# Fatigue Growth Behavior of Cracks in Pipelines Reinforced by Carbon Composite Wraps


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# Abstract

Pipe body cracking and seam weld crack-like defects can initiate in energy pipelines by various mechanisms. Their stable growth is highly influenced by cyclic operational pressures which can lead to premature failures. While an accepted way of repairing certain forms of cracking is by buffing, the traditional method of reinforcing unrepaired cracked areas in pipelines is by the application of overlay full-encirclement metallic sleeves, with the two allowable methods requiring some type of welding. A desired alternative to reinforcing pipelines with cracks and seam weld defects is the use of non-weldable light weight repair systems that can reduce or eliminate the fatigue growth of cracks and can conform to many pipe geometric changes.

A study was conducted to demonstrate the performance of three non-weldable carbon-epoxy composite wraps for reducing the fatigue growth of external axial cracks in pipeline samples taken from pre-1970 12-inch and 30-inch diameter pipelines. Cracks 3-inch long were introduced in the pipe body and seam weld locations with depths ranging between 35% - 56% wall thickness (WT). The test articles were subjected to pressure cycle loading from 10% to 72% specified minimum yield strength and approximately one cycle every 10 seconds. The reinforced cracks by the three carbon composite systems that reached 25,000 runout cycles grew by an average of 7.7% WT (STD = 8.6% WT) in the 12-inch diameter samples and by 13% WT (STD=12.8% WT) for those in the 30-inch test articles. There were rogue cracks that failed < 25,000 cycles only for cases when multiple cracks, equally spaced radially, were introduced to the same test sample. Overall, the fatigue crack growth of reinforced single cracks in the pipe body and in the seam weld was reduced by 3-5 times as compared with the unreinforced crack cases. The three carbon based composite repair systems, when designed, applied and tested as in this study, demonstrated to be effective in reinforcing pipelines with cracks in the pipe body and seam weld area. Moreover, the results in this study can be used to validate and refine existing carbon composite design methods and tools.


# Introduction

Pipe body cracking and seam weld crack-like defects can initiate in transmission pipelines during line pipe manufacturing practices and nucleate from existing imperfections during the pipeline service life. The confirmation or prediction of a cracking defect in a pipeline does not automatically warrant it unsafe for continued operation. This was settled long ago by experimental testing and analytical studies carried out initially by A. A. Griffith, C. Inglis, G.R. Irwin, P.C. Paris and later others who created the interconnected science and engineering discipline to explain and predict fractures, fittingly named fracture mechanics. Now days, the fracture capacity of a structure with a crack-like defect can be determined by a combination of knowing the crack characteristics, applied stresses, and the material response of the structure to fracture.

For pipelines with cracks under fatigue conditions, the focus turns to what can make existing sub-critical cracks extend or grow to become critical and fail prematurely. The main factors that control the fatigue growth of cracks are the inherent preferential slip plane in the line pipe material, the crack characteristics, the environment at the crack tip, and the fluctuating stresses. If the influence of any of these factors is reduced, so will the crack growth rate. The preferential slip path morphology for cracks to grow is material dependent which is set and is generally a minor concern during pipeline service. The ingress of a corrosive environment at the crack tip is possible, which can potentially lead to local material embrittlement. An adequate coating and appropriate pipeline corrosion protection levels can reduce the presence of corrosion and the possible formation of hydrogen that can migrate the crack tip. The main driving force to steadily grow cracks in pipelines is usually the combination of magnitude and frequency of the cyclic loading. The fatigue growth behavior of cracks follows a common pattern that can be simplified by a power law form, given by

$$\frac{da}{dN} = C\Delta K^m$$

where $da/dN$ is the crack growth rate per unit cycle, $C$ and $m$ are material properties obtained experimentally from curve fitting fatigue crack growth data and $\Delta K$ is the mechanical cyclic driving force commonly referred to as the stress intensity range, as defined by fracture mechanics [1]. Therefore, $\Delta K$ is directly related to the cyclic stresses that pipelines can experience, and if this crack growth driving force is diminished, so will be the fatigue crack growth rate resulting in an increase in fatigue crack life.

Other than buffing out cracks, the traditional method of reinforcing pipelines with sub-critical cracks is to reduce or eliminate their steady fatigue growth is by installing a full encirclement welded metallic sleeve. Type A sleeves repair crack-like defects (excluding through-wall defects) by welding two metal halve-shells longitudinally with unwelded circumferential ends, while Type B sleeves are applicable to repairing non-leaking and leaking cracks, and these sleeves are completely welded on the pipe [2]. The permitted repair methods for pipe body cracking and seam weld planar defects in ASME B31.4, B31.8 and CSA Z662 repair tables are welded steel sleeves. However, these codes allow for the use of other repair methods if the performance of the repair has been demonstrated through engineering analysis and testing. Moreover, the Pipeline and Hazardous Materials Safety Administration (PHMSA) stipulates a similar repair option clause in 49 CFR 192.713. Furthermore, the use of other methods is supported in industry recommended practice ASME PCC-2 and standard ISO 24817 which highlight the importance of installation procedures and quality control when using composite wraps as a repair method. A desired alternative to reinforcing pipelines with cracks and seam weld defects is the use of repair systems that can reduce the effective stresses around a crack and can conform to many pipe geometric changes. In this test program, carbon composite-based wraps were chosen to reinforce pipeline samples with synthetic cracks which were subjected to severe cyclic loading to demonstrate the performance of the installed non-weldable composite repair systems for reducing or eliminating the fatigue growth of cracks.

