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FINITE ELEMENT ANALYSIS OF COMPOSITE REPAIRS WITH FULL-SCALE VALIDATION TESTING

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ABSTRACT

Composite repair systems for pipelines are continuing to be used for increasingly difficult and complex applications which can have a high consequence of failure. In these instances, full-scale testing is typically pursued at a high-cost to the manufacturer or operator. Finite element analysis (FEA) modeling is a valuable tool that becomes especially attractive as a method to reduce the number of full-scale tests required. This is particularly true when considering the costs associated with recreating complex load and temperature conditions. In order for FEA to fill this role, it is necessary to validate the results through full-scale testing at the same loads and temperatures. By using these techniques, FEA and full-scale testing can be used in unison to efficiently produce accurate results and allow for the adjustment of critical parameters at a much lower cost than creating additional full-scale tests.

For this program, a series of finite element analysis (FEA) models were developed to evaluate the performance of composite materials used to reinforce corroded steel pipe in critical applications at elevated temperatures up to 120 °C. Two composite repair manufacturers participated in the study which was conducted on 12-inch x 0.375-inch Gr. X60 pipes with machined simulated corrosion defects that represented 50% wall loss. Load conditions consisted of axial compressive loads or bending moments to generate compressive stresses in the machined defect.

In the described evaluation program, FEA simulations were able to produce results which supported those found in full-scale validation testing. From the FEA models stresses and strains were extracted from the reinforced steel and composite materials. Good correlation was observed in comparing the results. Although limitations of the modeling included accurately capturing differential thermal strains introduced by the elevated test temperature, the results indicated that FEA models could be used as a cost-effective means for assessing composite repair systems in high-temperature applications.

INTRODUCTION

Over the last two decades, the composite repairs in the pipeline industry have seen significant increases in the technical complexity of desired applications. As a result, pipeline operators have been forced to demonstrate rigorous technical due diligence during design of the repair system prior to receiving the approval of industry regulators. For repairs associated with transmission pipelines, this is most often accomplished through full-scale testing that replicates the loads, temperatures, and pressures to be experienced by the repair system. In high-temperature applications, this can be an extremely costly endeavor. The use of FEA allows for critical parameters to be adjusted without the significant costs associated with multiple full-scale tests; however, this approach can only be used following the validation of initial modeling with the results of full-scale testing.

For this particular assessment, a comprehensive program was developed in which experimental and analytical approaches were used to evaluate the use of composite materials as a means for reinforcing corroded pipelines operating at elevated temperatures up to 120 °C. Experimental efforts focused on full-scale bending and compression testing of two prospective composite repair systems. One of the systems (System A) was a carbon-based repair system. The second system (System B) was a fiberglass (E-glass) based system.

- System A – Carbon Fiber
- System B – E-glass

The two prospective systems were selected using a full-scale testing regime that included internal pressure, axial compression, and bend tests [1]. Full-scale testing focused on the reinforcement of 12.75-inch x 0.375-inch, Gr X60 pipes.

In order to evaluate the effects of the composite repair systems on several pipe sizes under different design loading conditions, an FEA modeling program was developed and validated using results from the full-scale tests. Target design loads were provided by the operator and included axial compressive and bending loads with internal pressure equal to 72% of the pipe's specified minimum yield strength (SMYS). The load conditions were designed to generate compressive stresses in a simulated corrosion defect. The defect simulated 50% wall loss corrosion and was 8 inches in axial length by 12 inches in circumferential width. A photograph of the simulated corrosion defect is shown in Figure 1. From the FEA models, stresses and strains were extracted from the reinforced steel and the composite materials. A list of the test cases for both experimental and analytical techniques is provided in Table 1.

ANALYSIS METHODS

ABAQUS ver.6.13.1 general-purpose finite element code was used in performing all analyses. The base pipe was modeled using solid continuum elements (C3D8R) and the composites were modeled using continuum shell (SC8R) elements. The geometry of the FEA was modeled as half-symmetry in two planes making it a quarter-symmetry model; the XY and ZX planes are shown in Figure 2.

For description purposes the materials evaluated in the current study are classified into three categories that include steel, the load transfer material (i.e. filler material), and composite materials. With the exception of the steel base pipe, all materials were modeled elastically. Due to limitations in modeling the composite system, failure modes, such as delamination or other damage mechanisms, were not accounted for in the FEA model.

Material Definitions

The pipe samples used in full-scale testing included both Grade X42 and Grade X60 material. The FEA case matrix also specified Grade X46 for the 4-inch NPS and the 10-inch NPS pipes. The minimum yield and tensile strength for each grade of steel were obtained according to API 5L, *Specification for Line Pipe*. The degradation of yield as a function of temperature was assumed to be representative of low to medium-alloy steel pipe material.

