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DEVELOPING STRESS INTENSIFICATION FACTORS FOR COMPOSITE REPAIR SYSTEMS USED TO REPAIR DAMAGED PIPE

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ABSTRACT

For the better part of the past 15 years composite materials have been used to repair corrosion in high pressure gas and liquid transmission pipelines. This method of repair is widely accepted throughout the pipeline industry because of the extensive evaluation efforts performed by composite repair manufacturers, operators, and research organizations. Pipeline damage comes in different forms, one of which involves dents that include plain dents, dents in girth welds and seam welds. An extensive study has been performed over the past several years involving multiple composite manufacturers that installed their repair systems on the above mentioned dent types. The test samples were pressure cycled to failure to determine the level of life extension provided by the composite materials over a set of unrepaired test samples. Several of the repaired dents in the study did not fail even after 250,000 pressure cycles had been applied at a range of 72% SMYS. The primary purpose of this paper is to present details on how Stress Intensification Factors were derived using the empirically-generated data. The results of this study clearly demonstrate the significant potential that composite repair systems have, when properly designed and installed, to restore the integrity of damaged pipelines and piping systems to ensure long-term service.

INTRODUCTION

Composite materials were originally used to repair corrosion in transmission pipelines; however, research in the 1990s conducted by the Gas Research Institute on the Clock Spring system demonstrated that composite materials can also be an effective means for repairing dents and mechanical damage. Additional tests were also performed that further demonstrated the capacity of composite materials in repairing dents. When used to repair dents, composite repair systems minimize the flexure that takes place in the dent. When the dent is restrained and prevented from moving during pressure cycling, the alternating strains are reduced and the fatigue life of the dent is extended.

In response to past successes a Joint Industry Program (JIP) was organized to experimentally evaluate the repair of dents using composite materials. The program was co-sponsored by the Pipeline Research Council International, Inc. and six manufacturers testing a total of seven different repair systems. Additionally, a set of unrepaired dent samples was also prepared to serve as the reference data set for the program. The dent configurations included plain dents, dents in girth welds, and dents in ERW (electric resistance welding) seams. Testing involved installing 15% deep dents (as a percentage of the pipe's outside diameter) where the dents were cycled to failure or 250,000 cycles, whichever came first. The test samples were made using 12.75-inch x 0.188-inch, Grade X42 with a pressure cycle range equal to 72% SMYS (Specified Minimum Yield Strength). Strain gages were also placed in the dented region of each sample and monitored periodically during the pressure cycle testing.

The sections of this paper that follow include details on how the dent samples were fabricated, how the samples were tested that includes a detailed discussion on the results.

TESTING METHODS

Because the intent of the current study was to determine the level of reinforcement provided by composite materials, it was important that the severity of the dents be significant enough so that failure of the unrepaired dent sample would occur within a relatively small number of cycles. Using insights gained from prior studies [1, 2], a test matrix was selected with the intent of having fatigue failures occur in less than 10,000 pressure cycles, where the range of stress was equal to 72% SMYS (Specified Minimum Yield Strength). Experience has shown that in order for this condition to exist, a severe level of strain must be induced during the dent deformation process. Consequently, the dents were generated using a 4-inch diameter end pressed into the pipe 15% of the pipe's outside diameter while an internal pressure equal to 72% SMYS was applied while the dent was held in place. The sections that follow provide details on the installation of dents, along with details associated with the composite repair installation activities.

Dent Installation

Listed below are the specific steps that were employed during the test program. Note that the list has been broken into the following phases of work:

- Pre-test activities
- Dent installation
- Pressure cycling and monitoring
- Post-failure activities

Pre-test activities Listed below are the activities associated with the pre-test phase of work in the current test program.

1. Purchase 12.75-inch x 0.188-inch, Grade X42 pipe to required length (28-ft sample).
2. Perform material testing on all heats including chemistry, mechanical properties (yield, ultimate, and elongation), and toughness (Charpy at 32°F and room temperature). This data will be recorded for one pipe at the following locations:
    a. Base pipe
    b. ERW seam weld
    c. Girth weld
3. Mark orientation of ERW seam on each pipe as shown in Figure 1, as well as location for all six (6) dents in each pipe sample.
4. Cut pipes to length and note heat number to reference appropriate Mill Test Report.

5. Install girth welds and end caps.
    a. At the present time we will use sound girth welds with the idea of evaluating dent/weld defects in a future study. The girth welds will be X-rayed to ensure that they meet minimum API 1104 requirements.
    b. Two girth welds and two end caps required per sample.

Dent Installation Listed below are the activities associated with the dent installation phase of work in the current test program.

