations with engineering staff from the gas pipeline company, analysis were performed on the following combination of reinforcement levels. Each wrap of Armor Plate® Pipe Wrap corresponds to a material thickness of 0.0625 inches.

- 6 wraps of APPW with composite tensile strength of 10 ksi (safety factor of 3.0 on tensile strength)
- 16 wraps of APPW with composite tensile strength of 30 ksi (safety factor of 1.0 on tensile strength)
- 12 wraps of APPW with composite tensile strength of 10 ksi (safety factor of 3.0 on tensile strength)
- 12 wraps of APPW with composite tensile strength of 30 ksi (safety factor of 1.0 on tensile strength)

To model the combined strength of the steel and composite material, a simplified effective thickness was implemented. A more rigorous analysis would involve modeling the fiber orientation of the composite material; however, the intent was to estimate the reinforcement level and not calculate exact strain levels in the combined steel and composite materials. The following relation was used to determine the effective thickness for each of the four reinforcement configurations listed previously.

$$t_{eff} = t_{steel} + \left[\frac{\sigma_{comp}}{SF \cdot \sigma_{steel}} \right] \cdot \frac{N_{wraps}}{16} \quad (1)$$

where:

t_{eff}	Effective thickness (inches)
t_{steel}	Thickness of the steel pipe (inches)
t_{comp}	Thickness of the reinforcement composite material (inches)
σ_{steel}	Ultimate tensile strength of steel (ksi)
σ_{comp}	Tensile strength of composite material (ksi)
SF	Safety factor on composite strength (to address long-term degradation)
N_{wraps}	Number of composite wraps (for APPW each layer is 1/16 inch thick)

An example calculation is provided below where 12 wraps of composite material having a tensile strength of 30 ksi is used to reinforce pipe that is 0.375-in thick with a tensile strength of 60 ksi. The 30 ksi composite tensile strength is based on previous coupon testing completed in 1998 [2]. Note that a safety factor of 3.0 is used in the calculation to account for long-term degradation.

$$t_{eff} = 0.375 \cdot inches + \left[\frac{30 \cdot ksi}{3 \cdot 60 \cdot ksi} \right] \cdot \frac{12 wraps}{16} = 0.50 \cdot inches \quad (2)$$

Figure 2 shows the mesh for the finite element model and Figure 3 is a color contour plot showing stresses due to internal pressure. The maximum stress calculated with an internal pressure of 1,000 psi is 109.1 ksi, which corresponds to a stress concentration factor of 3.46 relative to the nominal hoop stress in the 24-in run pipe. Note in Figure 3 that the maximum stress occurs in the crotch region near the weld joining the run and branch pipes.

To estimate the failure pressure of the branch connection, SES performed a series of analyses using elastic-plastic plastic material properties. Figure 4 shows the results of these analyses and the corresponding estimated failure pressures. The failure pressure for the present discussion (also known as the lower bound collapse load) is defined as the pressure at which no additional increase is required to result in unbounded displacements. Or said another way, the deflection of the branch connection will increase significantly with only slight increases in internal pressure. SES used a tensile strength for steel of 60 ksi. If a tensile strength of 75 ksi had been used, the estimated failure pressures would have been on the order of 2,200 psi (closer to the actual pressure at which leaking occurred in the test sample).

Using the analysis results, it was recommended that 12 layers of the composite repair material be installed on the test sample.

BURST TEST RESULTS

Prior to performing the burst test, the branch connection was reinforced with 12 wraps of the composite material. The required number of wraps was calculated using the following relation.

$$t_{REINF} = \left[\frac{\sigma_{comp}}{\sigma_{steel}} \right] \cdot \frac{N_{wraps}}{16} \quad (3)$$

where:

t_{REINF}	Required reinforcement thickness (inches)
σ_{steel}	Ultimate tensile strength of steel (ksi) - 60,000 psi for Grade X42
σ_{comp}	Tensile strength of composite material (ksi) - 30,000
N_{wraps}	Number of composite wraps (for APPW each layer is 1/16 inch thick)

The reinforced branch connection was delivered to the SES test lab and testing was performed on May 6, 2005. Figure 5 shows the reinforced sample in the testing chamber, while Figure 6 shows the plot of pressure data recorded during testing. The maximum pressure that was recorded was 2,314 psi. At this pressure level the nominal hoop stress in the 24-inch pipe was 74 ksi.

