Air Pocket Analysis: Exploring the Effects of Air Pockets in Composite Reinforcement Systems for Pipes

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Abstract

Non-metallic, composite reinforcement systems for pipes have become a standard method for repairing a range of defects including corrosion, dents, gouges, cracks, girth welds, and seam defects. Composite repairs for pipes are hand-applied in the field, making application defects a potential source of concern, especially for larger repairs and hard-to-reach areas. The most common defects observed are air pockets trapped within the layers of the composite wrap.

This paper explores the effects of air bubbles of varying sizes and depths within the composite repair system. Specifically, this study will observe the effects on the pressure capacity of repaired pipes with designed defects by performing hydrostatic pressure tests. Also, the effects of air bubbles on the liquid tightness of composite wraps that are applied on pipes with through wall failures will be tested. Finite Element Analysis (FEA) was performed to analyze stresses on the composite wrap system with air pockets of various sizes and at a variety of interlaminar locations within the composite reinforcement system. Finally, the results of both the physical pressure testing as well as the computational analysis will help provide real-world guidelines to determine whether or not air bubbles are a potential cause for concern when using composite reinforcement systems.

Introduction and Background

Composite reinforcement systems are a widely accepted repair method for high-pressure transmission pipelines. Composite repairs can provide structural reinforcement to severely degraded pipelines, they are corrosion-resistant, they can fit complex geometries like flanges, T-joints, or elbows, and they can be applied on a live line without hot work such as welding.

Proper training is important to the installation of composite repair systems because they are hand-applied in the field. Field conditions can vary widely with many factors contributing to the difficulty level of the repair like application environment, time limitations, minimal clearance, difficult access, worker fatigue, or dangerous locations (i.e. repairing buried pipe adjacent to a busy highway). These factors can increase the chance of defects within the composite.

The most common application defect observed in the field is air bubbles in between the layers of the composite fabric, also called interlaminar air bubbles. Limited studies have been done to test the effectiveness of composite repair systems with interlaminar air bubbles present. The following tests were conducted to understand the effect of air pockets on resistance to pressure cycling, ultimate burst pressure, and liquid tightness of composite repair systems.

We summarize the results of a two-part testing and analysis program, including full-scale testing of 10-in pipes repaired with an air pocket defect and Finite Element Analysis models of varying air bubble circumferential lengths and radial thicknesses at different locations in the composite repair.

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Pressure Cycling and Burst Test of Air Bubble Defect

Testing was performed on 10-in diameter, SCH 40 steel pipe samples with 8 x 0.25-inch holes drilled into the center section of the pipe to simulate through-wall corrosion. 6 pipes were repaired with various, ASME PCC-2 compliant composite repair systems. The testing protocol used pipe samples repaired with simulated air bubble defects that were introduced during the composite repair installation. The results of the pressure cycling and burst testing of the experimental samples were compared to control pipe samples repaired with composite wraps installed without air bubbles. The testing protocol included burst pressure tests and a final test was performed using cyclic pressure loading to determine the anticipated life expectancy of the repair with an air bubble defect.

The carbon fiber composite wrap repairs were manufactured and installed by Advanced FRP Systems, and the testing and pipe fabrication was conducted at Composite Technology and Infrastructure (CTI) and ADV Integrity.

Composite Wrap Installation and Air Bubble Fabrication

The composite wrap repairs included 4 layers of carbon fiber composite fabric and 1 layer of fiberglass for a total repair thickness of approximately 0.190 inches. For each pipe, an air bubble defect was introduced between each layer of composite, so 4 separate defects were on each pipe. The air bubbles were isolated from each other by a minimum of 12 inches to reduce the likelihood of any interaction. Air bubbles were fabricated using industrial-grade plastic bubble wrap, and they were circular in shape ranging from 1 to 3 inches in diameter. The thickness of the air bubbles was approximately 3/16 of an inch. The presence of the air bubbles was confirmed by tap testing after the composite had cured.

