EVALUATING THE ABILITY OF COMPOSITE MATERIALS TO RESTORE MECHANICAL INTEGRITY TO PIPELINES HAVING WRINKLE BENDS

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ABSTRACT

Concerns exist among the pipeline industry about the effects of wrinkle bends on the long-term integrity of pipelines. For this reason, a study was conducted to assess the relative severity of wrinkle bends present in a pipeline system. Included in this study was an evaluation in using composite materials to determine the potential for life extension considering the presence of reinforcement. Strain gages were installed on select samples to determine alternating stresses. The effects of metal loss due to corrosion were also considered. The experimental results demonstrated that composite materials can extend the fatigue life of wrinkle bends when designed and installed properly.

HISTORY AND APPROACH

Wrinkle bending is a process where wrinkles are introduced in a steel pipe during construction to obtain pipeline alignment. Bending practices used during pipeline construction, up until 1955, typically resulted in circumferential pipe deformation or wrinkles on the inside bend radius of the pipe. Vintage wrinkle bends are often of the wave shape with outward deformations. Additionally, “Mild ripples” are those developed using modern day field bending techniques where such ripples bear a length to height ratio on the order of 12. Whereas the wrinkle bends found typically on pre-1955 built pipelines are sharper than these ripples with length to height ratios on the order of 4.

Using some of the insights extracted from prior wrinkle bend study, a program was developed to specifically assess the performance of wrinkle bends as a result of vintage construction on a vintage pipeline. The wrinkle bends used in the program were those cut out from a pipeline that was installed in late 1940s. This program involved the following aspects.

- Each pipe sample integrated two wrinkle bends. A total of four (4) test samples were pressure cycled, resulting in a total of eight (8) wrinkles. Table 1 provides details on the pipe materials that were used in this test program.
- Strain gages were placed on all of the wrinkles to make measurements during pressure cycling. The strain gage results also provided information regarding the level of strain reduction provided by the addition of composite materials.
- One wrinkle on each of the samples was reinforced using composite materials (i.e. 4 repairs and 4 unrepaired).
- After testing to failure, several of the wrinkles were fractured to determine the location of crack initiation.

Included in this article are discussions on the methods used to test the wrinkle bend samples and corresponding results. Also presented are results for the composite material and the reduced strain in the wrinkle bends and extended fatigue lives. The El Paso Pipeline Group provided funding and pipe materials for this study and Armor Plate, Inc. provided personnel and materials for making the composite repairs.

EXPERIMENTAL METHODS AND RESULTS

The initial focus of this study was to determine the fatigue lives for wrinkle bends extracted from El Paso’s pipeline system. This was accomplished by welding end caps to each of the three test samples and pressure cycling to failure. Prior to pressure cycling, an extensive level of effort was involved in sample preparation that included making wrinkle profile measurements, installing strain gages, grinding to represent corrosion, and reinforcing select wrinkles with composite material.

Previous research demonstrated that the dominant stress in wrinkles as axial based on the circumferentially-oriented fracture that typically develops [2]. This information is important for several reasons. First in designing the composite repair architecture the importance of axially-oriented fibers was noted. Secondly, the capped end condition of test samples generates axial stresses that are greater than axial stresses present in an actual pipeline where plane strain conditions exist. Consequently, experimental fatigue life results are likely conservative when compared to actual conditions. Table 2 provides test sample pressure cycle conditions including the specific applied pressure ranges.

The sections that follow provide specific details on test methods and also include results for the measured strains and recorded cycles to failure.

Measuring Wrinkle Profiles

The wrinkle severity ratio, h/L, is a geometric characteristic that describes the relative severity of a given wrinkle. Any integrity management program charged with assessing wrinkles (and dents for that matter) should consider the h/L ratio as the first-line grading tool. This ratio is simple to acquire in the field from an exposed pipeline. Figure 1 shows a wrinkle bend profile being measured. Profile measurements were made on the six wrinkles pressure cycled in the current study that resulted in the following h/L ratios.

