USING DIGITAL IMAGE CORRELATION TO ENHANCE THE EVALUATION OF A FIBERGLASS COMPOSITE REPAIR SYSTEM THROUGH TESTING

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Abstract

The repair and remediation of process piping and pipelines through the application of composite wraps is finding increased acceptance for a growing number of defects and anomalies. The field application of composites is intended to address defects such as wall loss originating from corrosion, internal erosion, and mechanical damage. Composite wraps do this while eliminating the need for hot work and costly shutdowns. InduMar Products' XCorr Composite pipe wrap entails a high-strength quadaxial fiberglass weave in an epoxy matrix to provide mechanical reinforcement and chemical protection to these anomalies in an easy to install format. Although composite repair systems can appear to be one size fits all, it is critical to evaluate the capabilities of specific systems, like XCorr, under loading and defect conditions of interest.

Testing regimens, such as those outlined in ASME's PCC-2 repair design and qualification standard, are intended to highlight the capabilities and limits of composite remediation, however more insight into component-specific performance is needed to continue driving widespread use. Much of the full-scale testing specified in PCC-2 is pass-fail in nature, with internal pressure being the primary data collected. While this is important in clearly relating repaired components to accepted working and design pressures, additional data is needed to fully characterize the repair system. Historically, strain gages have been used to extract additional data from full-scale tests of composite repairs. Although strain gages are important tools, they can introduce imperfections to critical repairs and can become misaligned when installed within the repair. In this study, digital image correlation (DIC) was used in lieu of strain gages to enhance test results, including during full-scale spool survival pressure testing as part of XCorr's PCC-2 composite repair qualification program. With full field displacement measurements, DIC provides the unique capability to retroactively place any number of virtual strain gages and extensometers at locations of interest during post-processing of the data. This allowed for a more detailed assessment of the composite repair design, with enhanced evaluation of its behavior under load. Data produced by DIC during the spool survival testing allowed for greater insight to how the composite material carried and distributed the load around an area of simulated corrosion on the spool survival sample. This paper will provide background information on the composites and repairs used in the study, results from the testing, details on incorporating DIC, and discussion on its use in other composite repair qualification programs.

Introduction and Repair System Background

In recent years, composite technology has been harnessed to provide alternatives to metal-based structural components in the form of lightweight/high-strength materials as well as to provide approaches to the repair of structural components across a broad range of industries and needs. Among others, critical repair needs have been identified in the areas of mechanical reinforcement of piping, rehabilitation of surfaces damaged by external wear, sealing of production systems containing aggressive chemicals, and protection of components suffering from environmental corrosion. As the specifics of the repair need change, so must the properties of the composite repair product. Because composites are composed of more than one material, the design and optimization of a repair requires an understanding of the fundamental properties of each material as well as how material properties combine to define product performance. Ultimately, there is the need to quantify performance from an engineering perspective, namely the need to measure the efficacy of a repair approach with respect to the performance characteristics of existing materials and components. While considered non-traditional from the historical engineering perspective, which has looked to use metals for both construction and repair, composites offer many unique characteristics in terms of their combined strength, reduced density, and ease of handling. To fully realize the potential of composites, additional methods of providing insight into their performance are needed in establishing the boundaries within which they can be safely and successfully employed. The use of digital image correlation (DIC) outlined in this report represents a promising approach to documenting direct correlations between composite component selection and strength performance.

A growing area of composite repair technology entails the use of an externally applied composite wrap to metallic piping to address a reduction in pipe wall thickness and the commensurate reduction in system performance rating. Wall loss can occur through either physical erosion or chemical corrosion, or combinations of the two. Wall loss has been observed to occur internally or externally, depending on the characteristics of the application and installation. Regardless, a reduction in the wall thickness of pressurized piping directly leads to a reduction in the hoop and axial strengths of the piping system and in its ability to operate safely under the originally specified conditions. The installation of a composite wrap is intended to build back wall thickness and corresponding strength. The approach has been judged to be a competitive alternative to pipe replacement by virtue of reduced repair time, the elimination of hot work associated with traditional pipe repair, and reduced repair cost. For example, the XCorr™ fiberglass-epoxy composite system has been designed as a field impregnated repair providing a path to simplified installation, superior mechanical strength, and high chemical resistance. For this system, a quadaxial fiberglass weave provides multidirectional mechanical reinforcement within a novolac epoxy resin matrix providing chemical resistance. The high-performance epoxy resin and advanced-weave fiberglass reinforcement have been documented as a PCC-2 compliant repair.

The qualification portion of the ASME PCC-2 standard is intended to highlight the capabilities and limits of composite remediation. Repair design in PCC-2 makes use of measured mechanical strength and physical property data to specify the composite thickness required to achieve a specific level of performance. Ultimately, prototypical repairs are performed on standardized defects and used to validate performance specifications. In the process of demonstrating the XCorr performance properties required to establish compliance, additional details of strength remediation were gained using DIC technology and illustrate the potential of informing the development of future composite repair solutions.