6. Install six (6) dents per sample having an initial dent depth of 15% using a 4-inch spherical end cap as the rigid indenter using the following process:
    a. Install first dent to 15% depth (1.9 inches for 12.75-inch OD pipe) and hold the indenter in place while sample is then pressurized to 72% SMYS (892 psi). In this regard, the simulated defect represents an in-service dent generated while the pipeline is operating.
    b. Record the load-deflection data for the six (6) dents on the **unrepaired sample only**.
    c. Record load required to generate dent and collect load-deflection data during the indentation process.
    d. Release load on indenter and measure profile of residual dent depth with pressure in pipe sample (experience has shown that an initial dent depth of 15% in a 12.75-inch x 0.188-inch pipe typically rebounds with pressure ~3 percent).
    e. Remove pressure and measure profile of dent as shown in **Figure 2**. These measured data can be used to calculate local bending strains in the dent.
    f. Inspections will be performed using either dye penetrant or magnetic particle to ensure that no cracks have been formed during the process of denting the pipes.
    g. Continue process (steps a through c) and install five (5) remaining dents – all dents will be made with internal pressure.
    h. Apply 10 pressure cycles from 0 to 100% MAOP (Maximum Allowable Operating Pressure) from 0 to 892 psi and measure all dent profiles. Figure 3 shows the indenter in position prior to denting, while Figure 4 shows the level of deformation that remained after the 10th pressure cycle had been applied to one of the girth weld samples.
7. Inspect girth welds via X-ray and include as part of documentation package for each sample (after denting to detect if any cracks were introduced during indentation).
8. Sandblast pipes where composite materials will be installed.

Pressure cycling and monitoring Listed below are the activities associated with the pressure cycling and monitoring phase of work in the current test program.

9. Install strain gages near dents in transition area on “halo” region of dent. Refer to details shown in Figure 1 for strain gage locations and associated numbering.
10. As appropriate, install composite repair materials. Figure 5 provides photographs of the installation efforts for the manufacturers that participated in the current study.
11. Fatigue test samples to failure by applying cyclic pressure ranging from 0 to 100% MAOP (where MAOP is 72% of SMYS or 892 psi for the given pipe). Cycle samples to failure or 250,000 cycles, whichever occurs first.
12. Record strain gage data for 10 cycles at the following test intervals: start-up, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000 cycles (assuming the strain gages survive). The length over which data will be collected is limited to either when the first fatigue failure occurs or when the strain gages stop working. This is consistent with SES’ typical data recording period for fatigue test samples.

Post-Failure Activities Listed below are the activities associated with the post-failure phase of work in the current test program.

13. As failures occur, cut out the failed leaking dent, re-weld, and continue pressure cycling.
14. Document the cycles to failure for each sample. The unrepaired defects can be visually examined and photographs will be taken of the resulting fatigue cracks. For the defects repaired using composite materials, the pipe will be cut outside of the repair to permit visual inspection of the internal surface of the pipe.
15. In addition to details on the dents, collect information on the composite repair systems including:
    a. Composite material thickness.
    b. Length of composite.
    c. Composite material type (fiber and resin type).
    d. Design calculations from manufacturer (if available).
16. For the unrepaired samples, measure the final dent profile after all testing has been completed.

Composite Repair Installation

As noted previously, six manufacturers installed a total of seven different repair systems in the current program. Each manufacturer was responsible for designing the reinforcement that included length of the repair and the required thickness. Specific details on the composite repair systems are not included; however, the following types of composite repair systems participated in the current study.

- E-glass fibers in an epoxy matrix (1)
- E-glass fibers in a water-activated urethane matrix (2)
- Carbon fibers in an epoxy matrix (2)
- Carbon fibers in a water-activated urethane matrix (1)
- Pre-cured E-glass fiber wrap (1)

Once all of the composite repair systems were installed, strain gages were installed on the outside surface of three of the six repair sleeves on each 28-ft long test sample (i.e. one plain dent, one girth weld, and one ERW seam test sample).

TESTING RESULTS

The primary focus of the current study was to evaluate the level of reinforcement provided by composite materials in repairing dented pipelines. The most basic method of assessment is to compare how many cycles to failure occurred for each respective dent type and repair system. Additional insights are gained in evaluating the strain gages that measured strains in the dented regions of the pipe.

Table 1 provides that dent depth data for the unrepaired dents. Note that a significant level of rerounding occurs after what was initially a dent depth equal to 15% of the pipe’s outside diameter. The sections that follow provide details on the measured cycles to failure and the strain gage data that were captured for the 6 unrepaired dents and the 42 dents repaired using 7 different composite repair systems.

Pressure Cycle Fatigue Data

All dented test samples were fatigue tested at a pressure range equal to 72% SMYS. As failures occurred, the failed pipe sections were removed and the remaining pipe was welded back together so that pressure cycling could continue. Table 2 provides a summary of all fatigue test results, while Figure 6 provides a graphical representation of the same tabulated data. The last column in this table includes an average for all six dents associated with each repair systems, as well as the unrepaired dent set. Although the average value does not permit a direct comparison of test results for specific repair system/dent type combinations, it is a useful value for comparing the overall performance of the different repair systems relative to the unrepaired dents.

The following general observations are made in reviewing the pressure cycle data.

- The average cycles to failure for the unrepaired dent samples were 10,957 cycles. The target *cycles to failure* for the unrepaired dents was 10,000 cycles.
- Two of the seven systems had 250,000 cycles with no failures that included a carbon/epoxy system and a pre-cured E-glass system.