A total of six 10-in diameter pipes were tested with varying air bubble defects and 2 different composite wrap systems manufactured by Advanced FRP Systems. Repair System 1 is designed to repair low-pressure piping systems, mainly water and wastewater piping systems. Repair System 2 is designed for high-pressure piping and high-risk materials including hydrocarbons and pressurized gasses.

Table 1. Physical Properties of Repair System 1 and Repair System 2

Property	**Repair System 1**	**Repair System 2**
Tensile Strength	102.1 ksi	90.48 ksi
Tensile Modulus	6.71 Msi	7.46 Msi
Elongation at Break	1.67%	1.47%
Lap Shear Strength	2,075 psi	3,465 psi
Adhesion to Blasted Steel	3,000 psi	2,950 psi
Per Ply Thickness	0.038 inches	0.038 inches

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Cyclic Pressure and Burst Pressure Test Procedure

The testing procedure is laid out in Table 2.

Table 2. Cyclic Pressure Test and Ultimate Burst Pressure Test

Cycle Testing	Pressure cycle sample between 100 and 500 psig.
	Run 25,000 cycles.
	Test is stopped as soon as a leak or loss of pressure is detected.
Pressure Hold/Burst Test	Pressure sample up to 100 psig at a rate of 100 psi/min. Hold and check for leaks.
	Pressure sample up to 250 psig at a rate of 100 psi/min. Hold for 1 hour.
	Pressure sample up to 500 psig at a rate of 100 psi/min. Hold for 30 min.
	Pressure sample up to 1000 psig at a rate of 100 psi/min. Hold for 3 minutes.
	Release Pressure. Record results.

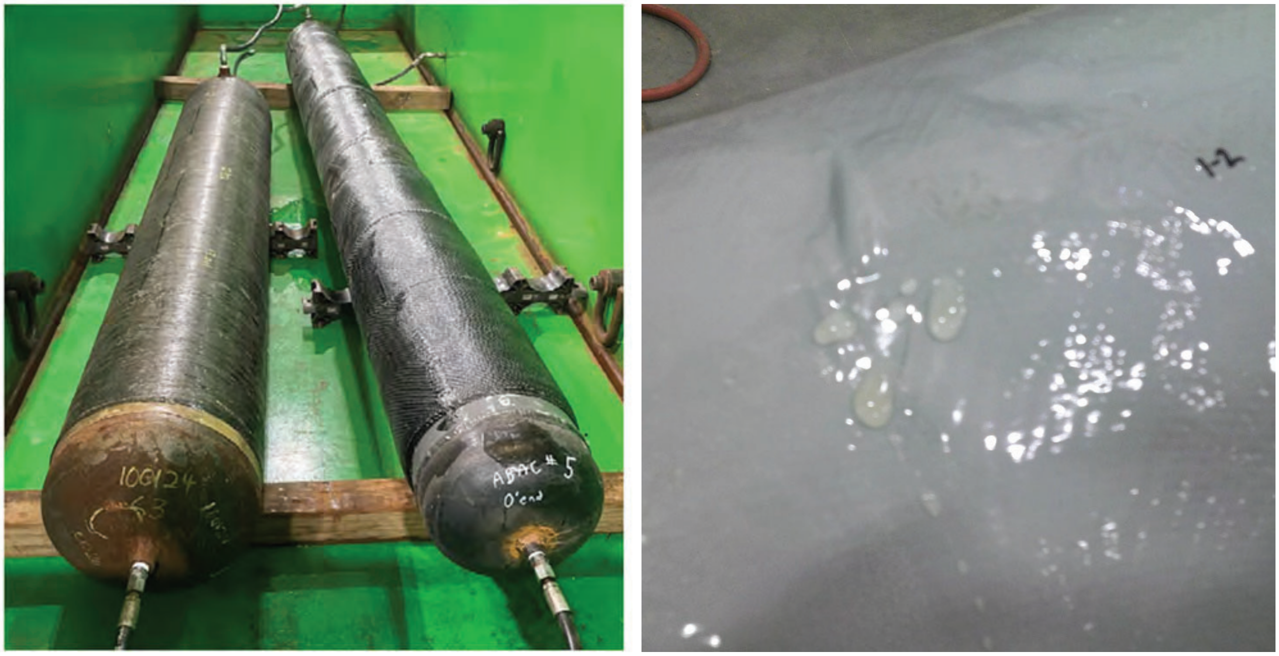

Figure 1. Pipe 6 before pressure cycling (left) and pinhole leak at air bubble in Pipe 3

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Figure 2. 10-in sample before burst test with composite repair with air pocket defects

Results

The results of the cyclic pressure and burst pressure tests are shown in Table 3.

