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REPAIR OF DENTS SUBJECTED TO CYCLIC PRESSURE SERVICE USING COMPOSITE MATERIALS

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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 dents in seam welds. An extensive study has been performed over the past several years involving multiple composite manufacturers who installed their repair systems on the above mentioned dent types. The primary focus of the current study was to evaluate the level of reinforcement provided by composite materials in repairing dented pipelines. The test samples were pressure cycled to failure to determine the level of life extension provided by the composite materials relative to a set of unrepaired test samples. Several of the repaired dents in the study did not fail even after 250,000 pressure cycles were applied at a range of 72% SMYS. 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 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 in previous studies comparing different composite materials, 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 eight 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 seams (high frequency). 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. 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 and 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 applied stress range 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. Therefore, to achieve this high level of strain the dents were generated using a 4-inch diameter end cap pressed into the pipe (15% of the pipe's outside diameter). An internal pressure (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.

Test Sample Phases of Work

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. Purchased 12.75-inch x 0.188-inch, Grade X42 pipe to achieved required sample length (28-ft per sample).
    a. Performed material testing including chemistry, mechanical properties (yield, ultimate, and elongation), and toughness (Charpy at 32°F and room temperature).
2. Marked 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.
3. Pipe material was cut to achieve desired sample length.
4. Installed girth welds and end caps.
    a. The girth welds were X-rayed after indentation to determine if any cracks were present.
    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.

5. Installed 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. The first dent was installed to a depth of 15% of the pipe's outside diameter (1.9 inches for the 12.75-inch OD pipe).
    b. The indenter was held in place while the sample was then pressurized to 72% SMYS (892 psi). In this regard, the simulated defect represents an in-service dent generated while the pipeline is operating.
    c. The load-deflection data was recorded for the six (6) dents in the **unrepaired sample only**.
    d. The indenter was removed while the sample was pressurized to capture the residual dent depth. Experience has shown that an initial dent depth of 15% in a 12.75-inch x 0.188-inch pipe typically rebounds after pressure has been applied to a final dent depth on the order of 3-5% (i.e. significant rerounding occurs).
    e. After the pressure was removed, the dent profile was measured as shown in Figure 2. These measured data can be used to calculate local bending strains in the dent.
    f. The above process was continued (steps a through d) to install the five (5) remaining dents – all dents were made with internal pressure.
    g. After all six dents were installed, 10 pressure cycles from 0 to 72% SMYS (0 to 892 psi) were applied after which the dent profiles were measured. 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.
6. Inspected girth welds via X-ray after denting to detect if any cracks were introduced during indentation.
7. 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.

8. Installed 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.
9. Composite repair materials were installed with no pressure in the pipe sample. Each manufacturer was responsible for designed their particular system.
10. Test samples were fatigue tested by applying cyclic pressures ranging from 0 to 100% MAOP (where MAOP is 72% of SMYS or 892 psi for the given pipe grade and geometry). Samples were cycled to failure or 250,000 cycles, whichever occurred first.
11. Strain gage data were recorded 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 was collected was limited to either when the first fatigue failure occurs or when the strain gages stopped 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.

12. As failures occurred, the failed leaking dent was cut out, the remaining sections were welded, and pressure cycling continued.
13. The cycles to failure for each dent were recorded. The unrepaired defects were visually examined and photographs were taken of the resulting fatigue cracks. For the defects repaired using composite materials, the pipe was cut outside of the repair to permit visual inspection of the internal surface of the pipe.
14. In addition to details on the dents, information was collected 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).
15. For the unrepaired samples, the final dent profiles were measured after all testing has been completed.