- Sample EP22-1A h/L = 0.093
- Sample EP22-1B h/L = 0.121
- Sample EP22-2A h/L = 0.095
- Sample EP22-2B h/L = 0.119
- Sample EP30-1A h/L = 0.132 (0.108 if adjusted for 40 percent corrosion)
- Sample EP30-1B h/L = 0.123 (0.103 if adjusted for 40 percent corrosion)

A useful tool for measuring the wrinkle profiles is the steel profile comb. A photograph showing the use of this comb on Sample EP22-1B is shown in Figure 1. Using this tool provides a quick check on the h/L ratio as the profile can be traced onto a sheet of paper thus permitting h and L to be measured. Also shown in this figure are the geometric wrinkle bend variables associated with the length, *L*, and height, *h*, values. The length, *L*, is represented as the distance over which the curvature of the wrinkle decays back to the original profile of the pipe. For the pipes used in this study, the length was relatively well defined as the pipe was generally straight outside of the wrinkle. This might not be possible for all wrinkle profiles.

Strain Gage Installation

Strain gages were installed on each of the tested wrinkle bends. The objective was to capture strains present in the wrinkle during pressure cycling. With end caps on a test sample, the axial stress in the pipe is one-half the hoop stress. However, in a buried pipeline which acts as plane strain, the axial stress is approximately one-third the hoop stress due to Poisson’s effect. This is an important point, as the axial loads during testing are approximately 70 percent greater than those observed in actual service. Hence, the measured strains and measured cycles to failure represent conservative, lower bound results. In other words, in actual service the fatigue lives for the given wrinkles will likely be greater than those recorded in the lab and reported in the test program.

Figure 2 is a schematic diagram showing where strain gages were installed on each wrinkle. As noted, there are two wrinkles on each test sample and a middle gage at location #5 was installed on the bare pipe between the wrinkles to capture nominal hoop and axial strain values. As noted in this figure, a total of nine strain gages were installed on each test sample. For the pressure cycle testing, data were recorded at 1 scan per second. After testing the results were output to an EXCEL spreadsheet for post-processing.

Installation of Composite Material

One of the primary objectives of this program was to assess the ability of composite materials to reinforce the wrinkles and reduce strain during pressure cycling. Armor Plate, Inc. provided materials and staff to install the Armor Plate Pipe Wrap (APPW) system on four of the six eight wrinkles. Prior to testing, all pipe samples were sandblasted to near white metal. It was decided that because of the large axial stresses present in a wrinkle, the repair should orient fibers in the axial direction. This differs from conventional composite repairs used to reinforce corrosion where the predominant fiber orientation is circumferential. The following composite reinforcement configuration was used, resulting in a total thickness of 0.564 inches. The length of each repair was approximately two feet, with one foot being on each side of the center of the wrinkle.

- Three layers hoop-oriented cloth totaling 0.188 inches (one-third composite thickness)
- Three layers axially-oriented cloth totaling 0.188 inches (one-third composite thickness)
- Three layers hoop-oriented cloth totaling 0.188 inches (one-third composite thickness)

The total thickness of the composite material equaled a value approximately 1.5 times the nominal pipe wall thickness. As noted, the inner and outer layer sets each equal 0.5 times the wall thickness and are oriented in the hoop direction, while the middle set of layers are oriented axially and have a thickness equal to 0.5 times the pipe wall thickness.

Strain gages were installed prior to installation of the composite material. Epoxy putty was used to create a smooth profile around the strain gage lead wires. Additionally, a layer of epoxy was painted to seal the exposed pipe prior to installation of the reinforcing material. Figure 3 shows a completed repair on the pipe sample using the composite reinforcement.

It is appropriate to discuss how composite materials are likely to reinforce wrinkle bends in situ. The composite materials used in this study utilized an E-glass material with a two-part epoxy resin. Fibers were oriented in both the circumferential and axial directions. Had the repair only included circumferential reinforcement, the level of overall reinforcement would have been reduced. Additionally, the elastic modulus of the material used in this program is on the order of 2 million psi. It is possible that further reduction in wrinkle bend stresses beneath the repair could be achieved using a material with a larger elastic modulus. However, based on previous research the E-glass material of the system used in this study out-performed other repair systems in extending the fatigue life of mechanical damage [3], even though those composite material typically have greater elastic modulii and failure strengths.

EXPERIMENTAL RESULTS

The presentation of results includes two topics of discussion that include a presentation of strain gage results and the recorded experimental cycles to failure. Results are presented in the sections that follow.