Strain Gage Data

An extensive array of strain gage data was collected in the course of the current test program. A total of 24 dents were fitted with one bi-axial strain gage rosette that measured hoop and axial strains in the steel beneath the repairs. An additional 8 strain gages were used to monitor the nominal hoop and axial strains in he pipe during pressure cycling. As discussed previously in the *Test Methods* section of this paper, data were collected at start-up, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000 cycles or until failure assuming that the strain gages survived. Data were collected at a rate of one scan per second with typical cycle periods being on the order of 10 seconds.

There were two primary objectives in monitoring the strain beneath the composite repairs. The first was to quantify the level of reinforcement provided by the composite material. It is expected that as the composite material is engaged that it reduced strain in the section of pipe around which it is wrapped. Prior research has shown that the key to increasing the fatigue life of dents is to reduce the amount of flexure that takes place in the dented region of the pipe. The second objective was to monitor that strain in the dented region as a function of cycle count and determine if this value changed over time.

An extensive assessment on the recorded strain gage data is outside the scope of this discussion; however, a summary of results is presented in Table 3. Provided in this table are the strain gage readings measured on the plain dents for each of the 8 test samples (16 dents in all). Although there is not a direct correlation between the average fatigue life (as observed experimentally) and the strain range, there are several noteworthy trends observed in viewing the data in Table 3.

- In general, those dents having the lowest reported strain ranges have the longest recorded experimental fatigue lives. System D had an average hoop strain range of 346 microstrain with no reported failures.
- The average hoop strain range for the base pipe was 1,000 microstrain, a value consistent with 72% SMYS divided by the elastic modulus of steel being 30 Msi (ε_{hoop} = 0.72 * 42,000 psi / 30 Msi = 1,008 microstrain). As noted 3 of the 7 repair systems had strain ranges of this magnitude; these three systems also recorded the three highest average cycles to failure.
- The strain gages placed on the unrepaired dents recorded large strain ranges (4,678 $\mu\varepsilon$). When using the DOE-B mean curve (refer to equation provided in the *Discussion* section of this paper), the estimated cycles to failure is 2,670 cycles.

The average strain reported in Table 3 is a general measure of the level of reinforcement provided by the composite material. Although having low strain ranges does not guarantee that a particular system will always have the longest fatigue life, reduced strain is a good indicator that the repair system is reducing flexure of the dent. A case in point is that System A had relatively high recorded strains; however, the dents repaired using this system had an average fatigue life of 215,271 (second only to the two systems that achieved run-out).

DISCUSSION

The results of this program confirm that in addition to reinforcing corrosion damage in pipelines, composite materials are also well-suited to reinforce dents. In this capacity composite materials are effective because they are able to reduce stresses in the reinforced pipeline. When plain dents have failed it has typically been due to cyclic pressures so that when composite materials are installed they increase the local stiffness of the dented region and reduce the alternating strains.

Although not specifically included in this paper, the thicknesses of the composite repairs were measured before testing. The average system thicknesses ranged from 0.175 inches to 0.671 inches. The stiffness of the composite is the product of modulus and thickness. Contrary to what might be expected, there was not a direct correlation between stiffness and cycles to failure. Therefore, one can conclude that in addition to the stiffness of the fiber and matrix, the load transfer material (i.e. filler material) plays a significant role in the ability of the repair systems to reinforce the dented pipes. The importance of this observation cannot be overstated. This trend has also been observed when considering the repair of extreme corrosion depths (i.e. 75% of the nominal wall thickness).

Provided in Table 2 is a listing of stress intensification factors (SIFs) that were calculated for each of the repaired dents as well as the unrepaired data set. Figure 7 provides a graphical representation of the same tabulated data. As observed, the maximum SIFs are those associated with the unrepaired dents (i.e. 3.76 for the unrepaired dent in an ERW seam, UR-ERW-1), while the minimum SIFs are those associated with the two repair systems that achieved run-out at 250,000 cycles (i.e. SIFs of 1.49 for Systems C and D).

- Calculate $\Delta\sigma$ using the known experimental cycles to failure, N, using the DOE-B mean curve [3] shown below. The DOE-B mean curve should not be used for design purposes; however, it is useful for estimating th remaining life of dented structures. See discussion below for recommended design curves.

$$N = 2.343E15 \cdot \left[\frac{\Delta\sigma}{0.145}\right]^{-4} \tag{1}$$

- Calculate nominal hoop stress range ($\Delta\sigma_{hoop}$) based on ΔP
- Calculate the stress intensification factor using the following relation: SIF = $\Delta\sigma / \Delta\sigma_{hoop}$
- The SIF can be used to predict remaining life for repaired dents when the pipeline's pressure history is known. To calculate remaining life the SIF is multiplied by the nominal hoop stress to calculate stress range. This value is then used as input into an S-N fatigue curve to calculate the design life, N_{design}. Finally, the remaining service life in years for a given pipeline is determined by dividing N_{design} by the annual number of pressure cycles at a given pressure range.