Composite System

The majority of composite repair systems utilize a load transfer material to impart the loads from the repaired system to the composite matrix used for providing reinforcement. For applications where metal loss is present, the defect area is filled with this load transfer material, thus it is often referred to as *filler material*. In modeling, the defects were filled with an incompressible load transfer material. The fiber lay-up is such that all fabric is oriented in the hoop direction, although the per-layer fiber orientation for each system in testing was not known. Both of the tested systems integrate an epoxy resin matrix formulated for high temperature applications. Each manufacture provided an estimate of the required thickness of repair, overlap, and taper for respective pipe sizes.

Geometric Modeling and Mesh Details

Figure 2 shows the modeling of the simulated defect in 12.75-inch x 0.358-inch, Grade X60 pipe. The same defect geometry was used for all pipe sizes modeled in this study. Although the defect shape and size were not parameterized functions of pipe size, the length of the pipe was parameterized. Due to symmetry, the length of the pipe was set as five times the nominal outside diameter of each respective pipe size, although in actuality the total pipe length is 10 times the nominal diameter. This was done to be consistent with the experimental axial compression tests in which the length of the samples was 10 times the pipe diameter. Length is an important consideration in compression analysis as it affects the slenderness ratio, which in turn affects buckling load. Typically, large slender columns *buckle*, intermediate columns *crush and buckle*, and short columns *crush*. Thus, by parameterizing the length as a function of pipe diameter, the slenderness ratio of all pipes was maintained.

Load and Boundary Conditions

The load conditions evaluated in the study were designated the "Flexible Design" and "Rigid Design" cases and were evaluated for both System A and System B. The Flexible Design and Rigid Design designations correspond to conditions associated with the full-scale bending and axial compressive loads, respectively. The compressive loads listed in Table 2 include pressure end loads; loading generated by internal pressure was applied as traction to the models. Internal pressure during testing and analysis was equal to 72% of the pipe's specified minimum yield strength (SMYS). The bending moment was applied using a kinematic coupling by specifying a rotation equal to that of the design bending moment. All loading conditions were applied such that compressive stresses were produced in the defect region.

Elevated temperatures were applied to the model in the form of a uniform pre-defined field. This method meant that all regions of the model experienced the same temperature.

EXPERIMENTAL

Full-scale validation testing was conducted using two repaired pipe samples for each repair system. One pipe per system was tested in compression, and one per system was tested in bending. Defects were identical to those modeled in the FEA analysis, and were located on 12.75-inch x 0.375-inch, Grade X60 pipes. Strain gages were placed on the validation test samples to allow comparison with FEA results. Internal pressure was applied hydrostatically using heat transfer oil.

The compression tests were intended to simulate in-situ operating conditions. Two load cases were considered for each sample. The first load case was a Design Capacity test that involved pressurizing the sample to 72% SMYS and applying a compressive load of approximately 450 kips (1 kip = 1,000 lbs). This load and pressure was held for 30 minutes. The second load case simulated a Hot Shutdown scenario in which the internal pressure was reduced to zero and the compressive load was maintained. Again, the compressive load was held for 30 minutes. Following successful completion of both load cases, the samples were then subjected to increasing compressive loads until gross plastic deformation, as measured by displacement transducers, occurred. All full-scale compressive testing was completed at a temperature of 120 °C. Figure 3 is a photograph of the full-scale compression test setup.

As with full-scale compression testing, two load cases were used to simulate possible in-situ bending at the repair site. Both load cases were conducted at 120 °C. A Design Capacity test consisted of pressurizing the sample to 72% SMYS and applying a bending moment of 129,073 ft-lbs. This load was applied twice with the sample rotated 180° between each step in order to subject the sample to both tension and compression. In each scenario, the load and internal pressure was maintained for 30 minutes. The second load condition simulated a hot shutdown scenario in which internal pressure was removed while the bending moment was held constant, again for 30 minutes. This was performed such that the simulated corrosion region was placed in compression. Following completion of both load scenarios, the bending moment was increased until gross plastic deformation occurred. Figure 4 is a photograph of the full-scale bend test setup.

RESULTS

Test results are provided for both the full-scale compression (Rigid) and bending (Flexible) tests along with the results of the FEA. In all comparisons, where the results from the experiment are compared with FEA, <u>solid lines</u> represent experimental data and <u>dotted lines</u> indicate results from FEA. In all cases, thermal strains obtained in FEA have been removed (i.e. zeroed out). Thermal strains are those strains generated in the pipe and composite materials after heat-up from ambient conditions to 120 °C. When thermal strains are removed, there is good correlation between the FEA and testing. Unless specifically indicated in the plots, the strains reported refer to the strains in the steel.