Strain Gage Results

The results from this effort are provided in Table 3. Note that the presented results are for the axial strain gage results. From previous research efforts and those demonstrated in this study, the maximum principal strains in the wrinkles are axially-oriented when the pipe is subjected to cyclic internal pressure. This differs from conventional pipe mechanics where the circumferential stresses and strains dominate for the non-deformed geometric condition. Also included are the plotted alternating hoop and axial strain gage results for Sample EP22-1 in Figure 4.

The following observations are made in reviewing the data provided in Table 3.

- As expected, the maximum strains are measured in Sample EP30-1 where 40 percent of the wall thickness was removed to simulate corrosion. This increased strain results in fatigue life reduction.
- The contribution of the composite materials reduces strain in the reinforced wrinkles. On average, the strain reduction is 42 percent. Considering a fourth order relationship between cycle life and strain range, a 30 percent reduction in stress effectively increases fatigue life by a factor of approximately 4.
- Elastic stresses are computed by multiplying the measured strain ranges by 30.

One important observation concerns the range of strains. Even though wrinkles (and dents) involve plastic deformation in their formation process, once several pressure cycles are applied to the sample a "shakedown" to elastic condition exists. This means that even though the defects are plastically deformed with additional pressure cycles an elastic response from the deformed region is likely. This trend was clearly evident in the recorded strain gage data. This simplifies efforts associated with estimating fatigue life from alternating stresses.

Fatigue Test Results

Each of the samples was pressure cycled until failure occurred. Each sample had two wrinkles. After the first wrinkle failed it was removed and continued testing would occur by moving the remaining end cap down and re-welding. Table 4 provides information on the number of pressure fatigue cycles applied to each sample. One sample (EP22-1) was cycled 93,125 cycles before failure occurred in the weld attaching the 1-inch NPT weld-o-let bosset to the sample's end caps. Pressure cycling was terminated as an extensive number of pressure cycles had already been applied. Several important observations are made in viewing the data provided in Table 4.

- Results from Sample EP30-1 clearly show the benefits derived in using composite materials to reinforce wrinkles. The fatigue life for the reinforced wrinkle was approximately two times the number of cycles to failure recorded for the unreinforced sample.
- The shortest fatigue lives were those associated with Sample EP30-1. The presence of the 40 percent corrosion contributed to the reduced fatigue life.
- The wrinkles in Sample EP22-1 included the presence of a flash weld seam weld. It is likely that this additional stress concentration contributed to the fracture initiation. Furthermore, additional testing involving only the reinforced sample generated a failure outside of the repair. Therefore, it is not possible to precisely ascribe the level of benefit associated with the repaired condition.

CONCLUSIONS

This article has provided findings on the study performed to assess the effects of wrinkle bends on the mechanical integrity on pipeline systems. The study involved a combination of full-scale cyclic fatigue testing, along with strain gage analyses, to determine cycles to failure and alternating stresses in the wrinkles. Also included in the study was the installation of a composite repair system on selected wrinkles to determine the potential for life extension considering reinforced conditions.

Also included as part of the study was assessing the effects of localized corrosion in the wrinkle and the effects of having a seam weld in the middle of the wrinkle. Before testing was started, the wrinkle profile was measured in order to capture the corresponding h/L ratios. The installed strain gages monitored strain during pressure cycle testing and also assessed the level of reinforcement provided by the composite material.

The minimum fatigue life recorded during testing was 19,252 cycles, which was in Sample EP30-1A that was fitted with 40 percent corrosion. It should also be noted that the applied pressure range was 100 percent of the maximum operating pressure. Hence, one can conclude that for wrinkles having geometries comparable to those evaluated as part of this study do not pose an imminent threat to the integrity of the pipeline, especially gas pipelines where significant pressure cycling is practically non-existent. This statement is predicated on several observations. First, wrinkles in seam and girth welds are subject to inferior performance, even though the unrepaired wrinkle EP22-1A was located in a flash seam weld and cycled 42,818 cycles. Secondly, the typical wrinkle severity ratio (h/L) in this study was on the order of 0.12. As this ratio increases, the cycles to failure will decrease. Lastly, although the 40 percent corrosion had a relatively long fatigue life, the presence of severe and pitted corrosion not considered specifically in this study will significantly reduce the remaining life of the pipeline system. This point has been confirmed in testing wrinkles having significant pitting.