Composite Repair Installation

As noted previously, six manufacturers installed a total of eight 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 (2)
- 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. What was initially a dent depth equal to 15% of the pipe's outside diameter is reduced to something on the order of 5%. 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 5 provides a graphical representation of the data listed in Table 2. The last column in Table 2 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 number of *cycles to failure* for the unrepaired dents was 10,000 cycles.
- Two of the eight systems had 250,000 cycles survived no failures in any of their repaired dents. These two systems 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 the 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 the 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 ($\varepsilon_{hoop} = 0.72 * 42{,}000$ psi / 30 Msi = 1,008 microstrain). As observed 4 of the 7 repair systems had strain ranges of this magnitude or less (C, D, G, and H); these systems also recorded the 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 in the steel at the dented location. 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 (4.4 mm) to 0.671 inches (17 mm). 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 amplification factors (SAFs) that were calculated for each of the repaired dents as well as the unrepaired data set. As observed, the maximum SAFs 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 SAFs are those associated with the two repair systems that achieved run-out at 250,000 cycles (i.e. SAFs 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 the remaining life of dented structures. See discussion below for recommended design curves.

$$N = 2.343\text{E}15 \cdot \left[\frac{\Delta\sigma}{0.145}\right]^{-4} \tag{1}$$

- Calculate nominal pressure hoop stress range ($\Delta\sigma_{hoop}$) based on ΔP
- Calculate the stress amplification factor using the following relation: SAF = $\Delta\sigma / \Delta\sigma_{hoop}$
- The SAF can be used to predict remaining life for repaired dents when the pipeline's pressure history is known. To calculate remaining life the SAF 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)
$N = 1.01 \times 10^{15} (\Delta\sigma / 145)^{-4} =$
$1.01 \times 10^{15} (140{,}340 \text{ psi} / 145)^{-4} =$ **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 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. For liquid transmission pipelines, which typically experience a larger number of pressure cycles than gas transmission lines, the above estimated remaining years of service will be less.

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 54 different unrepaired and repaired dent defects. However, the development of SAFs permits both pipeline operators and composite repair manufacturer suppliers with a direct means for determining the remaining life of dents and the associated extension of fatigue life when composite materials are used based on actual test data. From a design standpoint it is the authors' opinion that when using current composite technology the thickness of the composite should never be less than the thickness of the pipe when repairing dents.

It should be noted that the current test program utilized a specific set of dent types, pipe geometry and grade, and composite repairs (i.e. materials and thicknesses). However, the findings of this study should not be considered as limiting. For several composite repair systems to have demonstrated the ability to increase the fatigue life of unrepaired dents by a factor or more than 25 is a critically important observation. At the present time what is absent in industry is a cohesive, uniform set of design guidelines for repairing dents using composite materials; however, programs such as the one reported herein provide industry with the foundational data necessary to develop a guidelines. In the absence of definitive guidelines, qualification of composite repairs by performance testing is the best available option for industry. This is further supported by the fact that the nature of the filler is of critical importance. As there are no methods to identify what will and what will not work, all systems should be tested to validate performance.

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.

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 when properly designed and installed based on manufacturer-defined specifications, 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). It is expected that future activities will use information presented in this paper as the foundation for developing guidelines that can be used by other manufacturers and operators in designing composite repair systems for the repair of dented pipelines.

REFERENCES

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[7] Kiefner J. F. et al, *Estimating Fatigue Life for Pipeline Integrity Management*, Paper No. IPC04-0167, Presented at the International Pipeline Conference, Calgary, Canada, October 4 – 8, 2008.