Table 3. Repair Details and Results for Each 10-in SCH 40 Test Pipe

Pipe Number	Repair System	Air Bubble Size	Pressure at Failure	Notes
1	System 1	2 inch diameter	620 psi	Failed through end
2	System 2	2 inch diameter	950 psi	Failed through end
3	System 2	3 inch diameter	890 psi	Pinhole leak at a bubble then failed through end
4	System 2	1 inch diameter	1,000 psi	Failed through end
5	System 2*	2 inch diameter	Did not fail	Held 1,000 psi without loss of pressure
6	System 2*	2 inch diameter	Did not fail	Held 25,000 pressure cycles without loss of pressure
7	System 1 (Control)	No bubble	Did not fail	Held 1,000 psi without loss of pressure
8	System 2 (Control)	No bubble	Did not fail	Held 1,000 psi without loss of pressure

*Design included 1 extra layer of fiberglass for increased water tightness

Discussion

A control test without any air bubble defects held 1,000 psi pressure for both repair System 1 and 2. Initial testing with 2-inch air bubbles show a large discrepancy between the pressure capacity of Repair System 1 versus Repair System 2. A brief comparison of system properties is shown in Table 1 above.

The biggest difference between the two repair systems is the lap shear strength, which shows the overall bonding strength between the layers of the composite. Repair System 2 was specifically designed to maximize the interlaminar strength of the cured composite system. When a repair is performed on a pipe with a through-wall failure, considerable interlaminar strain is placed on the composite.

During the hydrostatic pressure tests, Pipe 1 through 4 all eventually failed through the end of the repair, and each of these failures occurred between the layers of the composite system, not between the composite and the steel substrate. In all four cases, the air bubbles between layers 1 and 2 and between layers 2 and 3 filled with water during hydrotesting. As the pressure increased, the composite

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began to unzip, starting at the location of the air bubble. The pressure ultimately made its way to the edge of the repair where a failure was noted.

After noting the presence of water in the air bubbles that eventually resulted in failure, an additional layer of fiberglass was included in the repair design to help create a water-tight layer underneath the carbon fiber reinforcement. This technique successfully prevented water from filling the air bubbles and raised the failure pressure rate above 1,000 psi. Ultimate failure was noted around 1,190 psi with Repair System 2 with an additional fiberglass layer with 2-inch air bubble defects.

In order to look at the effect of air bubbles on cyclic loading conditions, Pipe 6 was cycled 25,000 times from 100 to 500 psig. The pipe survived for all 25,000 cycles without loss of pressure. The pressure cycling conditions correspond to a pressure range of 400 psig. Assuming that in a real-world scenario the pipe would operate at 72% SMYS and the Maximum Operating Pressure (MOP) is 400 psig, then the resulting life of the simulated cycle test is 100 years based on the following calculation:

$$\text{Life} = \text{Test Cycles} / \text{Fatigue Safety Factor} / \text{Number of Cycles Per Year}$$

The fatigue safety factor used in the calculation was 10 based on existing research establishing pressure history data [1].

Modeling Behavior of Air Pockets in Various Conditions and Locations

The model developed evaluated the maximum principal strains on the composite repair per ASME PCC-2 allowable limits due to the presence of interlaminar air bubbles. The model only represented the behavior of the composite repair as a pressure containment system.

The FE models incorporated a two-dimensional (2D), plane strain circumferential cross-section geometry of a 10-inch NPS pipe x 0.365-inch wall thickness with a composite repair composed of 5 layers of bidirectional carbon fiber resulting in a total repair thickness of approximately 0.175-inch (shown in **Error! Reference source not found.**). The pipe steel material properties were modeled as linear elastic. The carbon fiber material properties such as modulus of elasticity and Poisson's ratio were determined from subscale coupon testing of the composite material. The effective modulus of elasticity in the hoop direction was approximately 5.75 Msi. The models were loaded by applying an internal pressure equivalent to 200 psig and 600 psig.