Full-scale Compression Testing

Results are first shown for the System A repair and then for System B. Figure 5 and Figure 6 plot comparisons of the axial strains measured during testing and those from analysis for Systems A and B, respectively, for axial. In both instances, the thermal strains in the analysis have been zeroed out. The testing data is kept unaltered. Axial strains in the defect, extracted at locations where Gages 1 through 4 were installed, are plotted from the FEA model. When axial strains are compared in the base pipe, there is strong correlation between the testing and FEA results.

Full-scale Bending Testing

Figure 7 (axial strain) plots data comparing the FEA and full-scale test results for full-scale bend testingusing the System A repair. Similar to Figures 5 and 6, Figure 7 depicts the comparison with the thermal strains from analysis zeroed out.

On observing the data for the bending test, an initial non-zero bending moment is observed without a corresponding strain, indicating that the strains had been zeroed at this initial stage. This is likely due to the fact that during full-scale testing, the pipe has to be simply supported and the weight of the pipe and other appurtenances may have contributed to this initial non-zero bending moment. In order to account for this difference in the initial non-zero bending moment observed in tests, the FEA plots have been adjusted by this initial non-zero bending moment. The initial non-zero bending moment was about 32.2 kip-ft.

For the purposes of comparing the bending test results for the System B repair with FEA, the FEA curves had been offset by an initial non-zero bending moment (23,987 lbf-ft) as observed in the tests. The strains are compared in the base pipe only as the strain gages inside the defect were not functional (Figure 8).

Tabulated Results

Following validation of the strains using full-scale testing results, the remaining load cases were completed with the strains recorded at points of interest. As discussed previously, thermal strains were zeroed for comparing the results from testing and FEA; however, thermal strains were not zeroed in the tabular results. Minimum thermal strain values are provided in the tables to provide the reader with the magnitude of thermal strains that were calculated. In general, the observed minimum thermal strains are constant for the range of analyzed pipe sizes.

Table 1 tabulates stresses and strains in the composite materials at design load. Since component strains are provided, appropriate signs are indicated. The maximum axial and hoop-oriented shear stresses observed in the entire composite are provided at the respective design loads while the minimum thermal strains observed in the entire composite are reported. Table 2 tabulates the maximum Mises stress and plastic equivalent strain (PEEQ) at design conditions.

DISCUSSION

FEA analysis was conducted based on facility design loads and field defect history. A Gaussian defect distribution was calculated based on a history defect ILI and dig verification, then representative defects were selected that would be as severe or worse than the expected defects found in the field. FEA of these defects with composite wrap repairs applied allowed for comparison against system design loads and consideration for bending and compression loads, which are not rigorously addressed in relevant industry standards, such as ASME PCC-2.

The FEA model was validated by full scale experiment, then used to extrapolate to different pipe sizes representative of the facility in question. It was observed that the modeling methodology has some limitations in capturing differential thermal strains; however, zeroing thermal strains facilitated a direct comparison of the FEA and testing results. Additional potential causes of discrepancy between the FEA and testing results could be the modeling assumptions that the first layer of the composite is perfectly bonded to the pipe and that temperature is uniform throughout the model. Long-term allowable compressive strains were determined from elevated temperature creep testing with a further derating factor to account for compressive vs. tensile loading [2]. Figure 9 shows the stress-rupture plot for System A from previous material testing. No long-term compression data for the materials in question was available. In the absence of actual data for the materials, a compression de-rating factor was used. The compression de-rating factor used was 22%, based on analysis of 41 materials reported in available literature [3,4]. This de-rating factor is conservative. It was found that the predicted strain in the composite under bending or compression load exceeded the allowable long-term compressive strains once the de-rating factor was applied.

If better test methods for long-term compressive creep damage measurement on fiber-reinforced composites were available, then the amount of conservatism could be decreased. This might enable composite wraps for use under the expected compression and bending loads. Further testing to determine these properties and decrease the conservatism in the de-rating factor may be considered but has not been performed at this time.