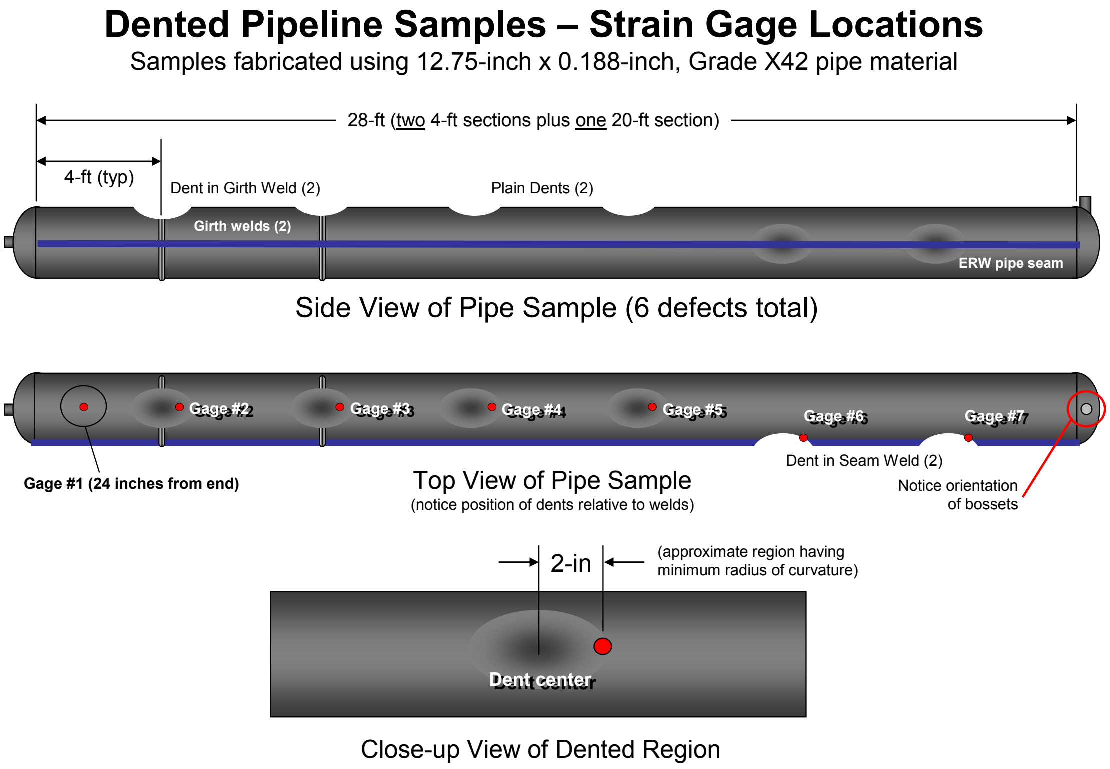


Figure 1 – Layout for pipe samples with 6 defects per sample
(the off-axis orientation of the dents interacting with the seam weld alleviates the need for an additional girth weld)

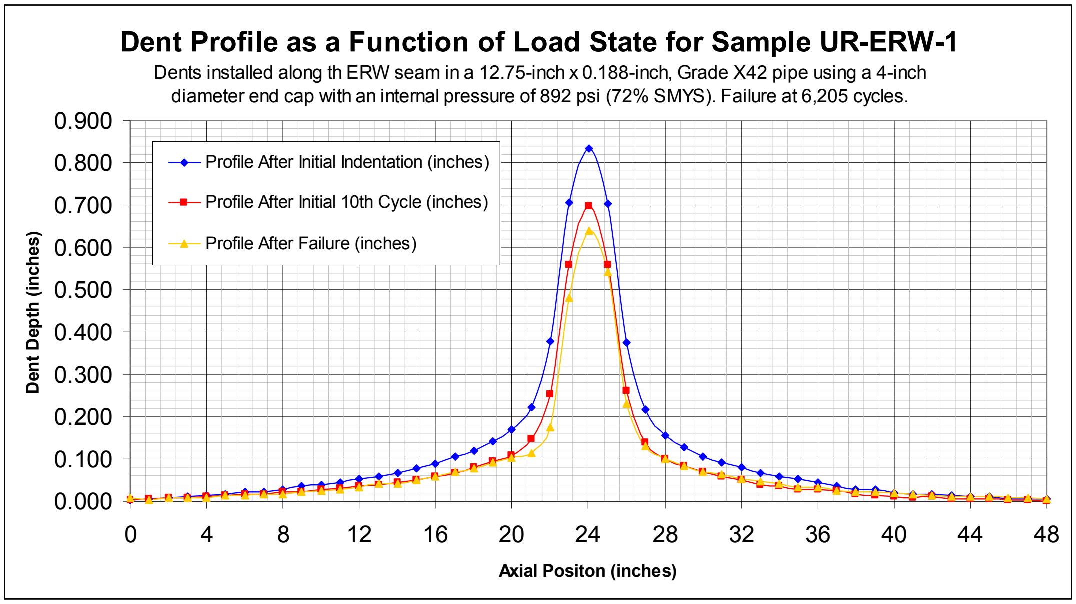


Figure 2 – Dent profile for unrepaired 15% dent in ERW seam
(residual initial dent depth of 6.54% with final post-failure dent depth of 5.01%)