Considering the insights gained in the present study, the following highlights are provided below for operators seeking practical applications.

1. The wrinkle bend, when exposed, should be inspected for surface conditions. Any stress risers or stress concentrators should be ground within acceptable limits and recoated. The presence of cracks is not acceptable.
2. Composite wrap of wet applied or wet lay-up systems may be used to repair metal loss of less than 40% in wrinkle bends (to evaluate deeper corrosion levels further studies should be conducted).
3. Precautionary measures must be taken to ensure that the wrinkle bend will not be subjected to flexure (pipe movement) during excavation activities or application of composite wrap.
4. The composite wrap, when used to reinforce wrinkle bends, should be installed so that a sufficient number of fibers are axially-oriented. For those systems having fiber orientations that are predominantly circumferential, 1/3 of the thickness of the wrap is installed circumferentially (inner layers), 1/3 axially (middle layers), and 1/3 circumferentially for an effective repair (outer layers).
5. Any wrinkle bend that may be subject to flexure should be cut-out.

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REFERENCES

[1] API RP 2A (1986), “Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms, American Petroleum Institute, Washington D.C.

[2] Kiefner, J.F. and Alexander, C.R., “Effects of Smooth Rock Dents on Liquid Petroleum Pipelines (Phase II),” API Publication 1156 – Addendum, October 1999, American Petroleum Institute, October 1999, Washington, D.C.

[3] Alexander, C.R., Francini, B., “State Of The Art Assessment of Composite Systems used to Repair Transmission Pipelines,” Proceedings of IPC2006 (Paper No. IPC2006-10484), 6th International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada.

[4] Alexander, C.R., Wilson, T., “Reinforcing Field Fabricated Branch Connections Using Composite Materials,” Proceedings of IPC2006 (Paper No. IPC2006-10483), 6th International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada.

[5] Alexander, C.R., Worth, F., “Assessing the Use of Composite Materials in Repairing Mechanical Damage in Transmission Pipelines,” Proceedings of IPC2006 (Paper No. IPC2006-10482), 6th International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada.

[6] Olsen, R., Clark, T., and Odom, T., “Evaluation of the Structural Integrity of Cold Field Bent Line Pipe”, 10th Biennial Joint Technical Meting on Line Pipe Research, EPRG/PRC, Paper 6, April 1995, Cambridge, UK.

[7] Rosenfeld, M. J., Hart, J. D., Zulfiqar, N., Gailing, R., “Development of Acceptance Criteria for Mild Ripples in Pipeline Field Bends”, IPC02-27124, ASME International Pipeline Conference, Calgary, Alberta, Canada, September 29-October 3, 2002.

Table 1 – Details on Pipe Test Materials

Sample Number	Pipe Geometry and Grade	Grade	Condition	72% SMYS
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired	779 psi
EP30-1B	30-inch x 0.312-inch	X52	Repaired	779 psi
EP30-2A	30-inch x 0.312-inch	X52	Repaired	779 psi
EP30-2B	30-inch x 0.312-inch	X52	Repaired	779 psi
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	858 psi
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	858 psi
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	858 psi
EP22-2B	22-inch x 0.312-inch	X42	Repaired	858 psi

Sample Number	MAOP	Test Pressure	In-Service Date	Seam type
EP30-1A	750	1082 psig	1948	DSAW
EP30-1B	750	1082 psig	1948	DSAW
EP30-2A	750	1082 psig	1948	DSAW
EP30-2B	750	1082 psig	1948	DSAW
EP22-1A (weld)	714	1081 psig	1947	Flash Weld
EP22-1B (weld)	714	1081 psig	1947	Flash Weld
EP22-2A	714	1081 psig	1947	Flash weld
EP22-2B	714	1081 psig	1947	Flash Weld

Note: Data are split into two tables for readability; note that the sample numbers are the same.