Demonstrating the use of composite wraps for repairing pipelines with cracks and seam weld planar defects has been previously investigated, with the intent to reduce or eliminate the stable crack growth by means of load transfer between the carrier pipe and the composite repair technology. Composite repair wraps are not intended to be applicable to all sub-critical cracks or blunt planar defects. For significant or near critical cracks and pipe locations, metallic Type A compressive sleeve or Type B sleeves are more appropriate options. In one study, in-service samples were removed from a 34-inch natural gas pipeline with known stress corrosion cracking (SCC) fields and reinforced using E-glass composite sleeves. Fatigue test results showed minimum fatigue crack growth extension for smaller SCC sizes [3]. In another study, single artificial seam weld planar defects 2-inch by 32% W.T. were introduced in the bond line of low frequency ERW 16-inch pipe samples removed from service. The blunt planar defect was reinforced using a carbon-fiber composite wrap and a hybrid repair system that used a combination of non-welded metal sleeves and composite overwrap. All repairs were installed with no internal pressure. The reinforced samples were pressure cycled from 10% to 72% SMYS and both repair systems reached the target number of test cycles of 3,500 cycles without a failure or crack initiation [4]. Recently, a larger test program was completed to evaluate fatigue growth of reinforced cracks in 16-inch and 22-inch diameter LF-ERW pipe samples that were all manufactured prior to 1970s [5]. Also investigated in the test program were 8-inch and 12-inch high-frequency ERW line pipes. Single cracks were initiated from starting notches that measured 1.5-inches to 3-inches in their axial length with depths ranging from 30% to 60% of the wall thickness that were placed in the seam weld and pipe body locations. The cracks had various starting depths and the samples were reinforced using carbon fiber wet layup systems installed by five composite repair companies. Some of the repairs were applied with the pipe under pressure, while others were installed with no pressure. The test cycle pressures ranged from 10% to 72% SMYS and the results showed an increased cycles to failure of 15 times when compared to the unreinforced pipe samples. It was reported in this study that the test samples reinforced with internal pressure did not provide a distinctive trend as compared with those installed at no internal pressure. The outcome of these full-scale test programs has demonstrated that pipelines with blunt or sharp planar defects of certain dimensions can be reinforced using composite wrap systems and the fatigue growth will be minimized, or in some cases eliminated, when subjected to aggressive cyclic loading.

# Line Pipe Material Description

Two pre-1965 API 5L line pipe steels were removed from service and made available to the fatigue test study described herein. The geometric characteristics and mechanical properties for both steels are presented in Table 1. The seam weld type for both line pipe steels is electric resistance welded (ERW).

**Table 1: Geometric Dimensions and Mechanical Properties of the Two Line Pipe Tested**

| Sample | Diameter [in] | Wall Thickness [in] | Measured Yield, Pipe Body [psi] | Measured Tensile, Pipe Body [psi] | Measured Tensile, Weld [psi] | Pipe Body KJmat, [ksi-sqrt(in)] | Seam Weld Bondline KJmat, [ksi-sqrt(in)] |
|---|---|---|---|---|---|---|---|
| 1 | 12.75 | 0.250 | 52,100 | 66,200 | 68,500 | 83.2 | 53.1 |
| 2 | 30 | 0.375 | 56,500 | 75,300 | 77,100 | 113 | -- |

# Characteristics of Initial Planar Defects

Pipe samples were cut to lengths between 6 to 8 feet and a single starter notch was placed in the center portion of the test sample. Each notch was made by Electro Discharge Machining (EDM) technique and oriented axially and external to the pipeline with an approximate depth of 30% W.T. for the 12-inch O.D. pipeline and 35% W.T. deep for the 30-inch O.D. samples. All notches were 3-inches long. Starter notches were placed in the ERW seam weld bondline and pipe body for the 12-inch pipeline samples and only in the pipe body for the 30-inch pipeline due to the limited supply of pipe. For the 12-inch pipe samples, three starter notches were placed in the pipe body to increase the number of crack cases. Figure 1 shows the placement of individual notches and for the case where three notches were introduced.

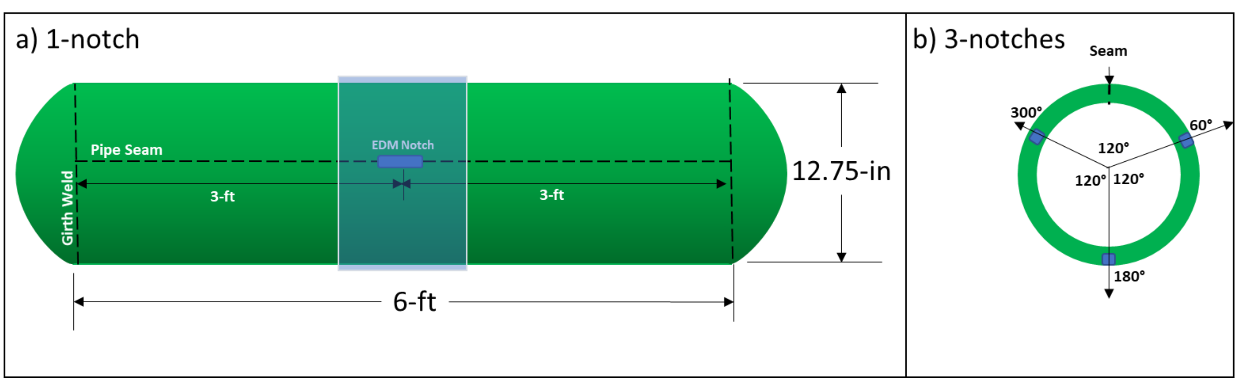


**Figure 1: Schematics of the Notch Placement with One EDM Notch and Three EDM Notches Configuration**

The cross-sectional shape of the manufactured EDM notch was a canoe-like with starting depths in the range 23.5% to 35.5% WT for notches in the pipe body and 25.2% to 31.6% WT for those in the ERW seam bondline. The test samples were cycled from approximately 10% to 72% SMYS to initiate cracks from the notches. The goal was to initiate fatigue cracks and let them grow to a target depth of 50% WT deep. The shape a typical starting notch is shown in Figure 2 along with the fatigue growth of a crack that emanated from the notch and grew through wall.

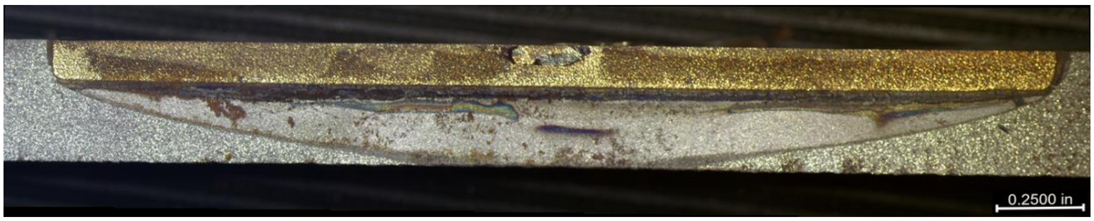


**Figure 2: Machined Notch Characteristics and Fatigue Crack Profile**

The resultant crack sizes in the 12-inch pipe samples were in the range of 32.8% to 55.5% WT with two rogue cracks growing 77% and 83% WT, which occurred in samples where three starter notches. The crack depths for the 30-inch pipe samples were in the range of 39.2% to 52% WT. After the cracks were initiated and before installation of the composite materials, the notches plus crack were heat tinted using a torch that reached approximately 500°F to leave a blue oxidation color along the pre-cracked surface. This step proved important to distinguish pre-crack growth from the post-repaired growth.