Figure 7 shows a crack that developed in the composite material in the crotch region of the branch connection. Note that this region is where the maximum stress occurred in the finite element model.

IMPLICATIONS OF ANALYSIS AND BURST TEST RESULTS

Using composite materials as a means for achieving reinforcement is a relatively unique application in terms of the area replacement method as defined in ASME B31.8. The analysis and burst test results both indicate that significant levels of reinforcement can be achieved using composite materials. These results are consistent with strain gage results obtained in the late 1990's on 16-in pipe reinforced with Armor Plate® Pipe Wrap. Once yielding in the steel pipe occurs, load transfer takes place and the composite material is loaded in tension and provides reinforcement to the steel. The phenomena is shown in Figure 8 where strain gages were installed on a corroded section of pipe beneath a composite repair. Once yielding starts in the steel carrier pipe, a reduction in stiffness takes place which results in load transfer to the composite material.

What is not addressed specifically in this paper is the strength degradation that will occur in the composite material over time. Imposing a safety factor of sufficient magnitude in the equation provided previously can be used to account for unknowns with regards to long-term performance. This is commonly used in calculations associated with fiber-reinforced plastic piping used in chemical plant and refineries applications. The result of imposing a larger safety factor is that the thickness of the reinforcing composite material is increased. In the absence of long-term data for Armor Plate® Pipe Wrap, the required number of wraps is selected to ensure that a safety factor of two exists on the burst pressure relative to the maximum operating pressure of the pipeline. As long-term data become available, it is possible that the required number of wraps can be adjusted to consider actual changes in strength of the composite material over time.

GUIDELINES FOR USING COMPOSITE MATERIALS

Although composites are gaining wide acceptance in terms of their ability to repair pipelines, it is clear that in order for a particular system to be used, the pipeline industry must ensure that each respective repair system provides an adequate level of reinforcement based on engineering principles. Provided below is a list of recommended assessment methods that should be considered prior to using any particular system as a repair or reinforcement material.