Table 2 – Test Sample Pressure Cycle Conditions

Sample Number	Pipe Geometry	Grade	Condition	ΔP (psi) (min to max)
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired (40% corrosion)	100-779
EP30-1B	30-inch x 0.312-inch	X52	Repaired (40% corrosion)	100-779
EP30-2A	30-inch x 0.312-inch	X52	Unrepaired	100-779
EP30-2B	30-inch x 0.312-inch	X52	Repaired	100-779
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	100-858
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	100-858
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	100-858
EP22-2B	22-inch x 0.312-inch	X42	Repaired	100-858

Table 3 – Measured strain range results for wrinkle samples

Sample	Condition	Peak of Wrinkle (Axial)		3 inches from Wrinkle (Axial)	
		De (me)	Dσ (ksi)	De (me)	Dσ (ksi)
EP22-1A (unrepaired)	Wrinkle in seam weld	1190	36	979	29
EP22-1B (repaired)	Wrinkle in seam weld	820	25	703	21
Percent reduction due to composite		31.1 percent		28.2 percent	
EP22-2A (unrepaired)		954	29	1096	33
EP22-2B (repaired)		757	23	868	26
Percent reduction due to composite		20.6 percent		20.8 percent	
EP30-1A (unrepaired)	40 percent corrosion	1960	59	1321	40
EP30-1B (repaired)	40 percent corrosion	1259	38	1213	36
Percent reduction due to composite		35.8 percent		8.2 percent	

Notes:

1. Sample EP22-1 fabricated from 22-in x 0.312-in, Grade X42 pipe
2. Sample EP22-2 fabricated from 22-in x 0.312-in, Grade X42 pipe
3. Sample EP30-1 fabricated from 30-in x 0.312-in, Grade X52 pipe

Table 4 – Fatigue Test Results

Sample Number	Pipe Geometry	Grade	Condition	ΔP (psi) (min to max)	Cycles	Notes
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired (40% corrosion)	100-779	19,252	Crack developed in center of wrinkle
EP30-1B	30-inch x 0.312-inch	X52	Repaired (40% corrosion)	100-779	41,171	Crack developed beneath APPW repair
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	100-858	42,818	Crack developed in center of wrinkle
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	100-858	55,371	Longitudinal crack developed outside of repair
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	100-858	93,135	Crack developed in bosset weld (test aborted)
EP22-2B	22-inch x 0.312-inch	X42	Repaired	100-858	93,135	Crack developed in bosset weld (test aborted)