# Carbon Composite Wrap Characteristics and Installation

Three vendors participated in this study with each providing carbon composite wrap technologies. Each vendor was allowed to determine the repair thickness using their own methods. The overall design goal was to calculate an optimal composite thickness to achieve a stress level in a reinforced pipe leading to a reduction in the crack growth rate and an increase in the burst pressure capacity of the pipeline. Provided to each Vendor were the pipe tensile properties and fracture toughness as well as an estimated initial crack depth. Vendors A and B utilized the same method to set the composite wrap thickness while Vendor C used a different method. The final calculated composite thickness was to achieve a fatigue crack growth life of near 25,000 cycles without failure, either by leak or rupture. The 25,000 fatigue cycles were arbitrarily decided as a runout cycles.

The final carbon composite wrap layers installed and the measured thickness by each Vendor are shown in Table 2 by pipe diameter. The average elastic modulus as provided by Vendor A = 9.1 Msi, Vendor B = 10.9 Msi, and Vendor C = 9.8 Msi. Therefore, the elastic modulus for each carbon composite material was very similar.

**Table 2: Measured Carbon Composite Layers and Final Thickness**

| Vendor | Pipe O.D. (in) | Nominal Wall Thickness (in) | Repair Layers | Measured Repair Thickness, Average (in) | Repair Thickness / Nominal Wall Thickness |
|---|---|---|---|---|---|
| A | 12.75 | 0.25 | 16 | 0.708 | 2.8 |
| | 30 | 0.375 | 21 | 0.749 | 2.0 |
| B | 12.75 | 0.25 | 28 | 0.623 | 2.5 |
| | 30 | 0.375 | 37 | 0.786 | 2.0 |
| C | 12.75 | 0.25 | 27<br>(Sample 28R = 36) | 0.408<br>(0.553) | 1.6<br>(2.2) |
| | 30 | 0.375 | 36 | 0.572 | 1.5 |

The pipeline internal pressure during the installation was zero for all but three test samples, one for each Vendor. Samples 12R, 20R, and 28R were the only ones for which composite installation was completed at 500-psig (28% SMYS). It has been reported previously that the installation pressure has limited effects on the fatigue crack growth behavior as compared with those installed at zero internal pipe sample pressure [5].

The carbon composite wrap installation by each vendor included the following steps:

- Clean surface with grit blast and wipped clean with a quick flash solvent such as Acetone
- Apply filler material to smooth wire connected to strain gage place across the crack
- Apply primer over the specified area and installed 1-2 layers of fiber glass, to provide cathodic protection between pipe and carbon composite
- Mix wet-out resin and saturate fiberglass layer before installing carbon fiber over the specified area
- Continue mix wet-out resin and saturate carbon fiber wraps and tightly apply each wrap in the target repair area until achieving the number of design layers or repair thickness
- Install curing wrap over the entire repair area to hold the epoxy during curing
- Remove shrink wrap after fully cured test specimen

# Fatigue Testing of Unreinforced Pipe Samples with Cracks

To demonstrate the benefit of using composite wraps to repair axial crack-like features in a pipeline, as series of unreinforced pipe samples with cracks provided a reference to compare the performance of the reinforced carbon composite products. The 12-inch pipe samples were fatigue tested from 100-psig (5% SMYS) to 1300-psig (72% SMYS) with approximately one cycle every 6 second, while the 30-in O.D. pipe samples were tested from 100-psig (7% SMYS) to 940-psig (72% SMYS) at one cycle every 15 seconds. Here, a total of 10 samples and 12 synthetic cracks were tested and Table 3 summarizes the test results. Samples 1U, 2U, 3U 4U, 5U, 6U and 7U had cracks in the base material while samples 8U, 9U and 10U had cracks fabricated in the ERW seam. Three samples were burst tested (1U, 4U, and 8U) and all other samples were pressure cycled to failure. The initial length for all cracks was 3-inches.

**Table 3: Fatigue Testing Results of Unrepaired Samples**

| Pipe O.D. (in) | Sample | Test | Crack Label | Initial Crack Depth (% WT) | ΔP (psi) | Pressure Cycles Reached | Fatigue Crack Growth Depth (%WT) | Failure |
|---|---|---|---|---|---|---|---|---|
| 12 | 1U | Burst | A | 34.4 | 100-1300 | - | 17.4 | Crack |
| | 2U | Fatigue | A | 31.2 | 100-1300 | 6,507 | 68.8 | Crack |
| | 3U | | A | 29.8 | 100-1300 | 5,297 | 70.2 | Crack A |
| | | | B | 27.9 | | | 28.8 | |
| 30 | 4U | Burst | A | 34.0 | 100-940 | - | 34.4 | Crack |
| | 5U | Fatigue | A | 34.8 | 100-940 | 4,273 | 65.2 | Crack |
| | 6U | | A | 34.9 | 100-940 | 4,871 | 65.1 | Crack |
| | 7U | | A | 33.2 | 100-940 | 7,685 | 66.7 | Crack |
| 12 | 8U | Burst | A | 31.3 | 100-1300 | - | 10.6 | Crack |
| | 9U | Fatigue | A | 28.9 | 100-1300 | 5,530 | 71.1 | Crack |
| | 10U | | A | 27.7 | 100-1300 | 8,990 | 72.3 | Crack A |
| | | | B | 29.6 | | | 38.0 | |

The fatigue crack growth starting from the notch is shown Figure 2 for samples 2U and 6U.