Nine cases were tested by varying the air bubble circumferential length, air bubble radial thickness and air bubble interlaminar location. **Error! Reference source not found.** shows a summary of the load case matrix.

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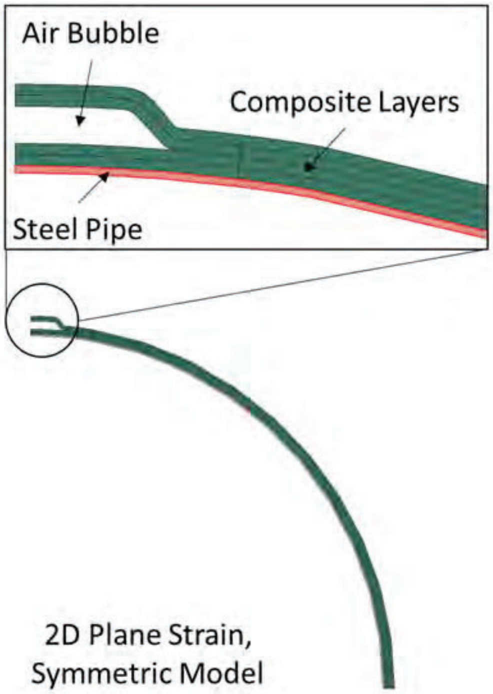

Figure 3: Overview of model geometry

Table 4. Load Case Matrix

Case	Air Bubble Circumferential Length (in)	Air Bubble Radial Thickness (in)	Air Bubble Location
1	0	0	No air bubble
2	1	0.125	Between 1st and 2nd layer
3	1	0.125	Between 2nd and 3rd layer
4	1	0.125	Between 3rd and 4th layer
5	1	0.125	Between 4th and 5th layer
6	2	0.125	Between 3rd and 4th layer
7	0.5	0.125	Between 3rd and 4th layer
8	1	0.250	Between 3rd and 4th layer
9	1	0.0625	Between 3rd and 4th layer

Load was applied to the model at 200 psig and 600 psig. Results of the simulated load are shown in Results

According to the analysis, at both 200 psig and 600 psig, air bubbles between the first and second layers exhibited the highest strains. Additionally, at both pressures, a narrower air pocket circumferential lengths resulted in a higher overall strain in the bubble region. Also, larger air pocket radial thicknesses resulted in overall higher strains.

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At 600 psig, the strains over 0.4% (ASME PCC-2 strain limit) were experienced at the inflection point on the outer layer (5th layer) and the inflection point on the inside layer (1st layer). For most cases, the strain was experienced through the layers below the air bubble. Error! Reference source not found. provides a summary of the strain results for all the cases at the two pressures.

Figure 4, 5, and 6 show the effect of each of those variables on the strains across the composite layers.

Table 5.

Results

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Table 5. Analysis Results for 200 psig and 600 psig

Pressure (psig)	Case	Max Strain (%)	Max Strain Location
200	1	0.10	Throughout total composite thickness
	2	1.90	Extensive over the first layer under bubble
	3	0.44	At external inflection point on 5th layer
	4	0.52	At external inflection point on 5th layer
	5	0.28	At external inflection point on 5th layer
	6	0.45	At external inflection point on 5th layer
	7	0.81	At external inflection point on 5th layer
	8	0.44	At external inflection point on 5th layer
	9	0.55	At external inflection point on 5th layer
600	1	0.29	Throughout total composite thickness
	2	4.23	Extensive over the first layer under bubble
	3	1.32	At external inflection point on 5th layer
	4	1.43	At external inflection point on 5th layer
	5	0.76	At external inflection point on 5th layer
	6	1.22	At external inflection point on 5th layer
	7	2.63	At external inflection point on 5th layer
	8	1.15	At external inflection point on 5th layer
	9	1.59	At external inflection point on 5th layer