Selecting an appropriate fatigue design curve is important. As discussed previously, the DOE-B mean curve is not to be used for estimating remaining life, although the DOE-B design curve is an option. Also, for relatively severe dents, the author has used the API X' curve from API RP 2A [4]. Provided below are three sets of equations that compare the DOE-B mean, DOE-B design, and the API X' design curves. The elastic stress range, $\Delta\sigma$**,** of 140,340 psi used in these equations corresponds to the measured strain of 4,678 $\varepsilon\mu$ (elastic stress of 140,340 psi) for the unrepaired plain dent that failed after 7,018 cycles.

DOE-B Mean Curve

$N = 2.343 \times 10^{15} (\Delta\sigma / 145)^{-4} =$

$2.343 \times 10^{15} (140{,}340 \text{ psi} / 145)^{-4} =$ **2,670 cycles**

DOE-B Design Curve (mean minus two standard deviations)

$N = 1.01 \times 10^{15} (\Delta\sigma / 145)^{-4} =$

$.01 \times 10^{15} (140{,}340 \text{ psi} / 145)^{-4} =$ **1,151 cycles**

API X' Curve

$N = 2 \times 10^{6} (\Delta\sigma / 11{,}400 \text{ psi})^{-3.74} =$

$2 \times 10^{6} (140{,}340 \text{ psi} / 11{,}400 \text{ psi})^{-3.74} =$ **167 cycles**

If one compares the above two design curves, the fatigue design margins relative to the actual experimental cycles to failure for the DOE-B and API X' design curves are 6.1 and 42.0, respectively. The design curves in the ASME Boiler & Pressure Vessel Curve impose a design margin of 20 on cycles to failure; therefore, one could conclude that the API X' is possibly too conservative, while the DOE-B design curve might not conservative enough. The selection of design curves is a function of each operator's risk tolerance. In light of the current study, one can conclude that a majority of the repair systems used in this study provide a significant improvement over the unrepaired dents.

In terms of remaining life, the 250,000 pressure cycles achieved by Systems C and D corresponds to a remaining life of 6,250 years considering a safety factor of 20 on *cycles to failure* and an *aggressive pressure cycle condition* for a gas transmission pipeline (20 cycles per year at a pressure range of 72% SMYS) as defined by Kiefner [7]. Correspondingly, using this same approach the average cycles to failure for the unrepaired dents is 27 years. The difference between these remaining years of service is a factor of more than 230 times.

One of the challenges in evaluating the extensive database of test results associated with composite repair systems is determining the most effective means for direct comparison. This challenge is even present in the program presented in this paper that involved evaluating 48 different unrepaired and repaired dent defects. However, the development of SIFs permits both pipeline operators and composite repair manufacturers with a direct means for determining the remaining life of dents and the associated extension of fatigue life when composite materials are used.

One final comment concerns the failure modes of plain dents and dents combined with girth and seam welds. The primary focus of this study has been on evaluating the performance of dents subjected to cyclic pressure service. Although burst failures can happen to these types of anomalies, these types of dents most often fail in fatigue [6]. When burst failures do occur, more often than not there are additional extenuating circumstances that contribute to the failures such as metal loss (i.e. corrosion), pre-existing flaws or cracks, and external loads.

In terms of general applicability to pipelines and piping systems, the approach presented in this paper can be used to develop SIFs for other pipe defect anomalies, as well as piping components such as elbows, tees, and miters. The empirical approach ensures that a limit state condition is achieved that includes the reinforcing contributions provided by the composite material.

CONCLUSIONS

Since the 1990s composite materials have been used to repair corrosion in high pressure transmission pipelines. The use of this advanced technology has gained wide acceptance throughout industry and over the past several years multiple Joint Industry Programs have been sponsored by pipeline operators and composite manufacturers to both evaluate their capabilities and demonstrate the range of their ability to restore integrity to damaged pipelines. The information presented in this paper has detailed the results from a test program aimed at evaluating the ability of composite materials to reinforce damaged pipelines including plain dents, dents in seam welds, and dents in girth welds subjected to cyclic pressures.

The results clearly demonstrate that properly designed and installed composite materials can significantly increase the fatigue life of dented pipelines. The average cycles to failure for six unrepaired dent defects was 10,957 cycles, while 2 of the 7 composite systems had no fatigue failures even after 250,000 pressure cycles had been applied. As noted previously, this extreme pressure condition corresponds to a remaining life of 6,250 years considering a safety factor of 20 on *cycles to failure* and an *aggressive pressure cycle condition* for a gas transmission pipeline (20 cycles per year at a pressure range of 72% SMYS).