Composite Repair Qualification

As composite repairs were increasingly utilized across industry, it was determined that a standardized approach for their design and qualification was needed. The ASME PCC-2 and ISO 24817 standards were developed to provide standardized guidance for the qualification and design of composite systems. These standards primarily address composites used to reinforce external wall loss and repair leaking defects in pipes and piping systems. Both standards outline a series of tests required to characterize the performance of composite systems and ensure they can be properly designed and installed in field applications. Qualification of a composite repair system first begins with a series of coupon-scale material tests used to quantify important design properties such as tensile strength, elastic modulus, glass transition temperature, coefficient of thermal expansion, and lap shear adhesion strength. The properties quantified through these tests then serve as inputs into design equations provided in later sections of the standards. Minimum requirements are relatively sparse in this portion of the standard, with exceptions being greater than 1% strain to failure in tension tests and a lap shear adhesion strength of at least 580 psi. Since composite repair systems require not only proper design but also correct application and installation, a full-scale demonstration test is also required for full qualification. The full-scale demonstration test is outlined in ASME PCC-2-2018 Article 401 Mandatory Appendix 401-III – Short-term Pipe Spool Survival Test. In this test, a pipe spool is fabricated with a machined wall loss region of pre-determined depth (Figure 1). The machined wall loss region is reinforced using the composite system and then pressurized to a calculated test pressure based on the pipe geometry and actual yield strength. The stated purpose of the test is to *confirm the repair system has acceptable interlaminar shear and bond strength* and demonstrate *the integrity of a structural repair up to the yield level of the original pipe.* Successful completion of this test requires that the repair system survive the calculated test pressure without *visual signs of degradation when* *inspected in accordance with Table 401-5.2-1.* The result is a pass / fail evaluation of a composite system's performance. An almost identical test methodology is utilized in ISO 24817. When combined with the necessary coupon-level tests, passing the pipe spool survival test results in a composite system that has completed the mandatory requirements for qualification.

Throughout the process of composite repair system qualification, the only performance data required for full-scale testing is internal pressure. While this can be sufficient for pass / fail criteria, it does little to quantify how the actual composite repair installation is performing. Historically, measurement devices such as strain gages have been utilized to provide this information. When properly installed, strain gages can quantify the amount of reinforcement provided by a particular repair system and the response of the substrate to applied loads. This is of particular importance when composites are utilized for applications outside of standard external wall loss reinforcement or leaking defect repairs.

ASME PCC-2 / ISO 24817 vs. Engineering Judgement

In many cases, composites are an ideal candidate for reinforcing pipeline defects that are more complex than external wall loss. Examples of this could include cracks, dents, wrinkle bends, and girth welds. In these instances, pass / fail criteria might not be as well defined and data on the performance of the composite is critical. For these applications not covered by standard design equations, design according to 'engineering judgement' is typically emphasized. Strain data is a critical factor in satisfying 'engineering judgement' as it can be used to relate material response to previously defined characteristics such as tensile strength and measured strain to failure. For the application described in this paper, DIC is utilized as a supplement to the standard pipe spool survival test so that the response of the composite repair to internal pressure can be characterized in detail. This provides validation of the approach that can be used in more complex repair scenarios where characterization of the composite load transfer is essential.

Digital Image Correlation

DIC is a data acquisition technique that allows for full-field surface displacement measurements through non-contact optical photogrammetry. Unique, stochastic patterns are applied to the test specimen surface and observed with a pair of stereoscopic cameras to measure full-field surface shape and displacements, allowing for the resolution of surface strains during testing. Relative surface movement is measured through stereo-triangulation which allows for development of three-dimensional (3D) displacement and strain measurements.

Being a non-contact diagnostic technique, with only a light coating of paint or similar patterning method applied to the article's surface, DIC has become a powerful tool in applications where traditional strain measurement techniques, such as resistive strain gages may impact test results. Additionally, DIC has advantages over other strain measurement techniques when the surface strain field is complex and inclusive of discontinuities due to test article geometry. When evaluating composite repair designs through full-scale pipe spool survival testing, both limitations/factors typically exist. This can be due to the presence of fibers, excess resin, or other irregularities at the surface inherent to the composite repair. Traditional physical strain gages provide extremely localized, single point in situ strain responses and must be chosen prior to testing. Strain capacity limitations also exist for traditional strain gages that are often exceeded during limit load testing. Another advantage of DIC is the ability to measure and record strains much greater than those that can be obtained using traditional strain gage rosettes. DIC allows for full-field strain measurements to be taken on the visible sample surface, and for placement of virtual strain gages and surface geometry measurements to occur retroactively during post-processing. This makes DIC a valuable asset for obtaining an enhanced assessment of the composite's performance during testing, especially throughout the research and development phases, to compare empirical test data to analytical simulations.

Test Methodology

The sample for the full-scale pipe spool survival testing was fabricated using 6.625-inch OD x 0.280-inch WT, A106 Grade B (specified minimum yield strength of 35,000 psi) pipe. Mechanical testing was performed on a section of the pipe prior to full-scale testing to determine measured yield and tensile strengths. The spool survival sample was determined to have yield and tensile strengths of 55,700 psi and 78,100 psi, respectively. The sample for the spool survival test contained a machined wall loss region in its center that was repaired using the XCorr system. This wall loss region was created by machining a 3.3125-inch wide by 6.625-inch long wall loss area that tapered from the full pipe wall thickness down to a 1.656-inch wide by 3.3125-inch long section where 75% of the pipe wall thickness had been removed (Figure 2). For this pipe geometry, 75% wall loss results in a minimum remaining wall thickness of 0.073-inches. Mandatory Appendix 401-III provides equations that specify the composite repair thickness for the spool survival sample based on the characteristic tensile strength of the composite material along with the above pipe and defect information.