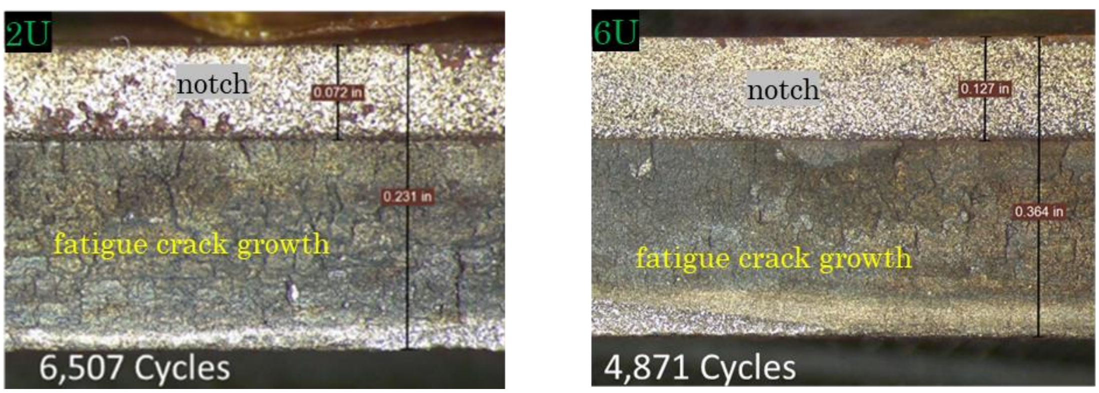


**Figure 3: Fatigue Crack Growth Behavior for Two Unreinforced Pipe Samples**

The repaired pipe samples assigned to each carbon composite wrap Vendor were fatigue tested next.

## Fatigue Crack Growth Behavior of Repaired Cracks

The starter notch size, orientation and placement in the pipe samples assigned to Vendors A, B and C were the same. The only difference was the starting crack depth achieved. After the completion of the cure time as per each Vendor's specifications, the repaired pipe samples were then set aside for full-scale fatigue testing. As with the unreinforced test samples, the 12-inch pipe samples were pressure cycle tested from 5% SMYS to 72% SMYS while the 30-in O.D. pipe from 7% SMYS to 72% SMYS also a room temperature. Each sample was tested until either reaching failure or when achieving the 25,000 runout cycles.

For Vendor A, the starting depths for all cracks were approximately between 35%-54% W.T., all with the same length of 3 inches. Table 4 shows the initial cracks dimensions and fatigue crack growth along with the number of test cycles. The only test samples that failed prior to reaching the designated 25,000 runout cycles were the samples with multiple cracks in the pipe body (11R and 12R), showing a post-repaired crack depth growth of 50% to 59.5% W.T. It is not clear why the 180° crack failed in both Samples 11R and 12R while the fatigue growth for crack at 60° and 300° was mitigated by the same repair wrap. The pipe samples with single cracks exhibited a fatigue growth between 2.0% to 8.7% W.T., far less depth growth than the samples with the runway cracks. Sample 12R was repaired while pressurized at 27% SMYS but saw a similar result as Sample 11R.

**Table 4: Fatigue Testing Results for Samples Repaired by Vendor A**

<table>
<tr><th>Pipe O.D. (in)</th><th>Sample No.</th><th>Notch / Crack Label</th><th>Initial Crack Depth (% W.T.)</th><th>Repair Thickness (in)</th><th>Post-Repaired Test Cycles</th><th>Post Repaired Fatigue Crack Growth (% W.T.)</th><th>Failure Mode and Location</th></tr>
<tr><td rowspan="6">12</td><td rowspan="3">11R</td><td>A - 60°</td><td>35.5</td><td rowspan="3">0.708</td><td rowspan="3">5,468</td><td>0.0</td><td rowspan="3">Leak in Crack B</td></tr>
<tr><td>B – 180°</td><td>40.5</td><td>59.5</td></tr>
<tr><td>C – 300°</td><td>49.0</td><td>0.0</td></tr>
<tr><td rowspan="3">12R</td><td>A - 60°</td><td>44.4</td><td rowspan="3">0.708</td><td rowspan="3">2,884</td><td>0.0</td><td rowspan="3">Leak in Crack B</td></tr>
<tr><td>B – 180°</td><td>50.0</td><td>50.0</td></tr>
<tr><td>C – 300°</td><td>48.9</td><td>0.0</td></tr>
<tr><td rowspan="3">30</td><td>13R</td><td>A</td><td>49.3</td><td>0.749</td><td>25,000</td><td>8.7</td><td>Burst at 122.7% SMYS in Unreinforced Seam</td></tr>
<tr><td>14R</td><td>A</td><td>45.6</td><td>0.749</td><td>25,000</td><td>2.0</td><td>Burst at 158.5% SMYS in Unreinforced Base</td></tr>
<tr><td>15R</td><td>A</td><td>51.9</td><td>0.749</td><td>25,000</td><td>6.6</td><td>Burst at 156.5% SMYS in Unreinforced Base</td></tr>
<tr><td rowspan="3">12</td><td>16R</td><td>A</td><td>54.0</td><td>0.708</td><td>25,000</td><td>5.1</td><td>Burst at 151.1% SMYS in Unreinforced Base</td></tr>
<tr><td>17R</td><td>A</td><td>45.7</td><td>0.708</td><td>25,000</td><td>3.0</td><td>Burst 145.7% SMYS in Unreinforced Base</td></tr>
<tr><td>18R</td><td>A</td><td>47.9</td><td>0.708</td><td>25,000</td><td>5.6</td><td>Burst at 150% SMYS in Unreinforced Base</td></tr>
</table>

Figure 4 shows an example of the fatigue crack growth mitigated by the carbon composite repair installed by Vendor A on pipe sample 14R. The initial crack depth was 45.6% W.T.