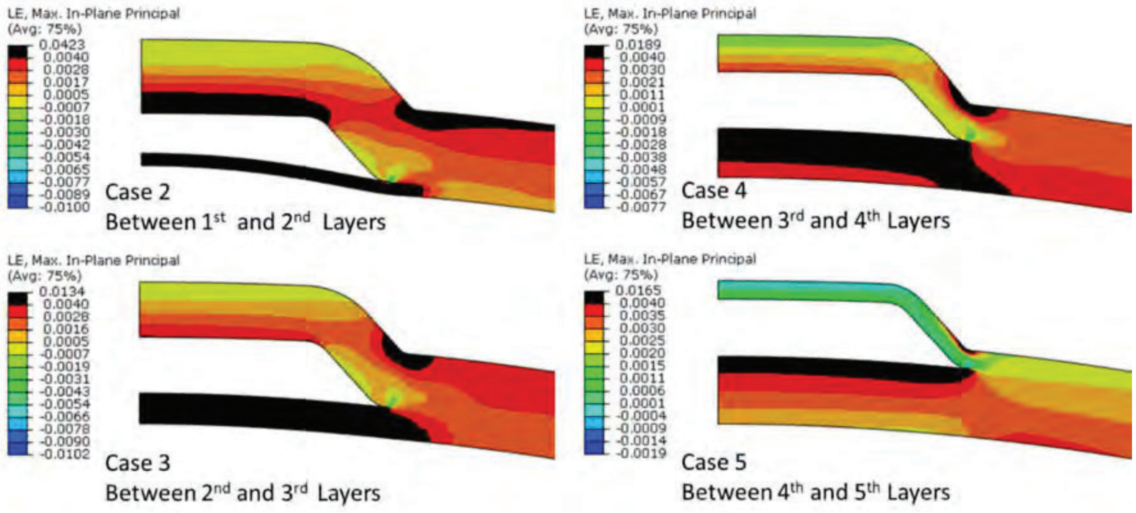

Figure 4: Air bubble location comparison at 600 psig (black contour represent strains above 0.4%)

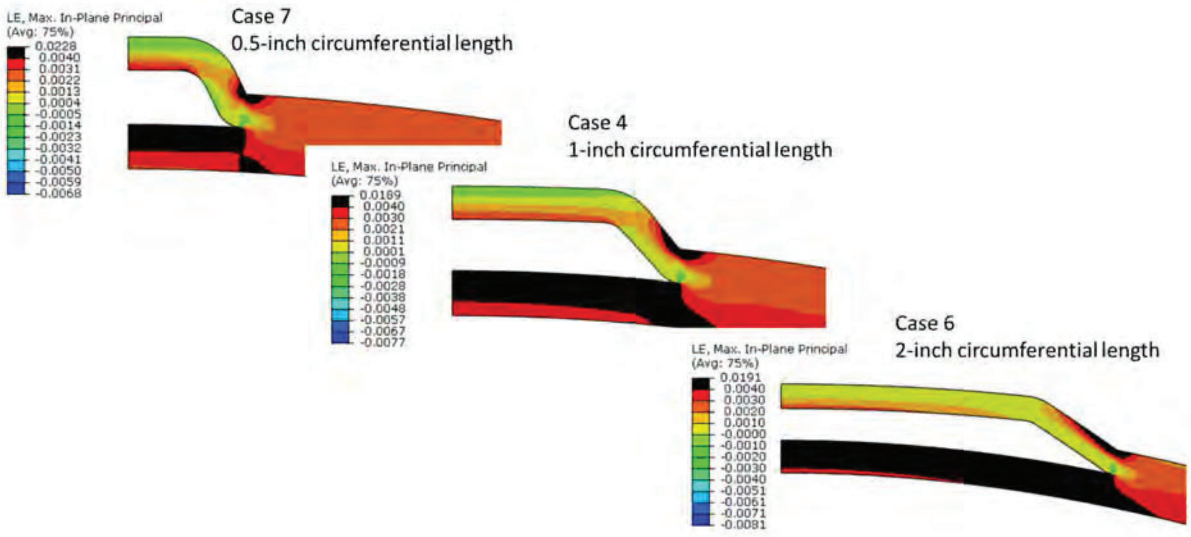

Figure 5: Air bubble circumferential length 600 psig (black contour represent strains above 0.4%)