To this end, the pipe defect corresponding to 75% wall loss was repaired by first filling the void with a hardened epoxy to create a smooth surface profile and to avoid stress concentrators at the edges of the machined defect. Next, per XCorr instructions, the quadaxial fiberglass reinforcement was manually infused with the 2-part epoxy resin, making use of a two-cartridge dosing system equipped with a static mixer to insure complete mixing. According to Appendix 401-III calculations, 8 composite plies, at a thickness of 0.06"/ply, were needed to remediate the defective pipe to a performance level able to achieve the calculated test pressure 4,708 psi. Once the requisite length of the 12.5" wide reinforcement was wetted, the uncured composite was tightly wrapped over the defective area, overwrapped with a compressive film, and allowed to reach full cure.

Once the repair installation was complete, the sample was placed in a shielded burst pit for pressurization. A stochastic pattern was applied to the surface of the composite and adjacent base pipe using a thin coat of white paint with a contrasting speckle pattern (Figure 3). Internal pressure was then increased until the calculated test pressure was achieved. After achieving the calculated test pressure, all internal pressure was removed so the sample could be inspected in accordance with Table 401-5.2-1. During this portion of the test, the speckle pattern was monitored using the DIC system. Since no visual evidence of degradation was observed, internal pressure was increased until failure occurred. In order to protect the camera system, DIC equipment was removed from the burst pit during the final pressure to failure. Figure 4 is a plot of internal pressure vs. time during the spool survival test. The maximum pressure achieved during the test was 5,422 psi, 15% higher than the calculated test pressure, before sample failure ultimately occurred in the simulated corrosion underneath the repair. Figure 5 is a photograph of the sample after burst. It should be noted that protective equipment could be designed and implemented to protect the DIC equipment during energy releases associated with failures during full-scale testing.

Results

During the test, the simulated corrosion region of the repair, along with a length of base pipe on either side, was observed using DIC to monitor surface strains. Figure 6 shows a capture of the full-field hoop strain overlay at 3,500 PSI. When compared to a nominal composite hoop strain of approximately 800 microstrain, the simulated corrosion's effect on the repair can clearly be seen as hoop strains exceeding 5,000 microstrain (10,000 microstrain = 1% strain) are observed at that location. Comparatively, the nominal pipe body hoop strain at this pressure was approximately 1,100 microstrain. This value is very close to the theoretical pipe body hoop strain predicted at this pressure. The peak strain observed on the composite surface is well below the measured tensile strain-to-failure of 1.38%, determined through coupon level testing of the composite system. Although the peak strain was well below the tensile strain-to-failure, the location of the peak strain was observed to correspond with the location of the ultimate failure. In addition to the hoop strains discussed, the sample's axial strain response was also included for this study. Figure 7 provides both the axial and hoop strain response overlays at various pressures during the pipe spool survival pressure test.

The full-field strain visualizations of the sample's response to applied loads allow for comparisons to theoretical results that individual strain gages might miss due to the complex strain distribution. For this case-study, a comparison between theoretical pipe body strain and that measured with DIC was performed to obtain good corelation between DIC measurements and theoretical results in a nominal area. Figure 8 provides charts of measured hoop and axial strains in the base pipe along with theoretical predictions. Figure 9 is a plot of measured maximum hoop and axial strains vs. applied internal pressure during the test.

The results of the theoretical and actual strain measurements of the pipe body, as well as composite maximum strains in the hoop and axial directions are tabulated at various pressures from the full-scale spool survival pressure test below in Table 1.

Table 1: Tabulated DIC Strain and Theoretical Pipe Body Strain Results at Various Pressure Steps during Full-Scale Spool Survival Testing

Internal Pressure	Composite Maximum Hoop Strain	Composite Maximum Axial Strain	Pipe Body Average Hoop Strain	Pipe Body Average Axial Strain	Theoretical Pipe Body Hoop Strain	Theoretical Pipe Body Axial Strain
PSI	*µm/m*	*µm/m*	*µm/m*	*µm/m*	*µm/m*	*µm/m*
1,000	1,111	372	297	79	333	81
1,500	1,709	558	463	111	500	122
2,005	2,399	741	610	145	668	163
2,509	3,167	975	779	193	836	204
3,005	4,118	1,273	932	219	1,001	244
3,500	5,065	1,464	1,089	263	1,166	284

A notable finding from the DIC results is the extent to which the wall loss defect affects hoop and axial strains observed on the surface of the composite. The wall loss region can be clearly identified from outer surface strains and the geometric extent for circumferential and axial strains to return to nominal levels can easily be measured. The DIC data allows for retroactive strain and geometrical measurements to be taken anywhere on the surface that was observed during test, as opposed to reliance on pre-installed sensors that only provide in situ point data. It is clear that this data along with visualization tools can aid in the design and assessment of repairs for complex defects or assist in the development of modified repair designs, such as patches, as a replacement for full-encirclement wraps.