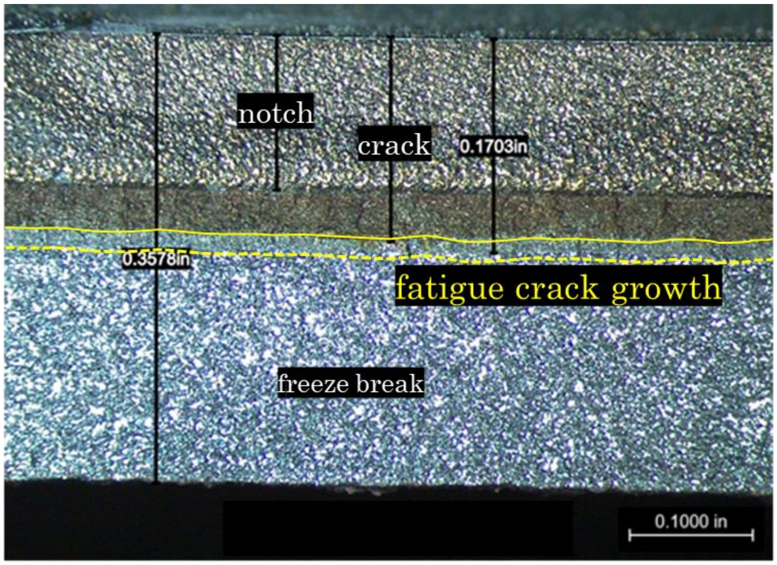


**Figure 4: Fatigue Crack Growth Appearance in Pipe Sample 14R**

For Vendor B, the assigned pipe samples were 19R to 26R and initial starting crack depth, number of composite wrap layers installed on each sample as well as the test pressure cycles, and fatigue crack growth are listed in Table 5. Sample 19R had three equally spaced notches in the base material and the crack from the 60° notch grew to a depth of 76.4% W.T. in 24,879 cycles, while the pre-cycle growth for cracks at 180° and 300° were less severe as they grew 11.2% and 10% W.T. respectively. The cracks in all other samples assigned to Vendor B had starting depths in the range of 35% to 54% W.T. and achieved the 25,000 runout fatigue cycles, exhibiting a fatigue crack growth depth between 4% to 9.5% W.T. Sample 20R was repaired with a pipe internal pressure of 500 psi and all three cracks survived 25,000 cycles with post-repaired growth ranging from 7.0% to 9.5% of wall thickness.

**Table 5: Fatigue Testing Results for Samples Repaired by Vendor B**

| Pipe O.D. (in) | Sample No. | Notch / Crack Label | Initial Crack Depth (% W.T.) | Repair Thickness (in) | Post-Repaired Test Cycles | Post Repaired Fatigue Crack Growth (% W.T.) | Failure Mode and Location |
|---|---|---|---|---|---|---|---|
| 12 | 19R | A - 60° | 76.4 | 0.623 | 24,879 | 23.6 | Leak at Crack A |
| | | B –180° | 41.0 | | | 6.0 | |
| | | C –300° | 36.9 | | | 3.5 | |
| | 20R | A - 60° | 54.3 | 0.623 | 25,000 | 9.5 | Burst at 166% SMYS in Notch B |
| | | B –180° | 35.0 | | | 7.0 | |
| | | C –300° | 40.9 | | | 8.1 | |
| 30 | 21R | A | 40.7 | 0.786 | 25,000 | 7.8 | Burst at 157.5% SMYS in Unreinforced Seam |
| | 22R | A | 39.2 | 0.786 | 25,000 | 5.1 | Burst at 145.2% SMYS in Unreinforced Base |
| | 23R | A | 42.6 | 0.786 | 25,000 | 6.1 | Burst at 156.9% SMYS in Unreinforced Base |
| 12 | 24R | A | 49.5 | 0.623 | 25,000 | 4.3 | Burst at 148% SMYS in Unreinforced Base |
| | 25R | A | 47.9 | 0.623 | 25,000 | 4.0 | Burst 163.8% SMYS in Unreinforced Base |
| | 26R | A | 44.9 | 28 | 25,000 | 4.2 | Burst at 158.7% SMYS in Unreinforced Base |

The fatigue growth behavior exhibited for crack B in sample 20R after 25,000 cycles is shown in Figure 5.

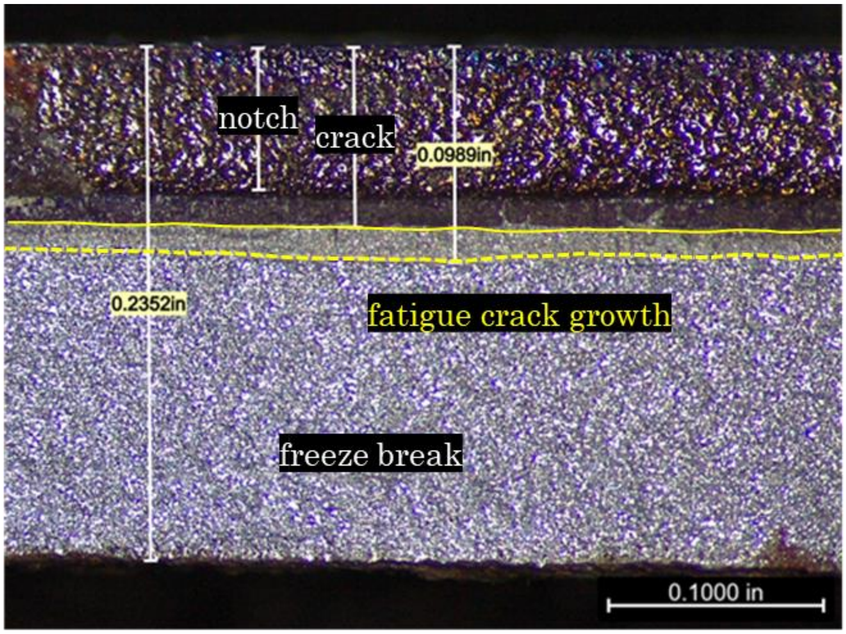


**Figure 5: Fatigue Crack Growth Appearance for Crack B in Pipe Sample 20R**

For Vendor C, the marked pipe samples were 27R to 34R and the starting crack characteristics, fatigue testing parameter and fatigue crack growth are presented in Table 6. The initial crack sizes ranging from 32% to 84% W.T. for the two samples with three cracks in each. The rogue crack in sample 28R with an initial depth 84% W.T. still achieved 2,335 cycles until it leaked. One crack in sample 27R reached through wall during the crack initiation phase, after which a metal plate was welded, and the fatigue testing continued. Samples 29R and 30R achieved 25,000 pressure cycles, while sample 31R reached 20,267 cycles. Even though it was demonstrated an increase on fatigue life compared to unreinforced samples, the post-repair growth for these test articles ranged from 30.5% to 43.1% W.T. This greater fatigue crack growth measured for samples 29R, 30R and 31R is somewhat expected because the thickness of the repairs were approximately 25% thinner than the other Vendors, with all repair systems having a similar elastic modulus, as indicated in Table 2. This demonstrates that fatigue life extension increases with the reinforcement capacity of the wraps, as there is a link between stiffness and thickness. For pipe sample 33R, the fatigue crack growth was nearly zero and for sample 34R only 5% W.T., while 35% W.T. for sample 32R. The cracks in these three pipe samples were in the ERW bondline.