REFERENCES

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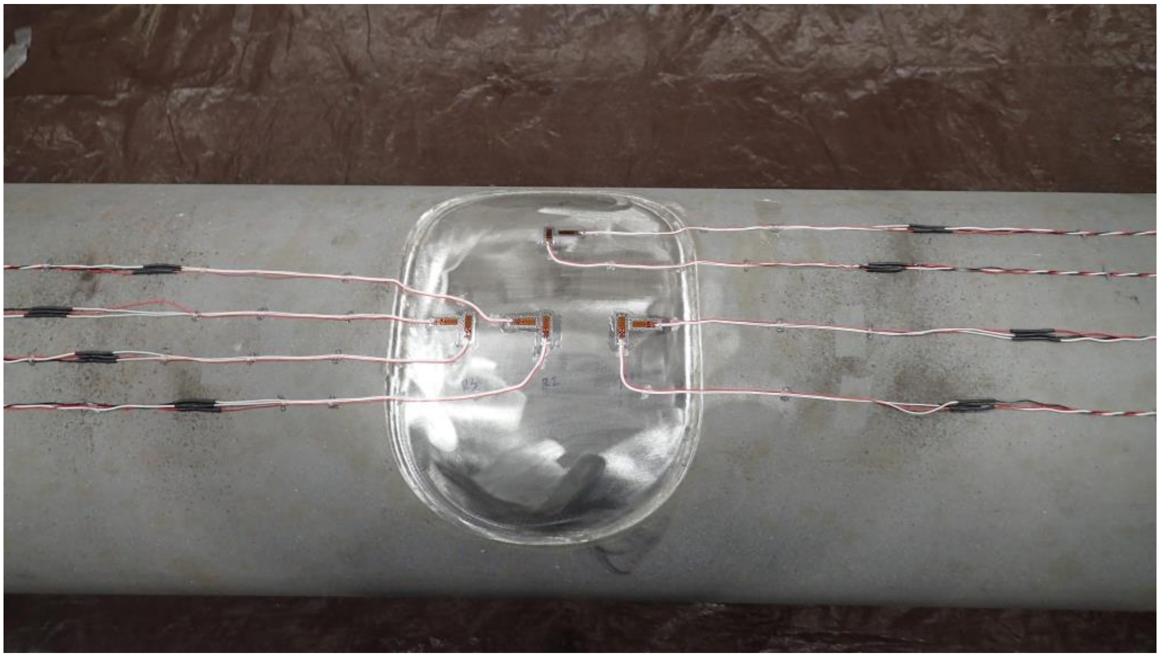

Figure 1: Photograph of 50% simulated corrosion defect

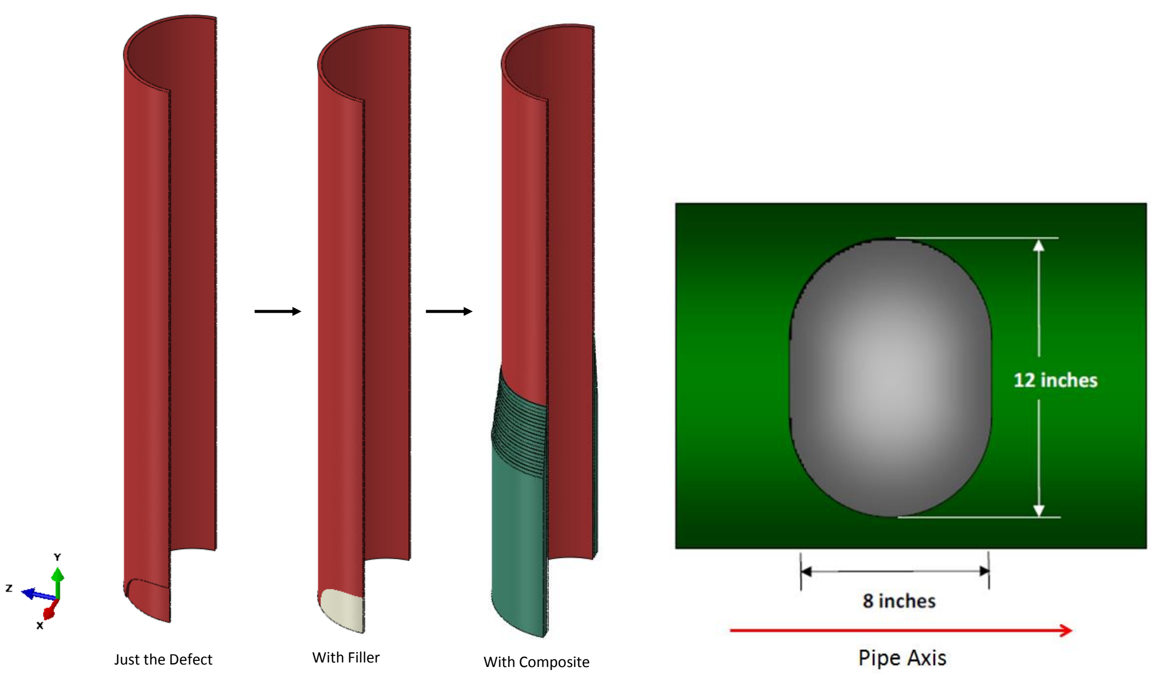

Figure 2: Modeled defect in 12 inch NPS x 0.358'' wall thickness. (left) Half-symmetry model showing the defect, filler and the composite. (right) 50% wall loss simulated corrosion defect dimensions (12'' circumferential, 8'' axial extent).