Discussion

The results of the DIC were shown to correlate well with theoretical predictions for strains in the base pipe. This comparison gives confidence to the results observed at the outer surface of the composite, which experiences more complex loading due to the presence of the machined wall loss area. The addition of DIC allowed for a non-invasive, quantitative assessment of composite repair performance in what is traditionally a pass / fail test. Although DIC was implemented for the pipe spool survival test in this instance, the results provided by DIC can influence future tests of the XCorr system, including additional PCC-2 and ISO 24817 tests such as ASME PCC-2 Appendix 401-V Survival Testing (ISO 24817 E.2 Survival Testing) where strains in the repair play a critical role in successfully passing a 1,000-hr, sustained load test.

Beyond the more detailed description of composite repair performance, DIC results also hold the potential to significantly inform the design of future repairs and repair products. One obvious area of development entails the DIC analysis of multiaxial strain for alternative defect geometries/conditions as well as the subsequent design of needed composite repair materials. For example, the imaging aspect of DIC promises the opportunity to directly correlate the spatially resolved strain behaviour of specific defect geometries such as cracks or wrinkle bends with the ultimate failure pathways of composite repairs. Furthermore, similar analyses conducted for repairs conducted with reinforcements varying in either weave construction or material composition will serve to advance composite repair design.

Future Implementation

Successfully demonstrating DIC on a standard composite repair test has implications for future, non-standard testing efforts as well. A topic of particular interest with composite repairs involves their installation when the pipe or piping has internal pressure. Previous studies have been performed examining the effect of installation pressure on composite repairs and have shown that, for external wall loss, it appears to have little effect on the performance of the composite when measured in terms of ultimate failure pressure and fatigue life [1]. Other preliminary investigations have been conducted examining other defect types; however, conclusive studies have not been published establishing criteria or quantifying differences in repair performance as a function of installation pressure, defect type, or operating conditions. DIC could be a uniquely valuable tool in aiding this effort by capturing the global response of the composite under these various conditions. Additionally, as composites continue to be used for reinforcement and repair of more complex defect types, DIC serves as an excellent evaluation tool.

References

[1] ASME PCC-2-2018, Repair of Pressure Equipment and Piping, Repair Standard, Article 401, Non-metallic Composite Repair Systems: High Risk Applications, American Society of Mechanical Engineers, New York, 2018.

[2] ISO 24817:2017, Petroleum, petrochemical and natural gas industries – Composite repairs for pipework – Qualification and design, installation, testing and inspection. International Organization for Standardization, Switzerland, 2017.

[3] Whelan, Bradley. "Internal Installation Pressure Effects on Composite Repairs." Paper presented at the CORROSION 2019, Nashville, Tennessee, USA, March 2019.