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

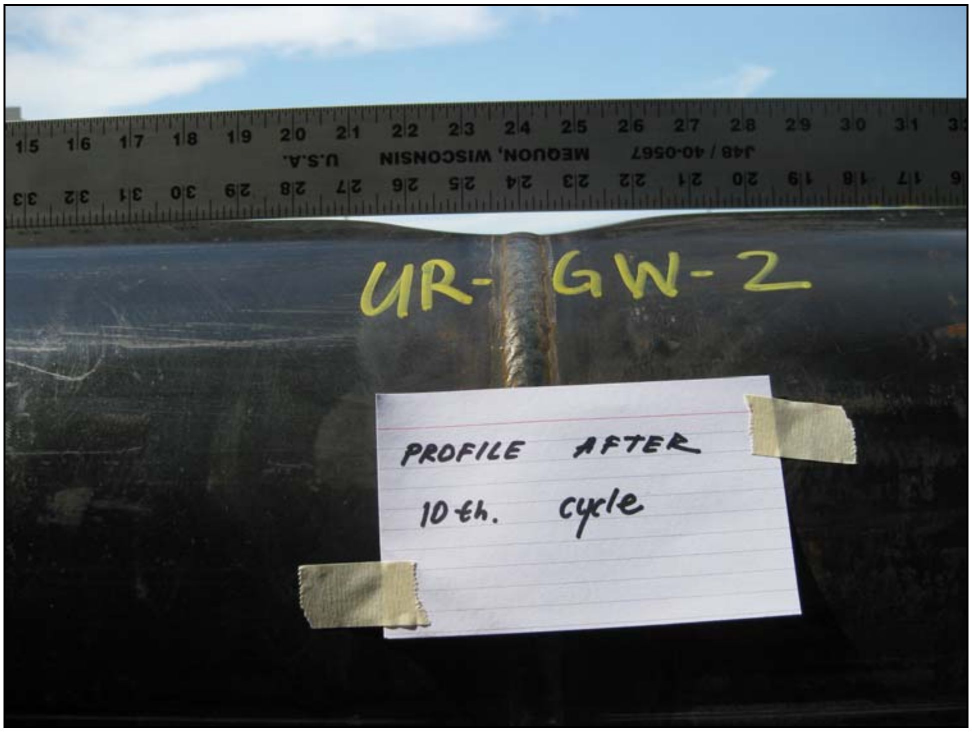