1. The composite material used in the repair system should possess sufficient tensile strength (on the order of 30,000 psi failure strength). The combination of the remaining pipe wall and composite material should possess a failure strength that is at least equal to the specified minimum yield strength (SMYS) of the pipe material. Although a strength equal to 100 percent SMYS is sufficient, it is recommended that a safety factor be placed on the maximum operating pressure (MOP). If MOP is assumed to be 72 percent, a safety factor of two corresponds to a stress level of 144 percent SMYS. While this may be an overly-conservative safety factor, the unknowns relating to the long-term performance of composites in aggressive soil environments require that a conservative position be taken.
2. The material should demonstrate that it can perform adequately in repairing corroded pipelines. This involves strength in burst mode, but also involves ensuring that the repair does not degrade with time or cyclic pressure service. Experimental testing must be conducted to address this issue. In addressing the effects of cyclic operating pressures, the service conditions in actual operating lines should be considered. A typical liquid pipeline may see approximately 1,800 cycles per year (at a 200 psi pressure differential), while gas transmission lines see 10 times fewer, or 60 cycles, for the same pressure level.
3. Testing should be conducted to address creep of the material under dead weight loading. Idealistically, a battery of tests should be conducted using weights as a percentage of the lower bound failure load for the given material (e.g. 10, 25, and 50 percent of tensile failure strength). Creep testing should also be conducted over several different loading time periods (e.g. 24 hours, 6 months, 2 years, etc.). Results from the creep rupture testing can be used to establish a design stress. Some composite manufacturers have selected a 50 year design life based on extrapolated results from 10,000 hour tests.
4. Lap shear testing should be conducted to ensure that an adequate bond exists between the pipe and wrap. For composite repair methods that are not monolithic (monolithic meaning that all layers combine to form a homogenous unit), these tests should also include composite-composite test samples as well as the composite-steel test coupons. The composite-composite sample is used to assess the bond strength between the layers, while the composite-steel samples are used to determine the lap shear strength at the interface between the pipe material and composite.
5. Testing should be conducted to address cathodic disbondment and the system should meet the requirements as set forth in ASTM G8 (Standard Test Methods of Cathodic Disbonding for Pipeline Coatings).
6. Repair materials should resist mild acid and alkaline environments, including a range of 4 to 11 pH. Alkaline soils may have a pH of 11 or higher, which will attack fiberglass and polyester resin. In general, epoxies can handle mild acids and strong alkalines.
7. Testing should be conducted to address water penetration into the system using test method ASTM G9 (Standard Test Method for Water Penetration and Pipeline Coatings).
8. The composite material should be able to withstand temperatures of the operating line on which it is to be installed. The operator should consider the effects of temperature in selecting regions of application (e.g. compressor station may see temperatures of 205 F).
9. Product must be environmentally-safe and possess low toxicity for the applicator.
10. To minimize the possibility for improper installation, the system must be user-friendly and have instructions that are easily understood. For two-part systems, the greatest problem associated with improper application involves incorrect mixing of the adhesive. Installation should only be conducted by a certified applicator.
11. The product must have clearly stated on it the expiration date (if applicable) of any component within the system. The system must demonstrate that it possesses adequate strength over a long period of time (2 to 3 year testing period). This should involve testing of the composite itself as well as adhesive bonds under load. Samples should be exposed to harsh environments (such as saturation in water) where composite properties are known to degrade with time.
12. A field monitoring program should be conducted to assess performance of the wrap over several years. This involves inspection of the buried line at least one year after installation. The repair should be inspected for soundness and any possible signs of degradation. Strain gages should be installed beneath the wrap to determine any changes in the pipe strain that occur with time. Idealistically, burst tests on repaired test samples should be completed at specified intervals of time.
13. The adhesive system must demonstrate that it can be used in a variety of temperature environments and permit installation in a range of ambient temperature conditions (e.g. between 0 F and 120 F). Ultimate responsibility is on the operator to ensure that the system can adequately cure and is not damaged at elevated ambient conditions.
14. For cold weather applications, the system should have sufficient toughness to ensure that the material does not become brittle and lose its ability to properly reinforce the pipeline.
15. When a repair method is used for restoring corroded pipes, calculations relating to its strength should incorporate severity of the corrosion using methods such as those used in ANSI/ASME B31G.
16. Long-term performance of the repair is critical. The system should be able to demonstrate that it will provide long-term reinforcement considering typical pipeline environmental conditions.

CONCLUDING COMMENTS

Readers will note that the reinforcement of branch connections a non-conventional approach to using composite materials. However, as demonstrated with the test results, reinforcement is provided to branch connection in a manner similar to reinforcement provided to straight sections of pipe. They key, as in all composite repairs, is the need to establish permanency of the repair in terms of the requirements set forth by the Office of Pipeline Safety in their January 13, 2000 ruling which stated that,

> *…corroded pipe may be repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe.*[3]

This paper has specifically addressed the performance of the composite material in reinforcing a branch connection. Typically, when composite materials are used on pipelines, they are employed as a repair method. Although in these conditions they do provide reinforcement, their primary purpose is to address some deficiency in the pipeline system as typical with corrosion and mechanical damage.

REFERENCES

1. Alexander, C.R. (February 2000), "Repair of Mechanically-Damaged Pipes Using Armor Plate® Pipe Wrap," ASME ETCE/OMAE 2000 Joint Conference, New Orleans, Louisiana.
2. Alexander, C.R., Wilson, F.D. (August 1999), "Analysis, Testing, and Proposed Guidelines for Use of Composites Materials in Repairing Pipelines," 1999 Pressure Vessel and Piping Conference, Boston, Massachusetts.
3. *Pipeline Safety: Gas and Hazardous Liquid pipeline Repair*, Federal Register, Vol. 64, No. 239, Tuesday, December 14, 1999, Rules and Regulations, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733; Amdt. 192-88; 195-68 (Effective date: January 13, 2000).