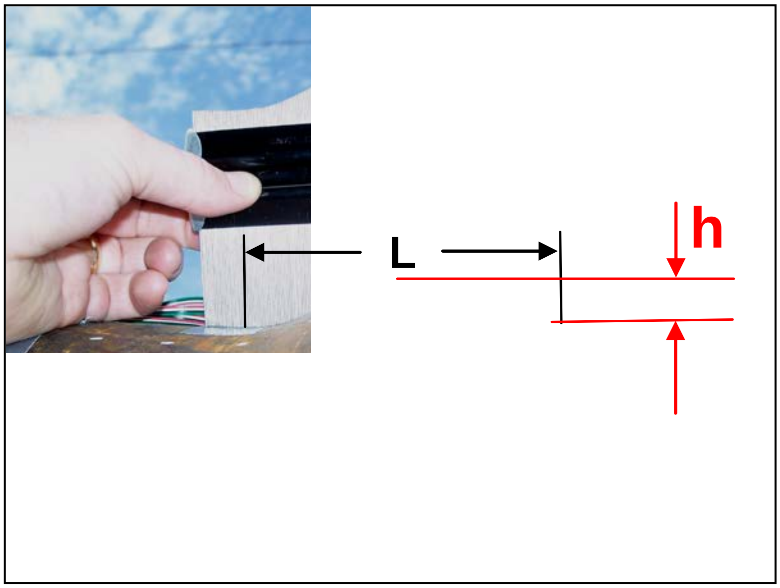

Figure 1 – Measurement made using steel profile comb with “h” and “L” values

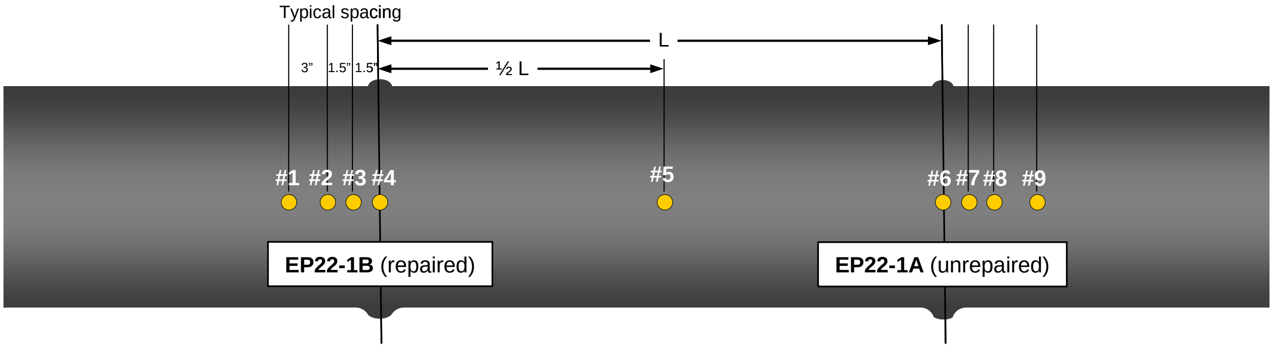

Figure 2 – Schematic showing strain gage locations
(markings specifically for the gage configuration on Sample EP22-1)

Figure 3 – Photo showing completed installation of composite material

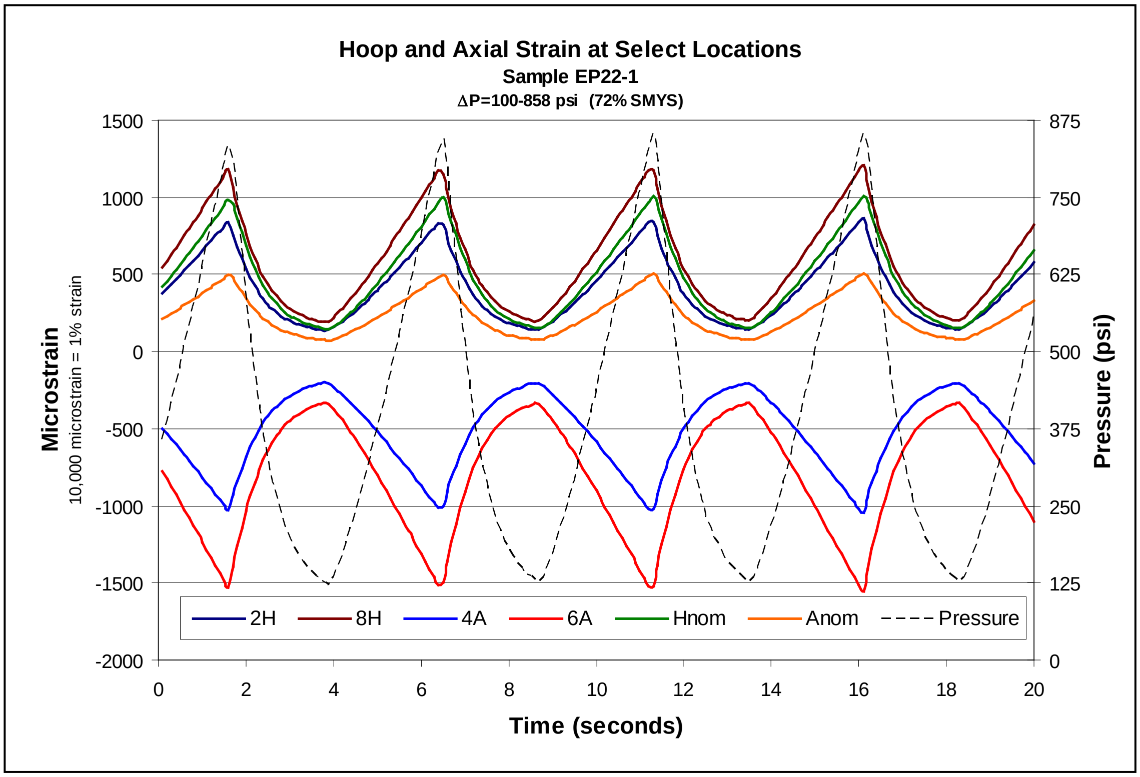

Figure 4 – Alternating hoop and axial strain gage results for Sample EP22-1

(Gages 1 - 4 REPAIRED and Gages 5 - 9 are UNREPAIRED | the nominal hoop and axial strains are Hnom and Anom)