**Table 6: Fatigue Testing Results for Samples Repaired by Vendor C**

| Pipe O.D. (in) | Sample No. | Notch / Crack Label | Initial Crack Depth (% W.T.) | Repair Thickness (in) | Post-Repaired Test Cycles | Post Repaired Fatigue Crack Growth (% W.T.) | Failure Mode and Location |
|---|---|---|---|---|---|---|---|
| 12 | 27R | A - 60° | Failed During Pre-Cycling | | | | |
| | | B – 180° | 39.3 | 0.408 | 25,000 | 4.9 | Burst at 166% SMYS in Unreinforced Seam |
| | | C – 300° | 45.3 | 0.408 | | 3.5 | |
| | 28R | A - 60° | 84.2 | 0.553 | 2,325 | 15.8 | Leak in Crack A |
| | | B – 180° | 39.6 | | | 0.0 | |
| | | C – 300° | 32.6 | | | 0.0 | |
| 30 | 29R | A | 40.9 | 0.572 | 25,000 | 36.3 | Burst at 152.4% SMYS in Unreinforced Seam |
| | 30R | A | 45.5 | 0.572 | 25,000 | 30.5 | Burst at 156.8% SMYS in Unreinforced Base |
| | 31R | A | 56.9 | 0.572 | 20,267 | 55.2 | Leak in Crack A |
| 12 | 32R | A | 55.5 | 0.408 | 25,000 | 35.6 | Burst at 173.4% SMYS in Unreinforced Base |
| | 33R | A | 52.7 | 0.408 | 25,000 | 0.0 | Burst 156.4% SMYS in Unreinforced Base |
| | 34R | A | 50.8 | 0.408 | 25,000 | 5.1 | Burst at 145.1% SMYS in Unreinforced Base |

The fatigue crack growth behavior exhibited in sample 34R after 25,000 cycles is shown in Figure 6.

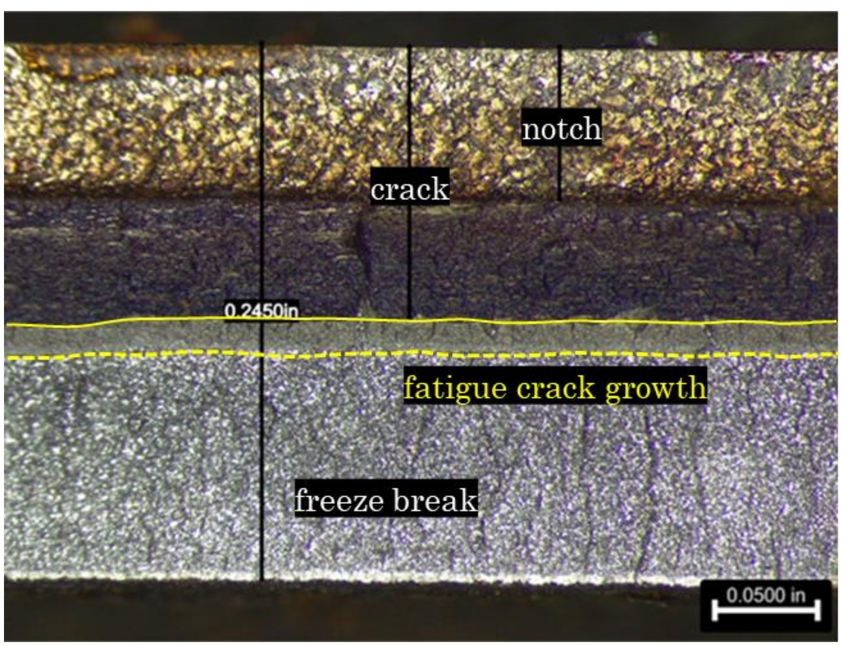


**Figure 6: Fatigue Crack Growth Appearance in Pipe Sample 34R**

# Discussion of Results

The fatigue crack growth results for the repaired 12-inch O.D. pipe samples are plotted in Figure 7, where the values shown below the abscissa are the average starting crack size percentages (notch + pre-crack growth), where 46% W.T. is the average starting crack depth (56% W.T. was upper bound). All cracks in the ERW seam survived 25,000 runout cycles with less than 10% post-repaired fatigue growth. A total of 26 cracks were tested in the either the base material or ERW seam of the 12-in pipe and four leaked prior to reaching the runout of 25,000 cycles. The 22 cracks that survived the 25,000 runout cycles either showed no post-repaired fatigue growth or were less than 10% of the wall thickness. It is noted that the unreinforced cracks grew through wall after 8,890 cycles or less. To have gone through wall, the cracks initiated from notches 3U-B and 10U-B would have required additional cycles; however, all the reinforced cracks in the ERW seam grew ≤10% W.T. after 25,000 cycles, which demonstrates the ability for the carbon composite wrap repair systems to retard crack growth.