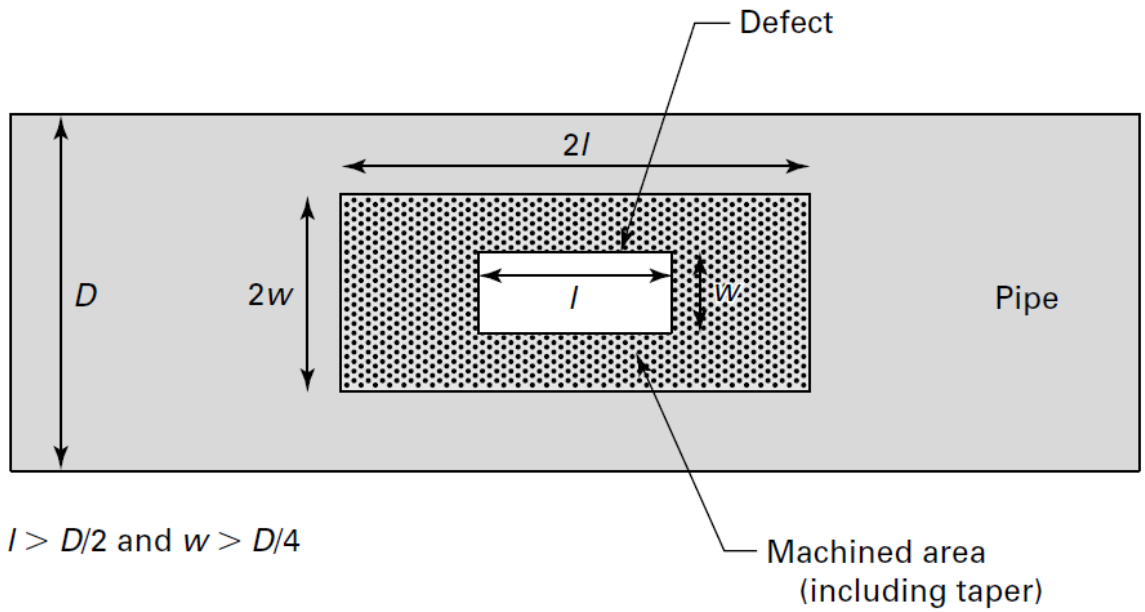


Figure 1: ASME PCC-2 pipe spool survival specimen specifications

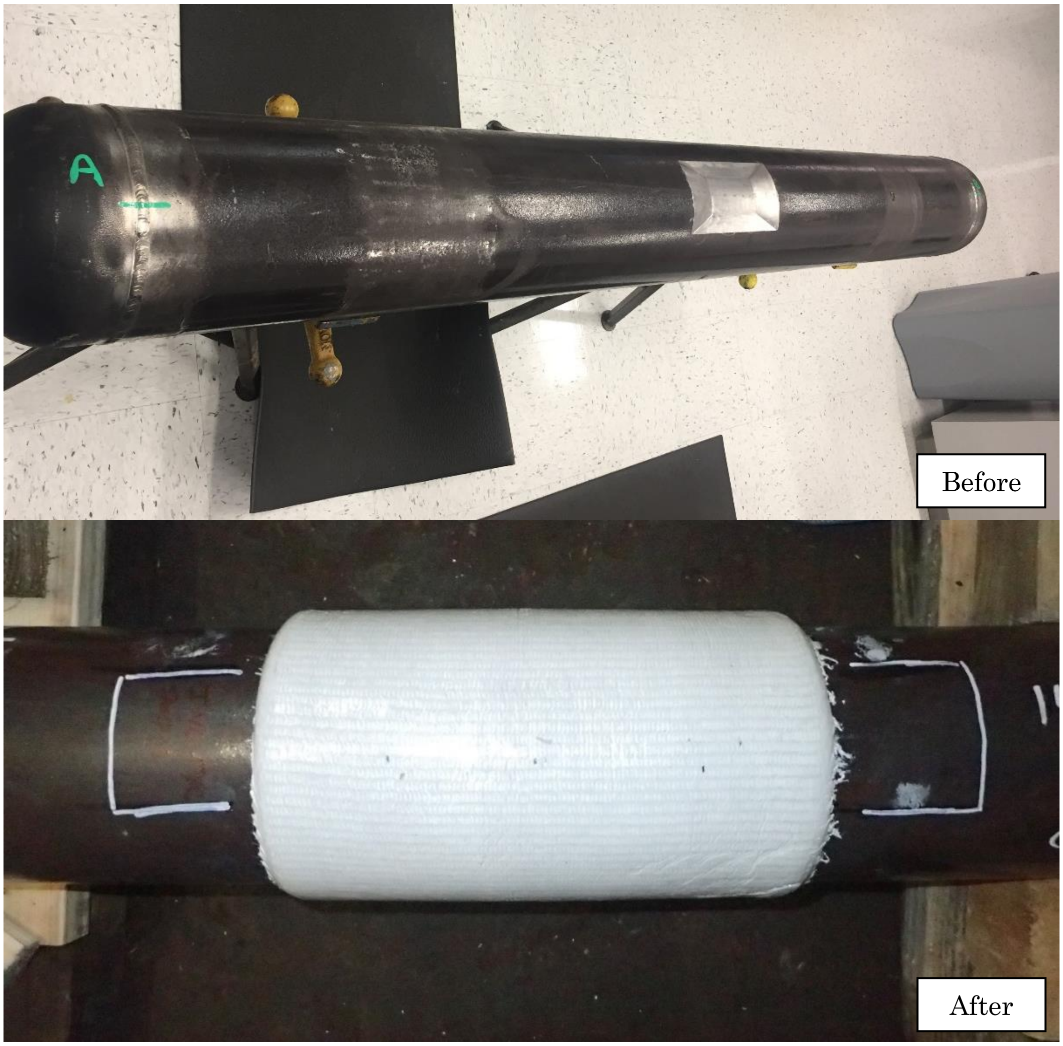


Figure 2: Photograph of pipe spool survival specimen before and after repair installation

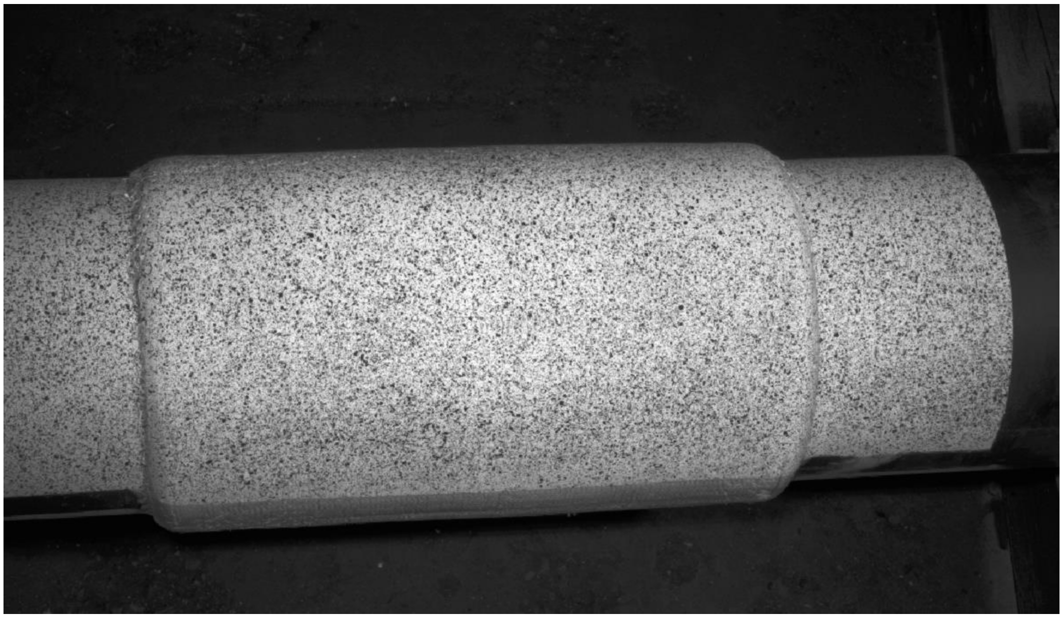


Figure 3: Pipe spool survival specimen with stochastic speckle pattern applied for DIC imaging