Figure 3: Photograph of full-scale compression test setup

Figure 4: Photograph of full-scale bend test setup

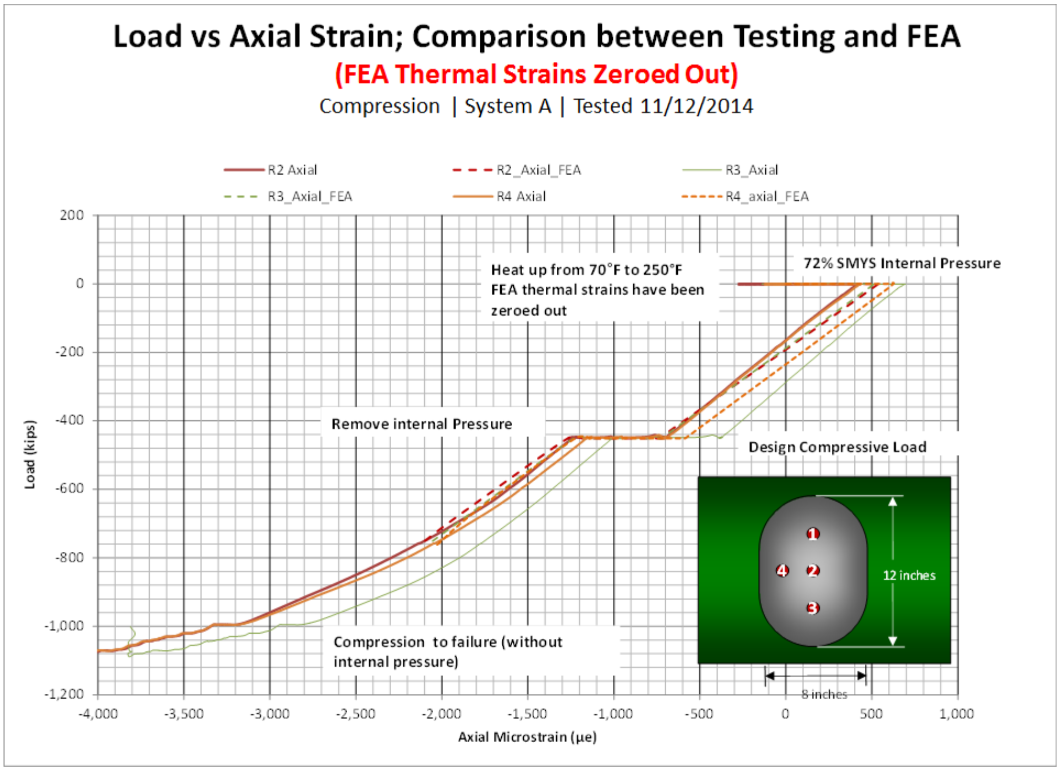

Figure 5: Comparison of axial strains for pipe loaded in compression. System A repair. Solid lines represent strains measured in the validation test. Dashed lines are FEA generated curves. Parametric curves should be read from top right to bottom left, as negative compression load increases over time.