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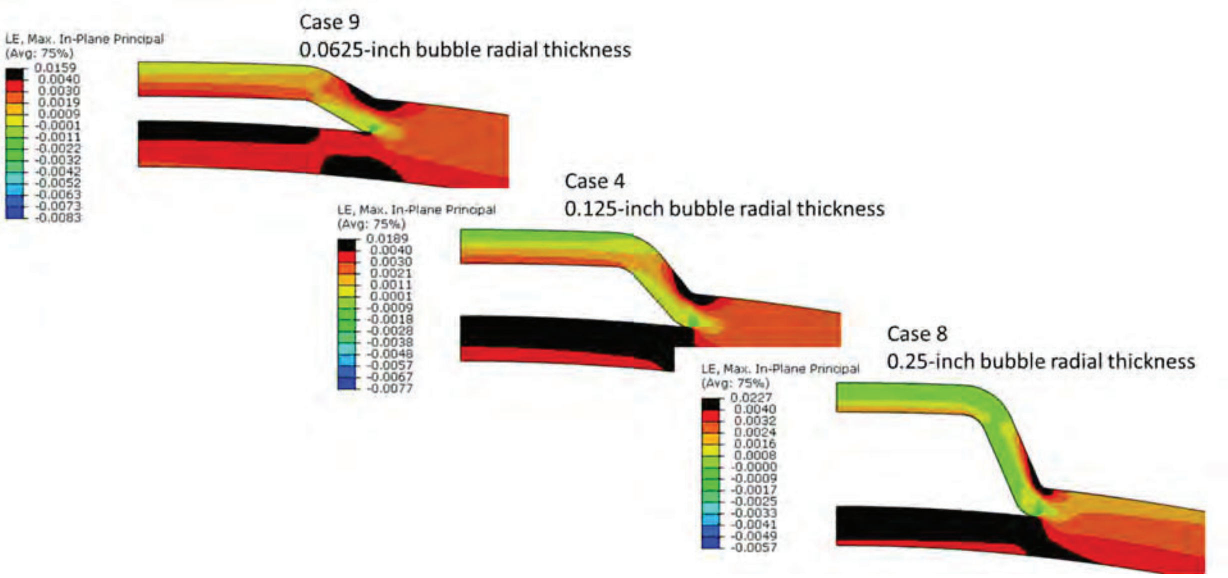

Figure 6: Air bubble radial thickness 600 psig (black contour represent strains above 0.4%)

Conclusion

Testing the effects of air bubbles on composite repair systems is extremely complicated and depends on several factors. The surface area, thickness, and depth of the air bubble all influence the increase in strain and eventual failure pressure of a composite wrap system. The physical properties of the wrap system itself are also a critical factor in determining the ultimate failure pressure of a repair with an air bubble-type defect.

The repairs tested in this paper correspond to a worst-case scenario, where the host pipe has through-wall failures that subject the composite to significant interlaminar strain. In the field, if air bubble-type defects are found in a composite repair, then all these factors must be taken into account before determining if the defect will affect the repair strength or longevity.

Air bubble defects have the largest decrease in pressure capacity when using composite systems with lower lap shear or interlaminar shear strength. When repairing pipes with through-wall failures, it is always best to choose a repair system with a high lap shear strength in order to prevent delamination between the layers.

From our experience, all composite repairs have air bubbles of some size, although they are often extremely small. We found no evidence that small air bubbles, less than 0.1 square inches, have any effect on the pressure capacity or the longevity of composite repairs; however, larger air bubbles clearly have a negative effect on the ultimate pressure capacity. As shown in the finite element analysis, the strain level clearly rises when the air bubble is closer to the inner surface of the pipe, although the

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effect of the size of the air bubble is not clear. Future testing programs may be able to provide more insight into the effect of the size of the air bubble on the effectiveness of carbon fiber composite wraps.

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