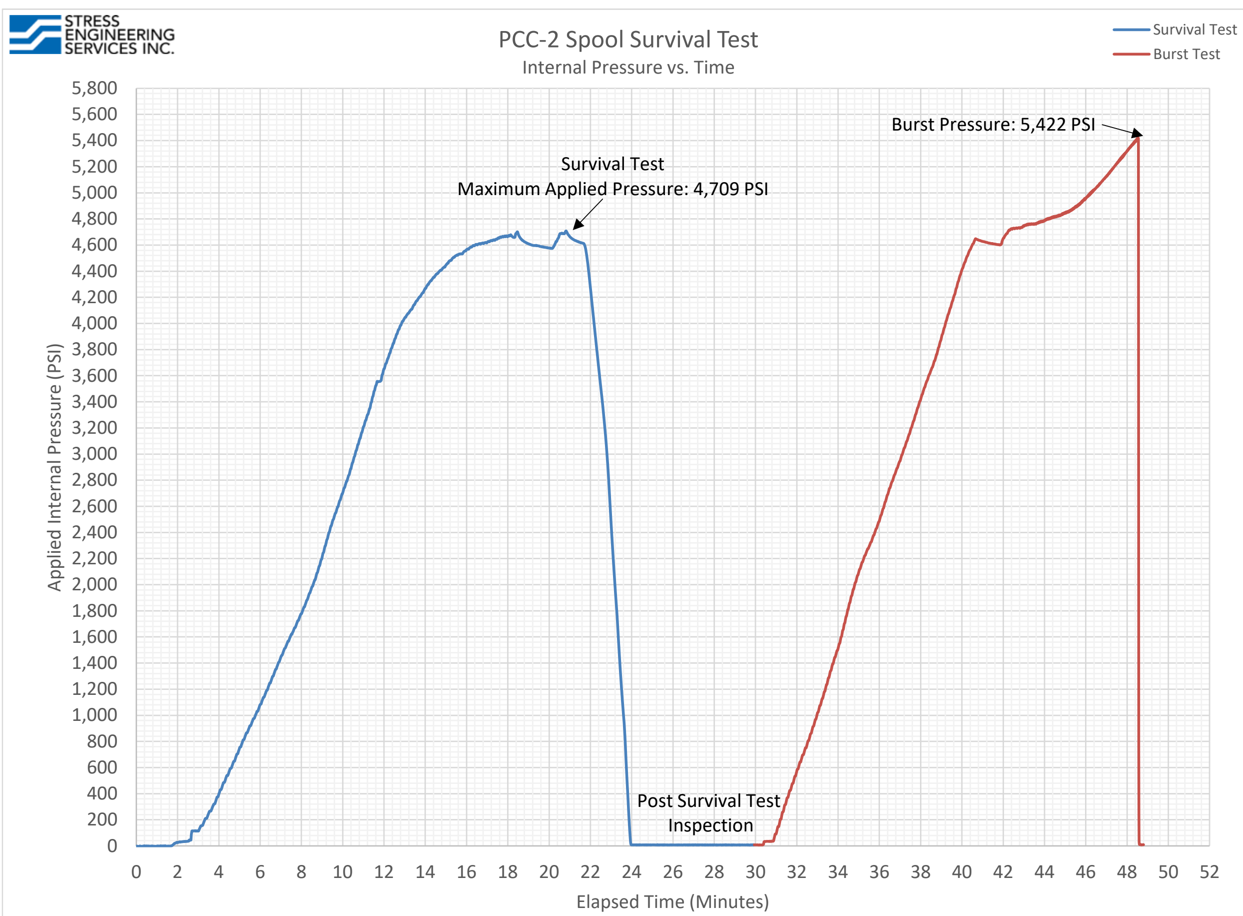


Figure 4: Plot of internal pressure vs elapsed time for survival and burst test

Figure 5: Photograph of sample following spool survival and burst test, isllustrating failure in machined wall loss region