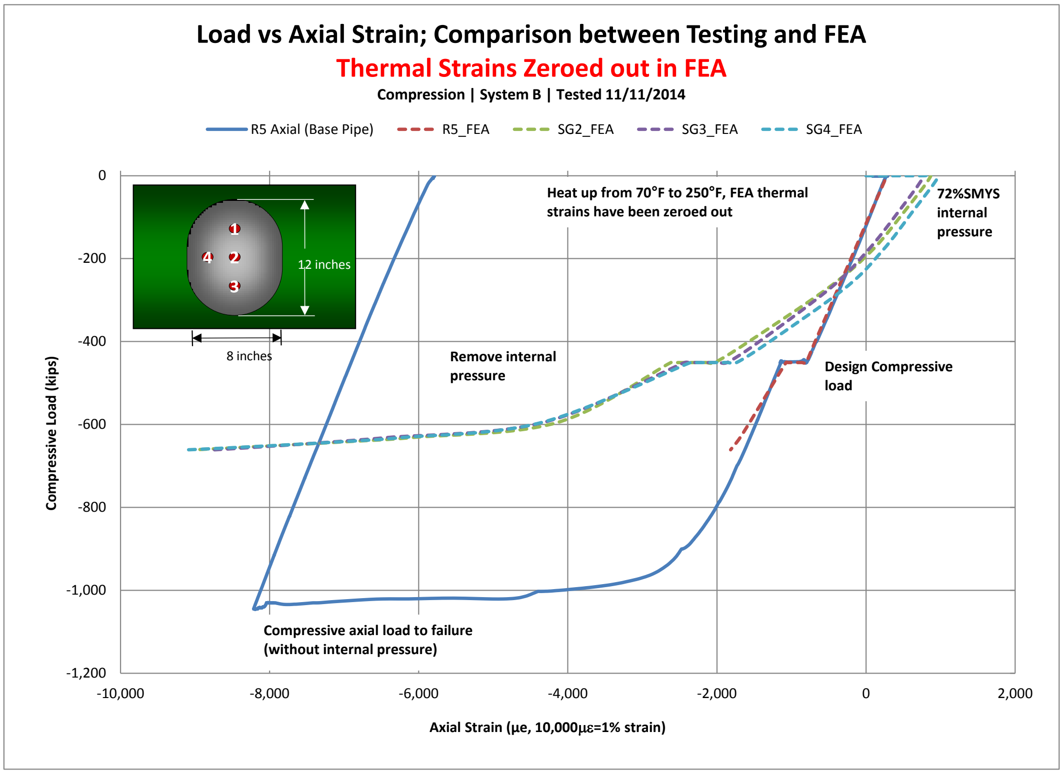

Figure 6: Comparison of axial strains for pipe loaded in compression. System B repair. Solid lines represent strains measured in the validation test. Dashed lines are FEA generated curves. Parametric curves should be read from top right to bottom left, as negative compression load increases over time.

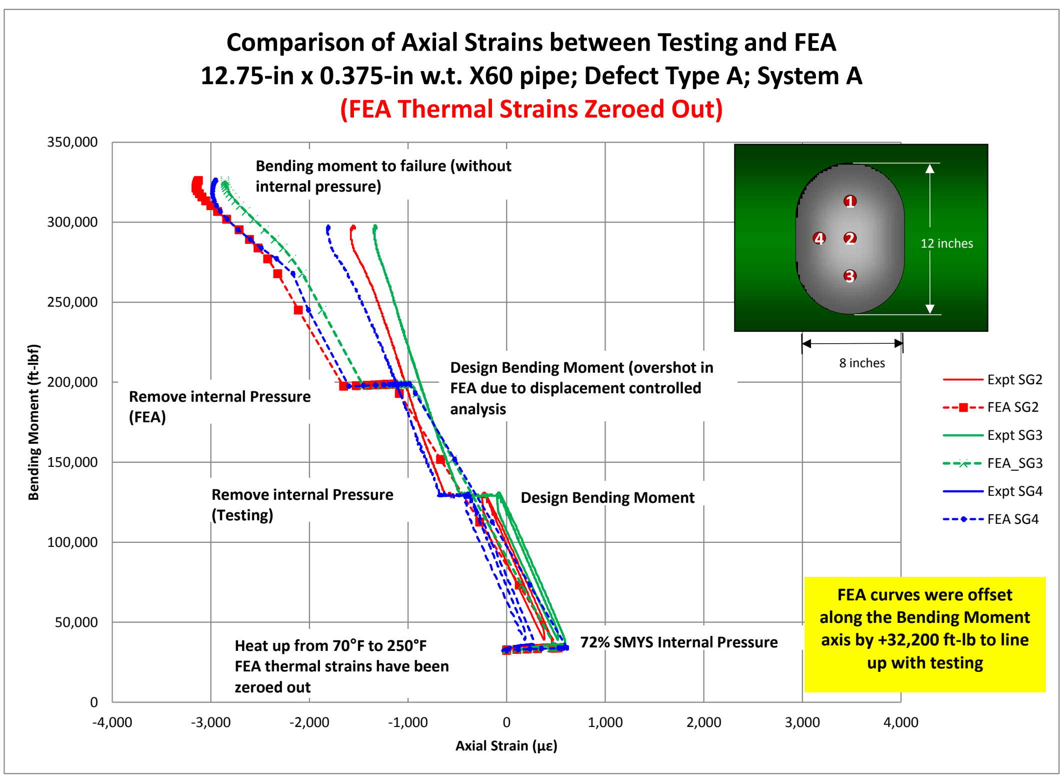

Figure 7: Comparison of axial strains for pipe loaded in bending. System A repair