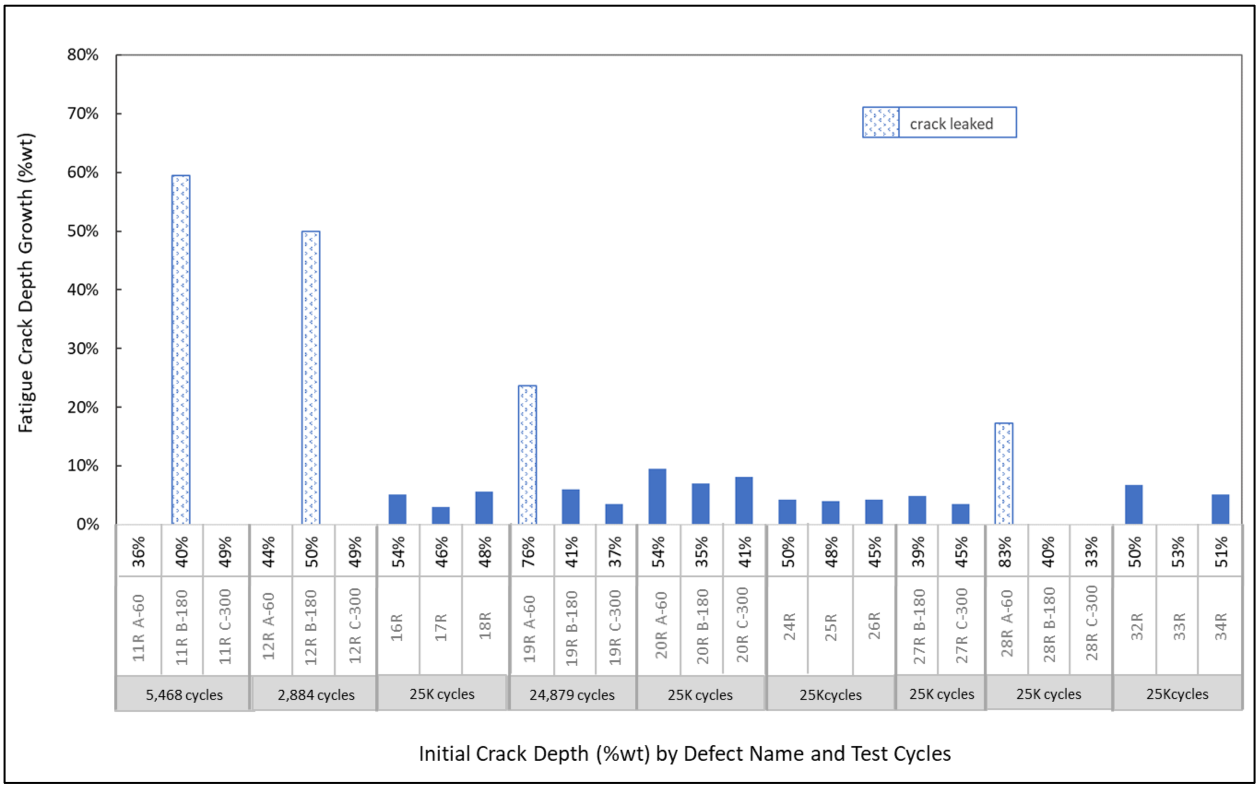


**Figure 7: Fatigue Crack growth for All 12-inch Pipe Samples**

The 30-inch O.D. pipe samples had similar performance to the 12.75-inch O.D. test articles, as presented in Figure 8. For the three unreinforced pressure cycled samples (designated as 5U, 6U, and 7U) they leaked at 5,610 cycles on average. Once reinforced, Vendor A Samples 13R, 14R, and 15R and Vendor B Samples 21R, 22R, and 23R, with one crack in each sample, had starting crack sizes that ranged from 39% to 49% of the wall thickness and reached 25,000 runout cycles. During the 25,000 post-repaired cycles, all six cracks grew less 10% of the wall thickness. The three 30-inch test samples repaired by Vendor C had samples 29R and 30R surviving 25,000 pressure cycles, while sample 31R reached 20,267 cycles. Even though it was demonstrated that fatigue life was increased compared to unreinforced samples, the post-repair growth for these test articles ranged from 30.5% to 43.1% of the wall thickness. As noted previously, the greater fatigue crack growth measured for samples 29R, 30R and 31R was expected because the repairs were approximately 25% thinner than the others with all systems having a similar elastic modulus. This demonstrates that fatigue life extension increases with the reinforcement capacity of the wraps, as expected because that is linked to stiffness and thickness.

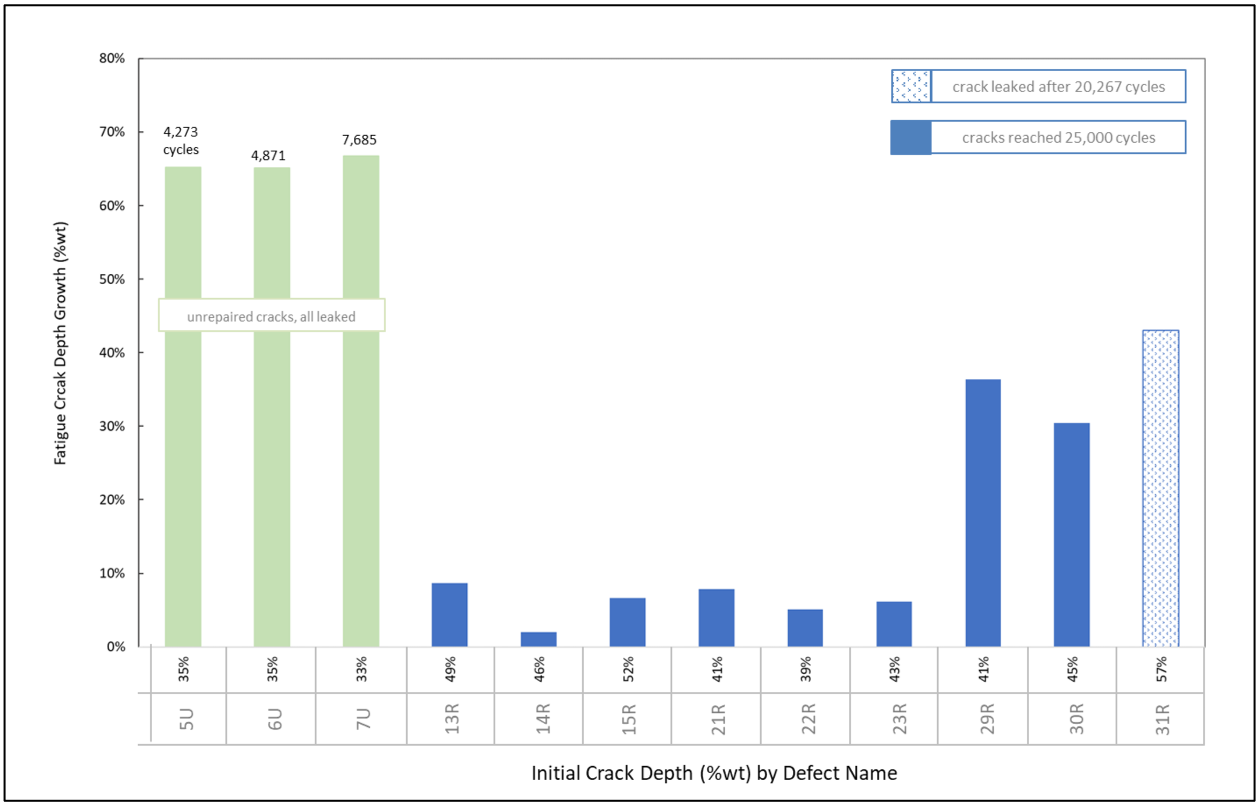


**Figure 8: Fatigue Crack Growth for All 30-inch O.D. Pipe Samples**

The pressure test cycles employed in this study were selected to accelerate the fatigue performance of the reinforced pipe samples. While subjecting test articles to similar test environments and loading conditions that are experienced by in-service pipelines would be ideal, the timing to complete such tests would be unreasonable. Analytical fatigue crack growth studies using the most aggressive cyclic loading scenarios (i.e., liquids pipelines) usually lead to many months or years for an unrepaired subcritical crack to reach a failure condition. Nevertheless, a correlation of the tested cyclic pressure severity to common operational pipeline cyclic pressures for natural gas and liquids pipelines was carried out to ascertain the relative severity and equivalency of test pressures with simulated pipeline fatigue life. An example of the test cyclic pressures for sample 6U (30-inch pipe) are shown in Figure 9, which were superimposed to gas pipeline pressures provided by some of the participating pipeline operators. This comparison illustrates the relative severity of the test cyclic pressures to typical pipeline operational cyclic pressures. It is noted that it took less than a day for this test sample to fail (4,871 cycles).