Figure 1 - Photograph of branch connection prior to reinforcement

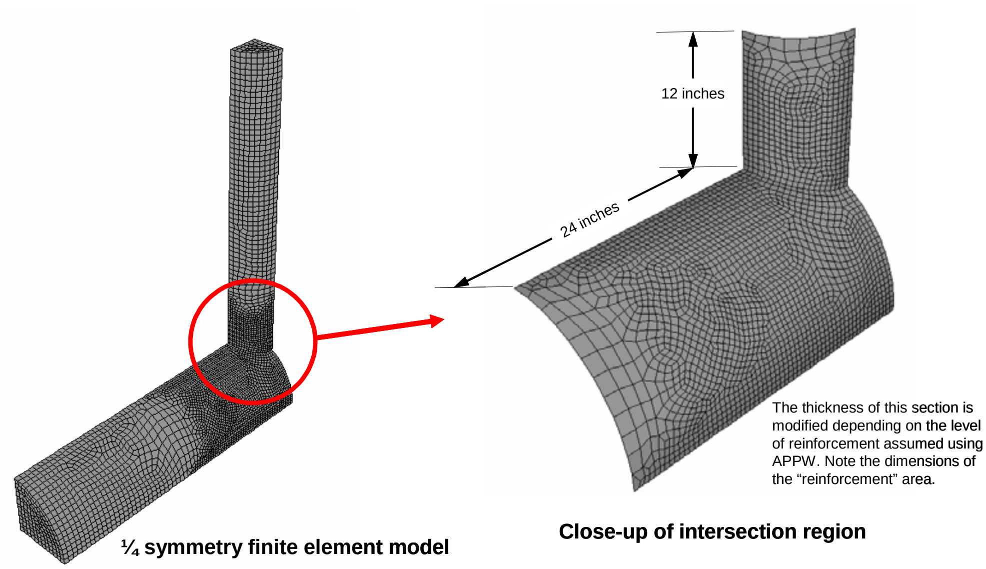

Figure 2 - Details on finite element model

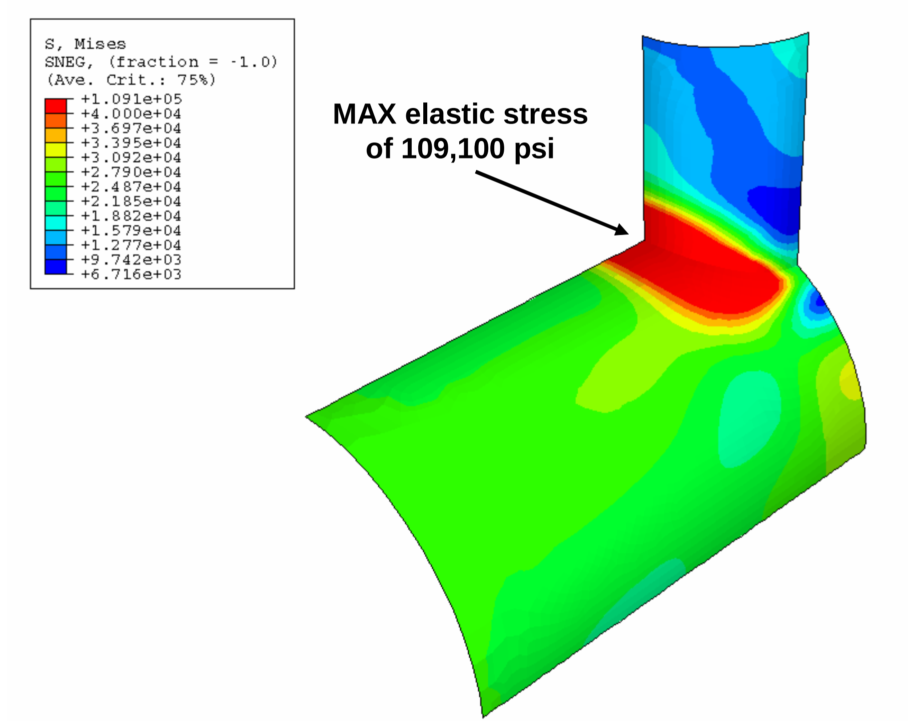

Figure 3 - Stress contour plot with 1,000 psi internal pressure (<u>elastic stress</u> shown)