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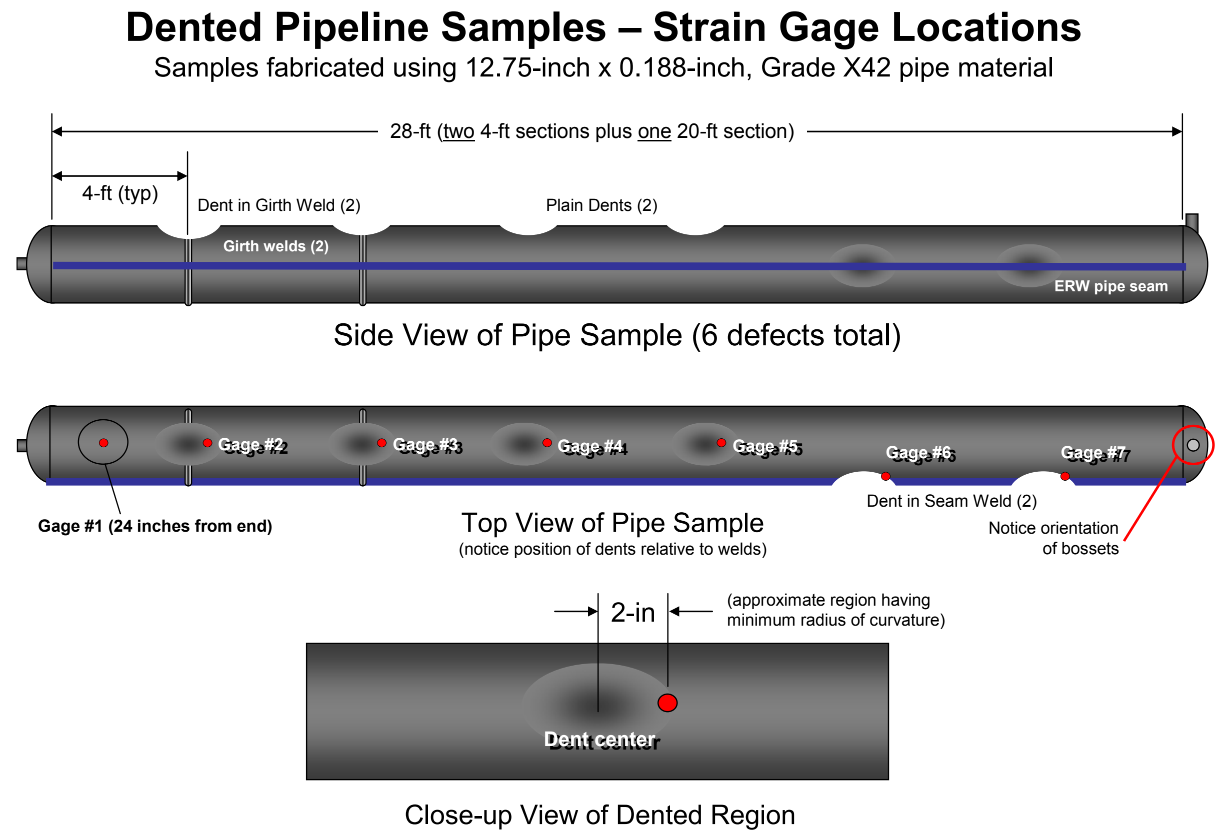

Figure 1 – Layout for pipe samples with 6 defects per sample
(the off-axis orientation of the dents interacting with the seam weld alleviates the need for an additional girth weld)