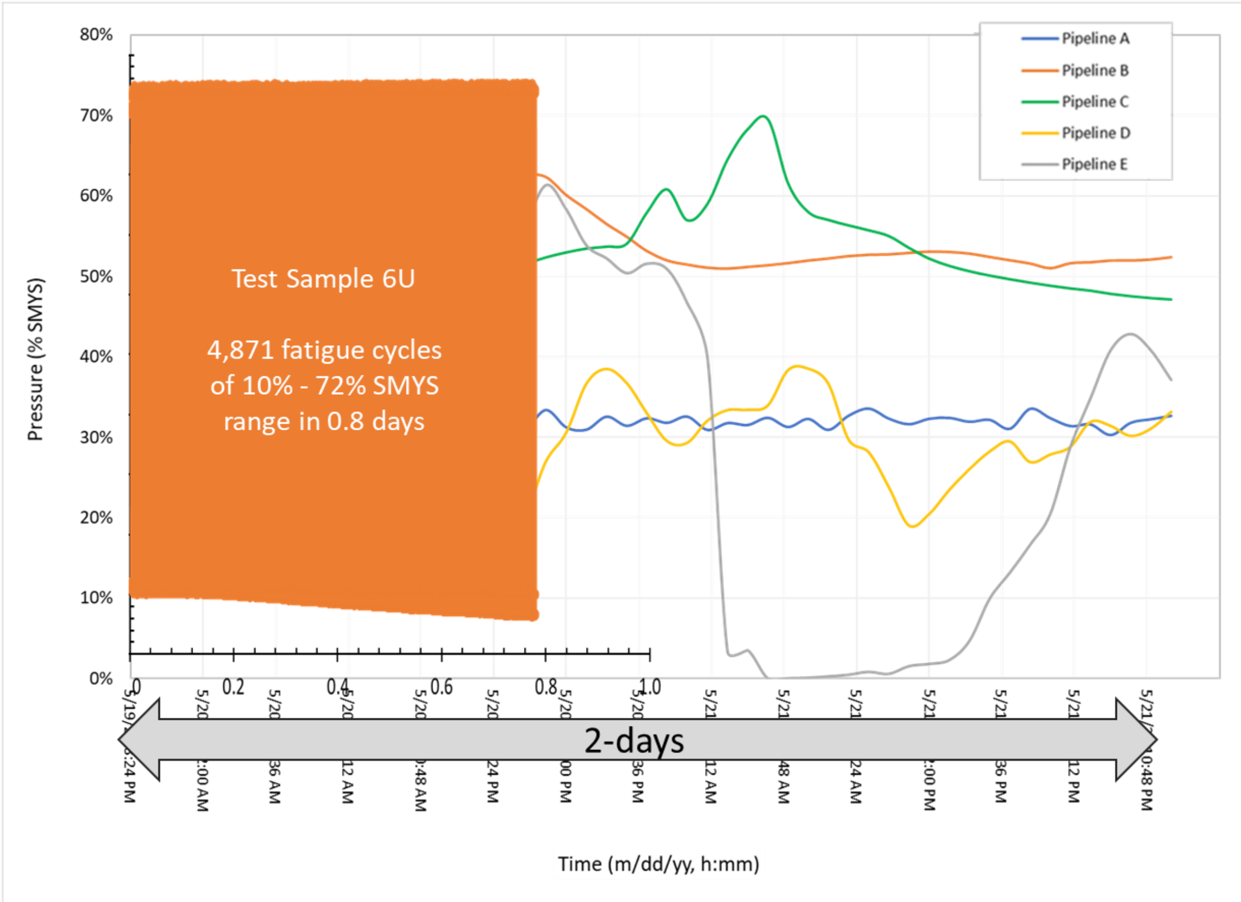


**Figure 9: Test Cyclic Pressures for Sample 6U and Typical Pipeline Operational Pressures**

The relative severity (magnitude and number of cycles) of the test cyclic pressures translates conservatively to fatigue crack growth life in the range of 600 to 1,000 years for common pipeline cyclic pressure severities, for the crack sizes tested and the pipeline cyclic pressures provided.

# Concluding Remarks

Carbon-epoxy composite repair systems as designed, installed and tested in this study showed to be a viable repair option for axial crack-like defects with starting depths of up 56% W.T. and 3-inch long.

The unreinforced samples with cracks in the pipe body failed in the range of 5,300 to 7,680 fatigue pressure cycles, while those in the ERW seam bond line ranged from 5,530 to 8,990 fatigue cycles. The failure mode for all unreinforced test samples was a leak. The reinforced cracks by all three carbon composite vendors that reached 25,000 fatigue cycles grew by an average of 8% of W.T. in the 12-inch O.D. samples and by 13% of W.T. for the 30-inch samples. There were four pipe samples, all in 12-inch pipe, that failed unexpectedly with one crack in each leaking in less than 25,000 fatigue cycles. These unexpected failures all occurred on samples that had three cracks, most with similar starting cracks depths. Metallurgical examination of their crack growth path and inspection of the reinforced composites did not show irregularities. The factors that resulted in the unusually higher crack growth rate behavior for the four cracks are inconclusive. Since the unreinforced and reinforced samples have both shown that cracks in the same pipe spool, with no obvious material differences can grow at different rates, the repair design should take unexpected growth into account.

The cycles to failure of the reinforced fatigue cracks increased by 3 to 5 times when compared to cycles to failure of unreinforced cracks, while excluding the four cracks that led to premature failures. The results of this study indicate that the three carbon-epoxy composite repair systems, when properly designed and installed, can effectively reinforce pipelines with crack-like defects subject to the conditions evaluated in this study. Moreover, the results in this study can be used to validate and optimize existing carbon composite designs and tools for reinforced pipelines with planar defects.

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