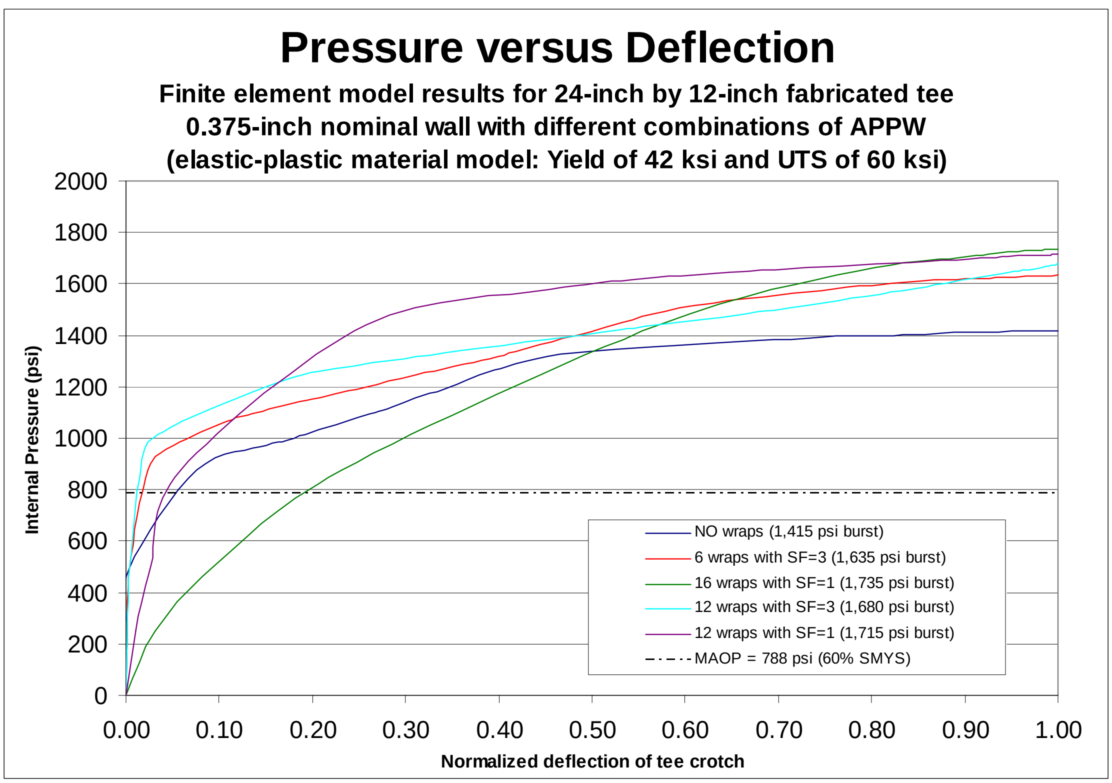

Figure 4 - Plot showing deflection of branch connection to estimate burst pressure