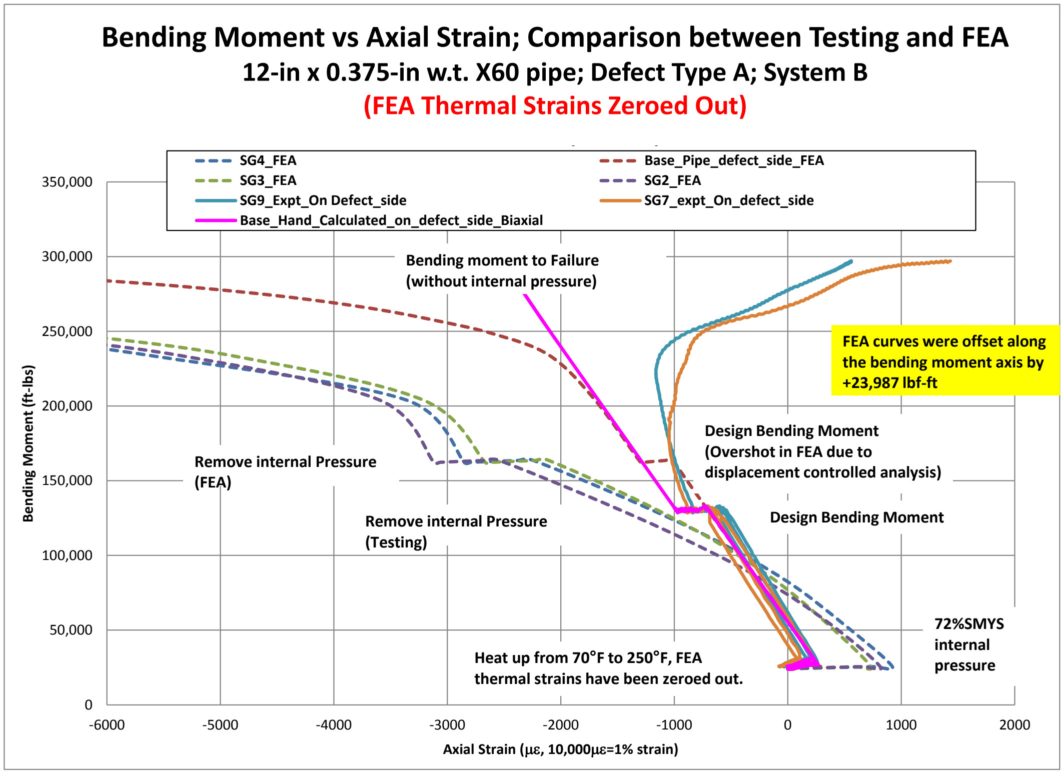

Figure 8: Comparison of axial strains; Pipe loaded in bending; System B repair

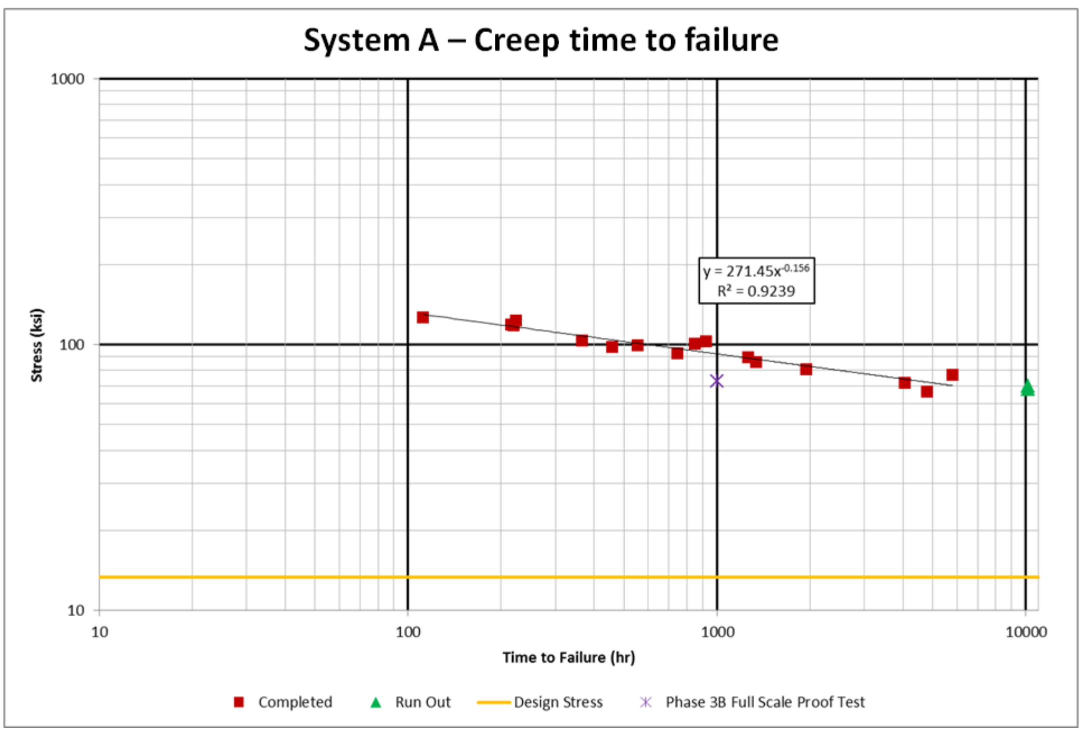

Figure 9: Creep rupture results for System A

Table 1: Stresses and strains in composite at design load

Pipe Loaded in Bending													
NPS(in.)	O.D(mm)	API 5L Grade	t (mm)	Design Bending Moment (N-m)	Design Bending Moment (lbf-ft)	Failure Bending Moment (lbf-ft)	Minimum Strain in Composite at Temperature Loading (με)		Strain in Composite at Design Load (με)			Maximum Shear Stress at interface at Design Load (psi)	
							Hoop (με)	Axial (με)	Hoop (με)	Axial (με) (Max)	Axial (με) (Min)	Hoop (psi)	Axial (με)
4	114.3	X46	8.41	14,800	10,916	25,467	1,082	1,054	5,990	4,408	-93	1,171	1,106
6	168.3	X60	9.5	57,500	42,410	72,300	1,078	880	7,138	3,719	-484	-1,167	-1,242
8	219.1	X60	12.7	119,700	88,286	111,167	1,072	877	8,168	-3,338	-368	-2,058	-2,518
10	273.1	X46	11.13	107,400	79,214	192,000	1,066	880	5,711	2,635	83	-803	-937
12	323.9	X60	9.1	151,700	111,888	264,500	1,073	882	5,774	2,797	154	-784	-941
12	323.9	X60	9.5	175,000	129,073	294,167	994	884	4,954	2,992	10	-758	-1,003
Pipe Loaded in Compression													
NPS(in.)	O.D(mm)	API 5L Grade	t (mm)	Design Axial Compressive Load (N)	Design Axial Compressive Load (lbf)	Failure Axial Compressive Load (lbf)	Minimum Strain in Composite at Temperature Loading (με)		Strain in Composite at Design Load (με)			Shear Stress at interface at Design Load (psi)	
							Hoop (με)	Axial (με)	Hoop (με)	Axial (με) (Max)	Axial (με) (Min)	Hoop (psi)	Axial (με)
24	609.6	X60	14.5	5,696,069	1,280,527	2,196,000	1,039	869	6,321	1,895	-138	-926	-930
16	406.4	X60	10.7	2,794,905	628,320	1,076,800	1,036	879	5,303	1,916	-119.4	-684	-915
12	323.9	X60	9.5	2,000,000	449,618	761,600	993	882	4,714	2,155	-154.6	-691	-933