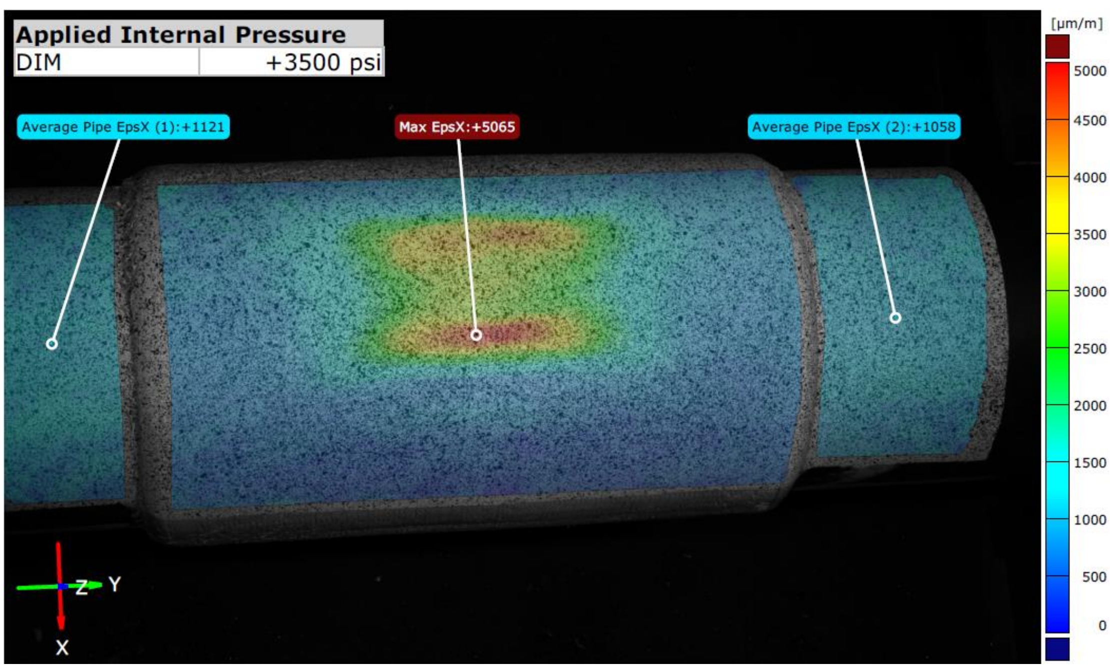
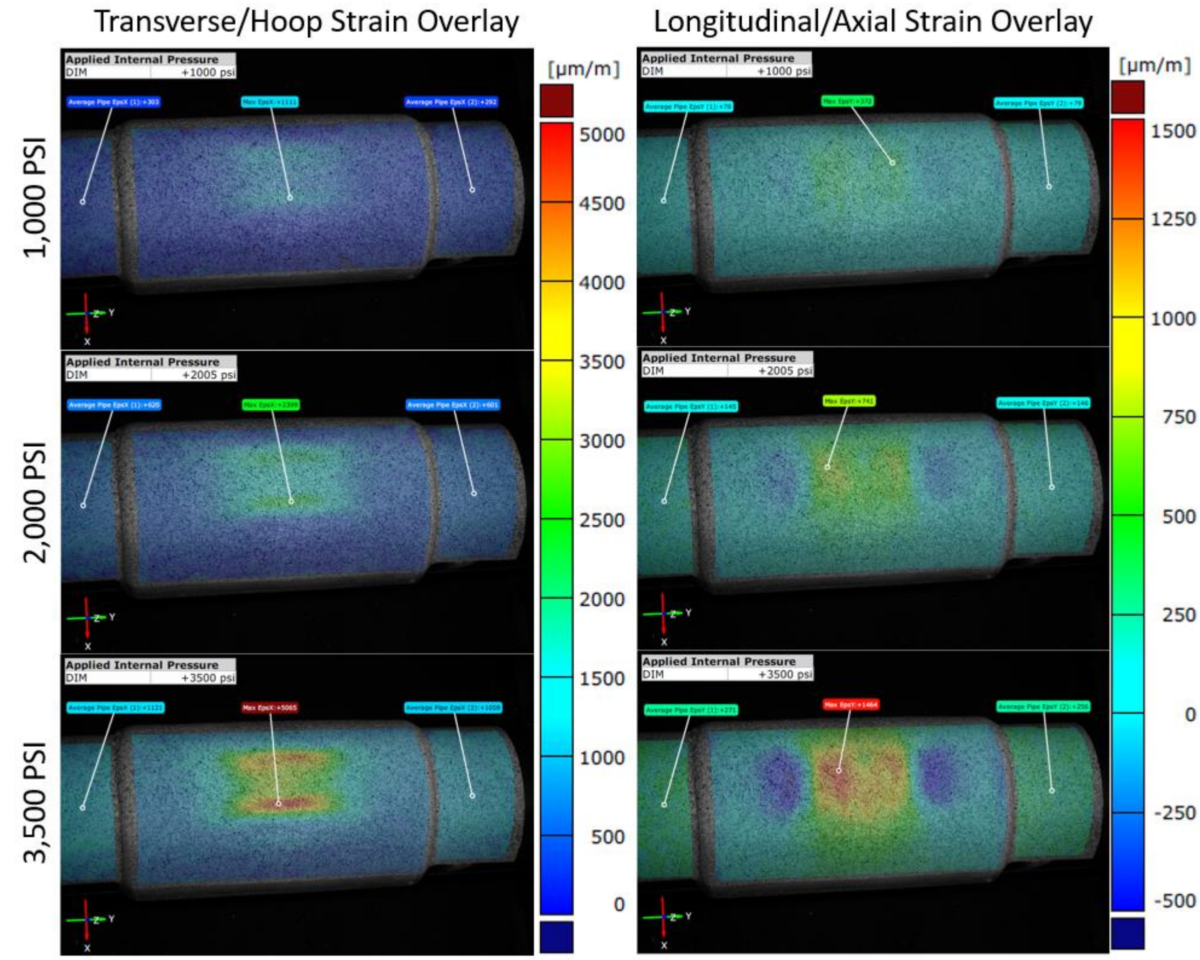


Figure 6: Overlay of composite repair and pipe body hoop strain at 3,500 PSI acquired using DIC during pipe spool survival pressure test.