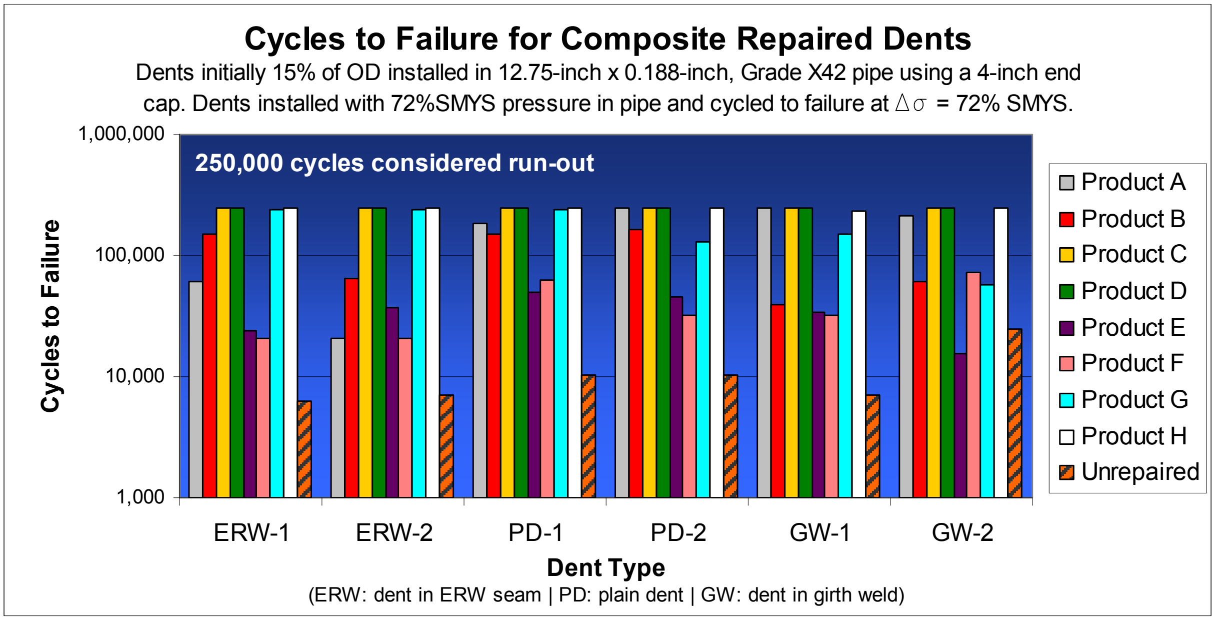
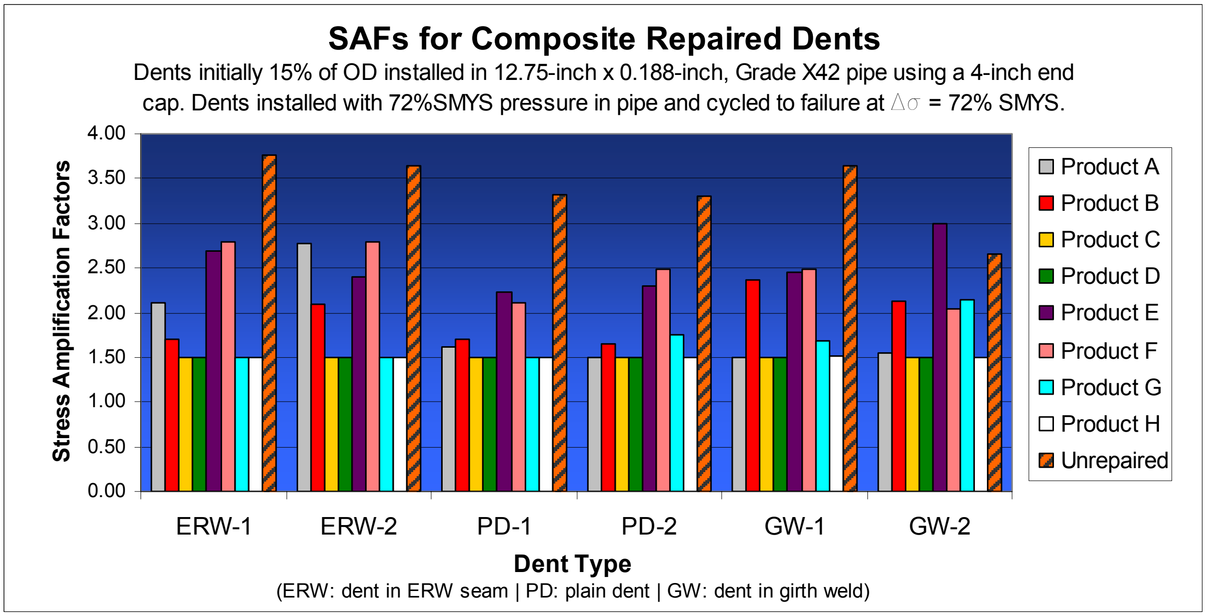