12	323.9	X60	9.1	1,891,008	425,116	729,000	1,073	885	5,508	1,908	-128.9	-717	-919
6	168.3	X60	7.9	1,082,486	243,353	327,600	961	1,064	5,637	2,654	-310.7	-799	-1,823
Rows highlighted in blue indicate that these cases have been tested for the two composites under consideration; FS = Full Scale Testing													

Table 2: Stresses and strains in steel (inside defect) at design load

Pipe Loaded in Bending										
NPS(in.)	O.D(mm)	API 5L Grade	t(mm)	Design Bending Moment (N-m)	Design Bending Moment (lbf-ft)	Failure Bending Moment (lbf-ft)	Maximum Mises Stress and Plastic Strain inside defect			
							Temperature Load		Design Load	
							von Mises Stress (psi)	PEEQ (με)	von Mises Stress (psi)	PEEQ (με)
4	114	X46	8.41	14,800	10,916	25,467	12,190	0	43,187	2,770
6	168	X60	9.5	57,500	42,410	72,300	14,300	0	53,363	824
8	219	X60	12.7	119,700	88,286	111,167	13,360	0	54,710	2,027
10	273	X46	11.13	107,400	79,214	192,000	13,960	0	33,330	300
12	324	X60	9.1	151,700	111,888	264,500	14,160	0	41,953	0
12	324	X60	9.5	175,000	129,073	294,167	16,750	0	46,963	0
Pipe Loaded in Compression										
NPS(in.)	O.D(mm)	API 5L Grade	t(mm)	Design Axial Compressive Load (N)	Design Axial Compressive Load (lbf)	Failure Axial Compressive Load (lbf)	Maximum Mises Stress and absolute Strain inside defect			
							Temperature Load		Design Load	
							von Mises Stress (psi)	PEEQ (με)	von Mises Stress (psi)	PEEQ (με)
24	609.6	X60	14.5	5,696,069	1,280,527	2,196,000	11,770	0	50,240	0
16	406.4	X60	10.7	2,794,905	628,320	1,076,800	14,590	0	42,080	0
12	323.9	X60	9.5	2,000,000	449,618	761,600	16,810	0	50,350	0
12	323.9	X60	9.1	1,891,008	425,116	729,000	14,240	0	44,580	0
6	168.3	X60	7.9	1,082,486	243,353	327,600	15,380	0	52,040	212
Rows highlighted in blue indicate that these cases have been tested for the two composites under consideration; FS = Full Scale Testing										