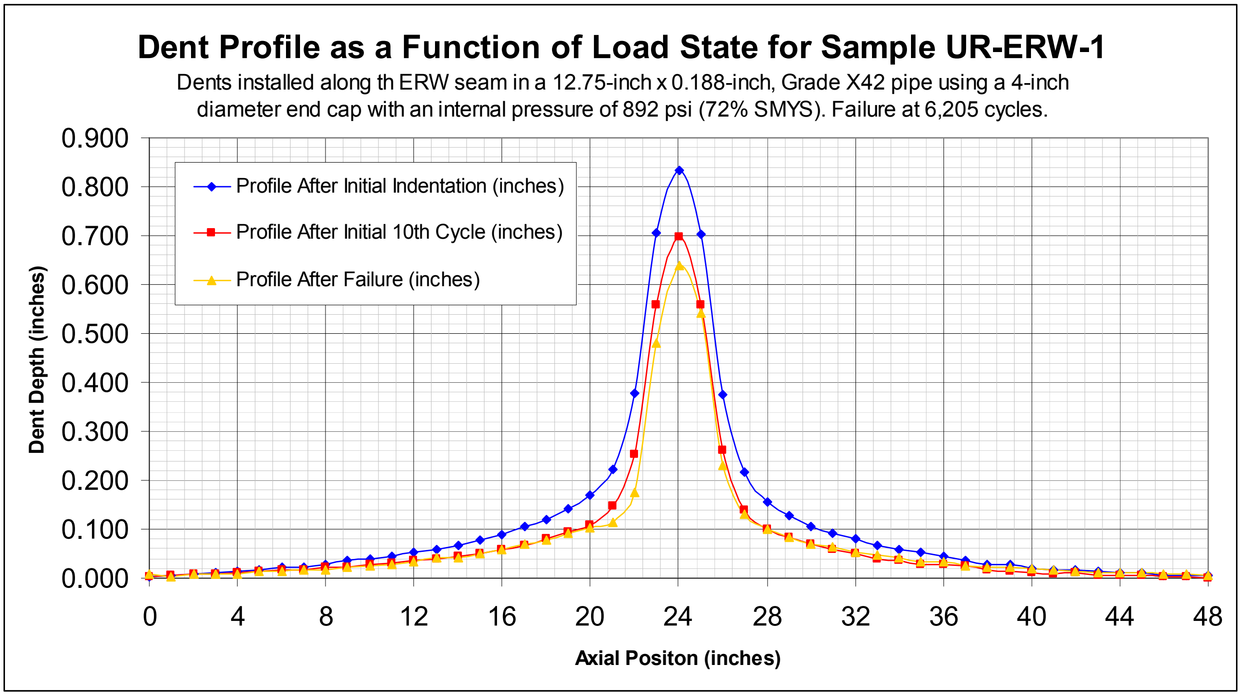

Figure 2 – Dent profile for unrepaired 15% dent in ERW seam
(residual initial dent depth of 6.54% with final post-failure dent depth of 5.01%)

Figure 3 – Close-up view on indenter on girth weld

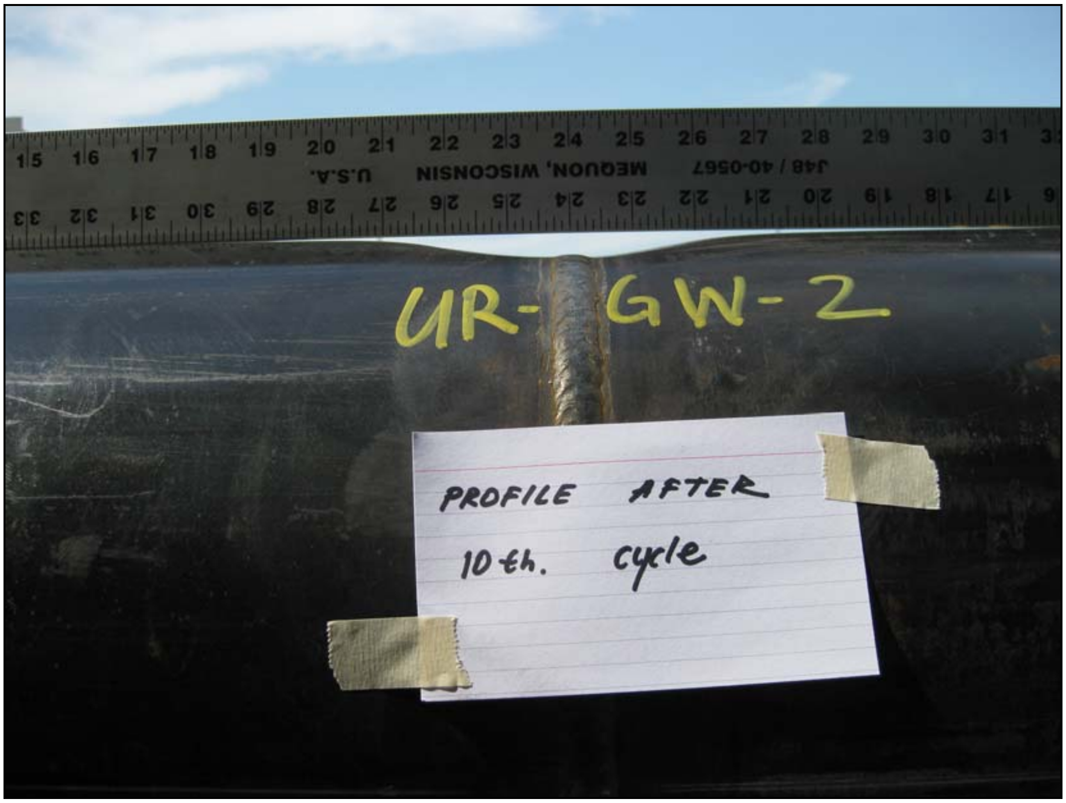

Figure 4 – Remaining dent profile after the application of 10 pressure cycles

Figure 5 – Installation of composite systems that participated in dent repair program