Note- Different scales used for hoop and axial strain overlays

Figure 7: Overlays of hoop and axial strain fields at various pressures during the pipe spool survival pressure test

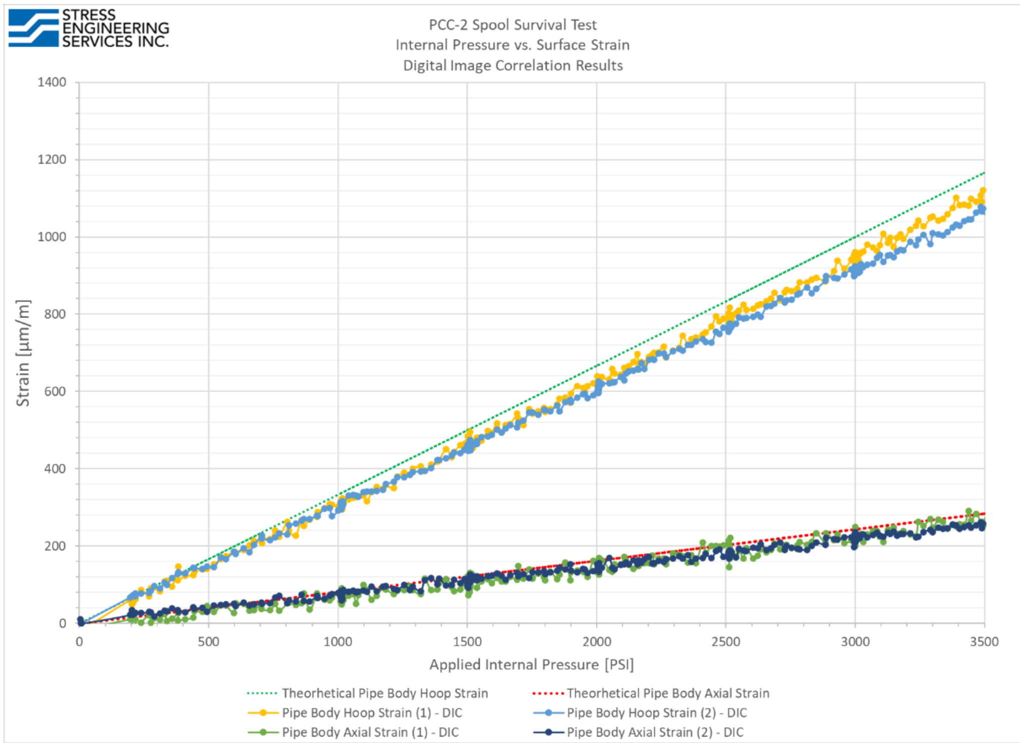


Figure 8: Plot of pipe body strains acquired using DIC and theoretical pipe body strains vs. internal pressure

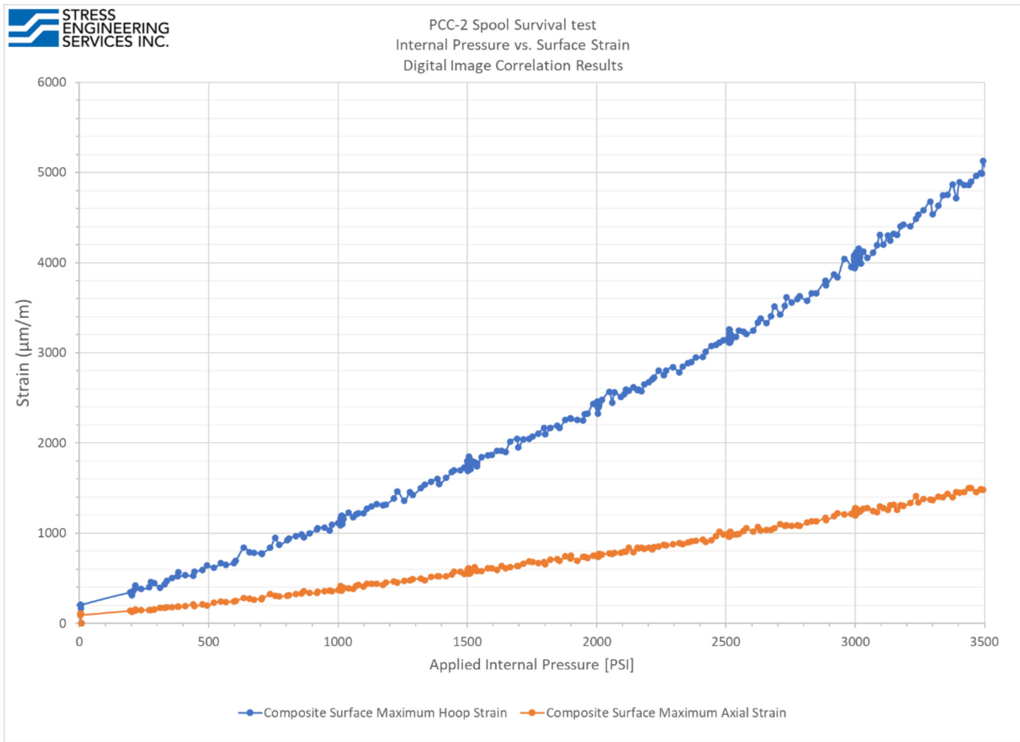


Figure 9: Plot of recorded composite repair strains acquired using DIC vs. internal pressure