Figure 4 – Remaining dent profile after the application of 10 pressure cycles



One system was pressure cycled to 358,470 cycles when the ERW seam failed.

Figure 5 – Pressure cycle results for all dented test samples



Calculating Stress Amplification Factors (SAFs)

1. Calculate $\Delta\sigma$ using known cycles to failure, N
2. Calculate nominal pressure hoop stress range ($\Delta\sigma_{hoop}$) based on ΔP
3. SAF = $\Delta\sigma / \Delta\sigma_{hoop}$
4. The SAF can be used to predict remaining life for repaired dents when the pipeline's pressure history is known.

DOE B-curve

$$N = 2.343 \times 10^{15} \bullet \left[\frac{\Delta\sigma}{0.145}\right]^{-4}$$

$\Delta\sigma$ in units of ksi

Figure 6 – Calculated Stress Amplification Factors (SAFs) 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 SAFs

Product	Sample	# of Cycles	Modified N	Δσ (ksi)	SAF	AVG
A	A-ERW-1	61,757	61,757	64.0	2.12	162,308
	A-ERW-2	20,881	20,881	83.9	2.78	
	A-PD-1	181,857	181,857	48.9	1.62	
	A-PD-2	248,684	248,684	45.2	1.49	
	A-GW-1	309,934	250,000	45.1	1.49	
	A-GW-2	210,671	210,671	47.1	1.56	
B	B-ERW-1	148,892	148,892	51.4	1.70	104,581
	B-ERW-2	63,979	63,979	63.4	2.10	
	B-PD-1	148,892	148,892	51.4	1.70	
	B-PD-2	165,809	165,809	50.0	1.65	
	B-GW-1	39,655	39,655	71.5	2.36	
	B-GW-2	60,260	60,260	64.4	2.13	
C	C-ERW-1	305,353	250,000	45.1	1.49	250,000
	C-ERW-2	305,353	250,000	45.1	1.49	
	C-PD-1	305,353	250,000	45.1	1.49	
	C-PD-2	305,353	250,000	45.1	1.49	
	C-GW-1	305,353	250,000	45.1	1.49	
	C-GW-2	305,353	250,000	45.1	1.49	
D	D-ERW-1	261,742	250,000	45.1	1.49	250,000
	D-ERW-2	261,742	250,000	45.1	1.49	
	D-PD-1	261,742	250,000	45.1	1.49	
	D-PD-2	261,742	250,000	45.1	1.49	
	D-GW-1	261,742	250,000	45.1	1.49	
	D-GW-2	261,742	250,000	45.1	1.49	
E	E-ERW-1	23,890	23,890	81.1	2.68	34,254
	E-ERW-2	37,011	37,011	72.7	2.41	
	E-PD-1	50,334	50,334	67.4	2.23	
	E-PD-2	44,987	44,987	69.3	2.29	
	E-GW-1	33,900	33,900	74.3	2.46	
	E-GW-2	15,400	15,400	90.6	2.99	
F	F-ERW-1	20,511	20,511	84.3	2.79	40,017
	F-ERW-2	20,445	20,445	84.4	2.79	
	F-PD-1	62,324	62,324	63.8	2.11	
	F-PD-2	32,273	32,273	75.3	2.49	
	F-GW-1	32,366	32,366	75.2	2.49	
	F-GW-2	72,183	72,183	61.5	2.04	
G	G-ERW-1	241,864	241,864	45.5	1.50	177,657
	G-ERW-2	241,864	241,864	45.5	1.50	
	G-PD-1	241,864	241,864	45.5	1.50	
	G-PD-2	131,040	131,040	53.0	1.75	
	G-GW-1	151,603	151,603	51.1	1.69	
	G-GW-2	57,704	57,704	65.1	2.15	
H	H-ERW-1	356,446	250,000	45.1	1.49	247,075
	H-ERW-2	358,470	250,000	45.1	1.49	
	H-PD-1	358,470	250,000	45.1	1.49	
	H-PD-2	358,446	250,000	45.1	1.49	
	H-GW-1	232,449	232,449	45.9	1.52	
	H-GW-1	313,747	250,000	45.1	1.49	
UR	UR-ERW-1	6,205	6,205	113.7	3.76	10,957
	UR-ERW-2	7,018	7,018	110.2	3.64	
	UR-PD-1	10,163	10,163	100.5	3.32	
	UR-PD-2	10,334	10,334	100.1	3.31	
	UR-GW-1	7,023	7,023	110.2	3.64	
	UR-GW-2	24,996	24,996	80.2	2.65	

Table 3 – Summary of Strain Gages Results for Unreinforced/Reinforced Plain Dents
(strain gages located beneath composite repairs in dented region of steel pipe)

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
H	245	275	260	250,000	279,811,711
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.