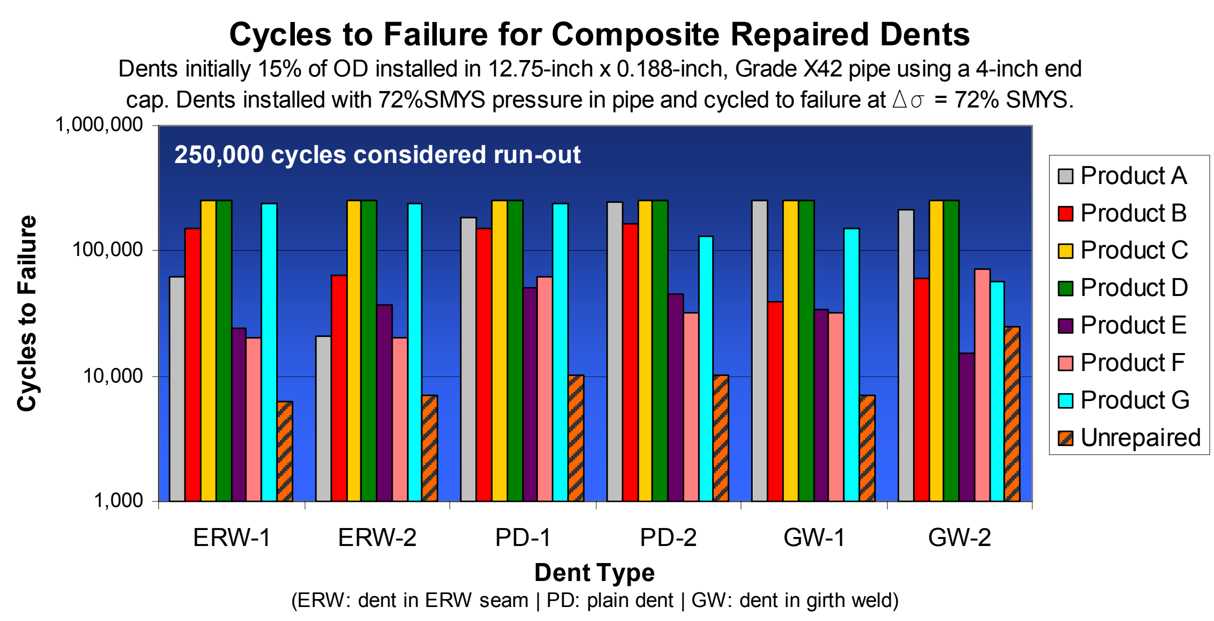

Figure 6 – Pressure cycle results for all dented test samples

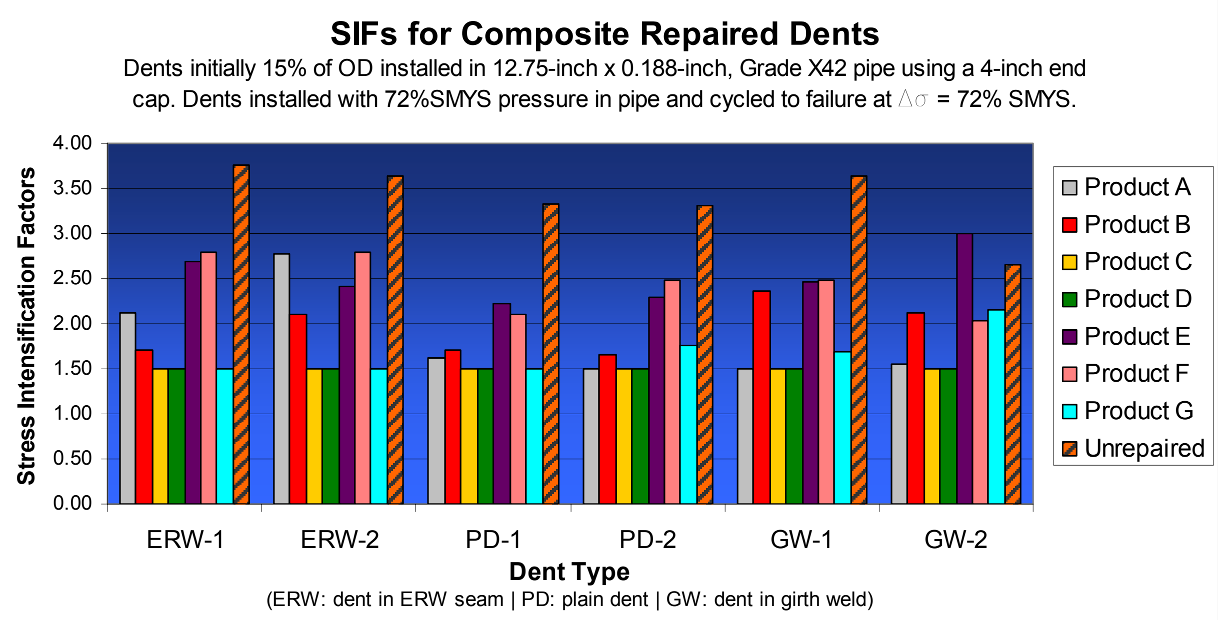

Figure 7 – Calculated Stress Intensification Factors (SIFs) for dented test samples

Table 1 – Summary of Depths from Unrestrained Dents

(initial dents depths equal to 15% of pipes outside diameter)

Dent Type	Number	Profile After Initial Indentation (inches)		Profile After 10 Pressure Cycles (inches)		Final Profile After Fatigue Failure (inches)	
		Dent Depth (inches)	Dent Depth (%)	Dent Depth (inches)	Dent Depth (%)	Dent Depth (inches)	Dent Depth (%)
Plain	UR-PD-1	0.775	6.08%	0.601	4.71%	N/A	N/A
	UR-PD-2	0.765	6.00%	0.616	4.83%	N/A	N/A
ERW	UR-ERW-1	0.834	6.54%	0.699	5.48%	0.639	5.01%
	UR-ERW-2	0.895	7.02%	0.725	5.69%	0.638	5.00%
Girth Weld	UR-GW-1	0.699	5.48%	0.554	4.34%	N/A	N/A
	UR-GW-2	0.657	5.15%	0.560	4.39%	N/A	N/A