Figure 5 - Sample in test chamber prior to testing

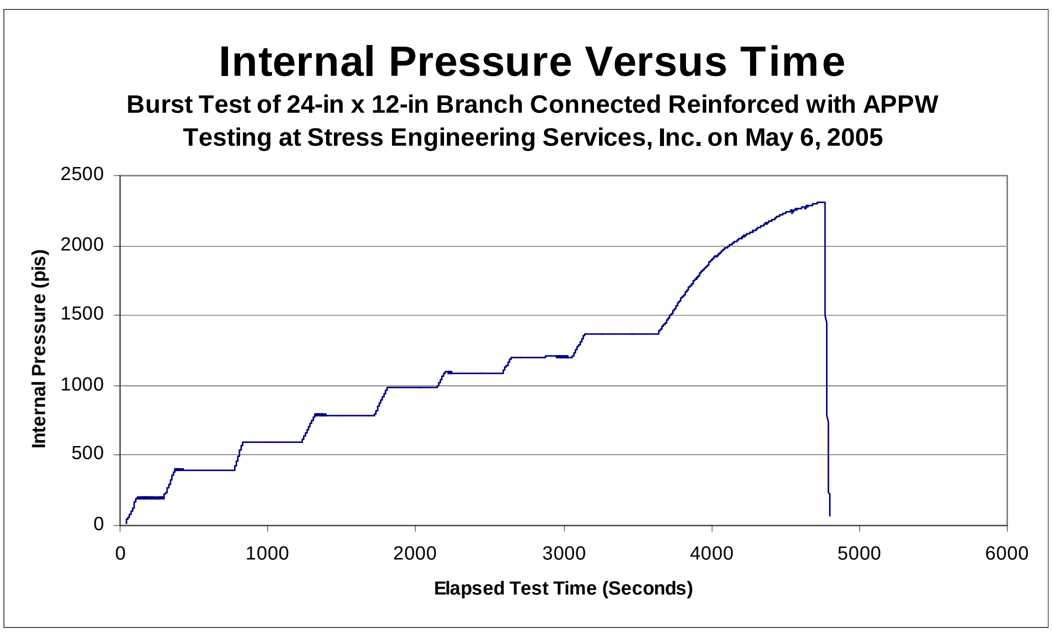

Figure 6 - Plot of pressure versus time recorded during testing (leak occurred at 2,314 psi)

Figure 7 - Crack in composite material in crotch region of branch connection

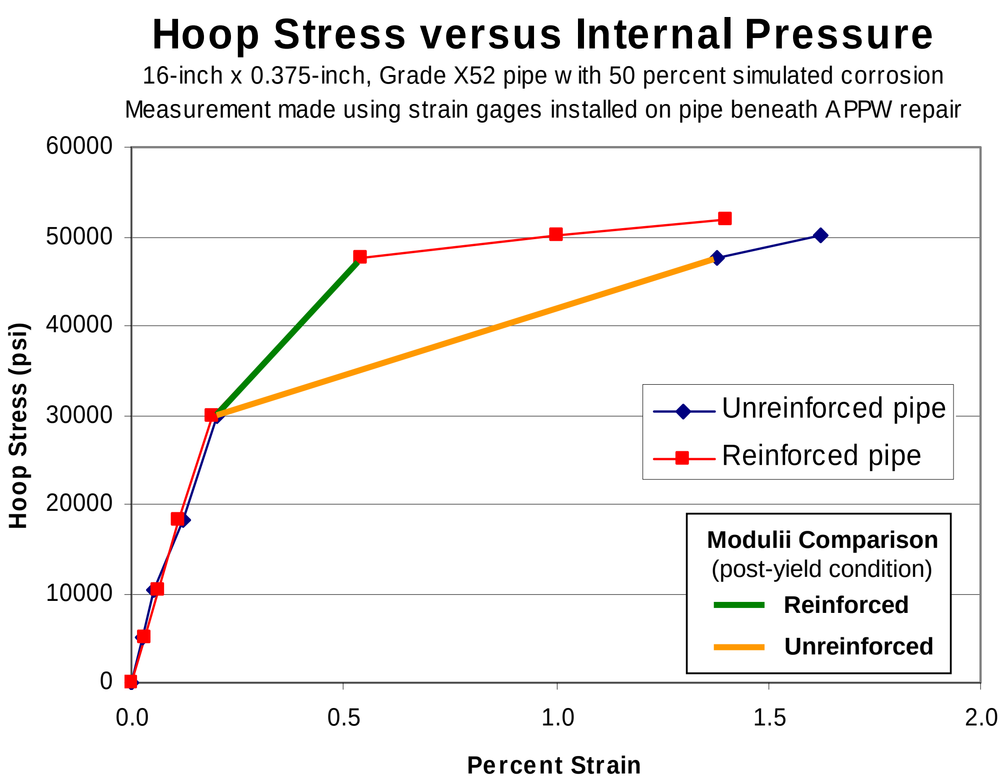

Figure 8 – Load transfer between steel carrier pipe and Armor Plate® Pipe Wrap composite material