Table 2 – Summary of Fatigue Data and Calculated SIFs

Product	Sample	# of Cycles	Δσ (ksi)	SIF	$N_{average}$
A	A-ERW-1	61,757	64.0	2.12	162,308
	A-ERW-2	20,881	83.9	2.78	
	A-PD-1	181,857	48.9	1.62	
	A-PD-2	248,684	45.2	1.49	
	A-GW-1	250,000	45.1	1.49	
	A-GW-2	210,671	47.1	1.56	
B	B-ERW-1	148,892	51.4	1.70	104,581
	B-ERW-2	63,979	63.4	2.10	
	B-PD-1	148,892	51.4	1.70	
	B-PD-2	165,809	50.0	1.65	
	B-GW-1	39,655	71.5	2.36	
	B-GW-2	60,260	64.4	2.13	
C	C-ERW-1	250,000	45.1	1.49	250,000
	C-ERW-2	250,000	45.1	1.49	
	C-PD-1	250,000	45.1	1.49	
	C-PD-2	250,000	45.1	1.49	
	C-GW-1	250,000	45.1	1.49	
	C-GW-2	250,000	45.1	1.49	
D	D-ERW-1	250,000	45.1	1.49	250,000
	D-ERW-2	250,000	45.1	1.49	
	D-PD-1	250,000	45.1	1.49	
	D-PD-2	250,000	45.1	1.49	
	D-GW-1	250,000	45.1	1.49	
	D-GW-2	250,000	45.1	1.49	
E	E-ERW-1	23,890	81.1	2.68	34,254
	E-ERW-2	37,011	72.7	2.41	
	E-PD-1	50,334	67.4	2.23	
	E-PD-2	44,987	69.3	2.29	
	E-GW-1	33,900	74.3	2.46	
	E-GW-2	15,400	90.6	2.99	
F	F-ERW-1	20,511	84.3	2.79	40,017
	F-ERW-2	20,445	84.4	2.79	
	F-PD-1	62,324	63.8	2.11	
	F-PD-2	32,273	75.3	2.49	
	F-GW-1	32,366	75.2	2.49	
	F-GW-2	72,183	61.5	2.04	
G	G-ERW-1	241,864	45.5	1.50	177,657
	G-ERW-2	241,864	45.5	1.50	
	G-PD-1	241,864	45.5	1.50	
	G-PD-2	131,040	53.0	1.75	
	G-GW-1	151,603	51.1	1.69	
	G-GW-2	57,704	65.1	2.15	
UR	UR-ERW-1	6,205	113.7	3.76	10,957
	UR-ERW-2	7,018	110.2	3.64	
	UR-PD-1	10,163	100.5	3.32	
	UR-PD-2	10,334	100.1	3.31	
	UR-GW-1	7,023	110.2	3.64	
	UR-GW-2	24,996	80.2	2.65	

Table 3 – Summary of Strain Gage Results for the Unreinforced and Reinforced Plain Dents
(strain gages located beneath composite repairs in dented region of steel pipe, cf. Figure 1)

Product	Hoop Strain (microstrain)			Plain Dent Experimental $N_{average}$	DOE-B mean (calculated cycles to failure)
	Plain Dent #1	Plain Dent #2	Average		
A	1,753	1,990	1,872	215,271	104,232
B	1,748	1,894	1,821	157,351	116,284
C	950	1,148	1,049	250,000	1,055,984
D	317	374	346	250,000	89,736,075
E	1,645	1,455	1,550	47,661	221,530
F	1,544	1,814	1,679	47,299	160,900
G	901	1,018	960	186,452	1,508,618
Unrepaired	N/A	4,678	4,678	10,249	2,670

Notes:

1. The unit of measure typically used for strain gages is *microstrain* (με), where 10,000 microstrain equals 1 percent strain.
2. The average hoop strain range for the base pipe was 1,000 microstrain, a value consistent with 72% SMYS divided by the elastic modulus of steel being 30 Msi (ε_{hoop} = 0.72 * 42,000 psi / 30 Msi = 1,008 microstrain).
3. The $N_{average}$ value is the average number of experimental cycles to failure for each respective plain dent data set (fatigue data for plain dents presented in Table 2).
4. The last column, denoted as DOE-B mean, is the calculated cycles to failure using the DOE-B mean curve (shown below) and the average measured hoop strain. Hoop stress in unit of "ksi" is calculated by multiplying hoop strain by elastic modulus (30 Msi) and then dividing by 1,000 psi / ksi. For example, System had an average recorded hoop strain of 960 με; the corresponding stress range is 960 με * 30 Msi / 1,000 = 28.8 ksi.