CAAP Annual Report

Date of Report: *October 19, 2016*

Contract Number: *DTPH56-14-H-CAP02*

Prepared for: *DOT/PHMSA*

Project Title: *Wall Break-through in Composite Repaired Defects*

Prepared by: *The University of Tulsa*

Contact Information: *Michael W. Keller, mwkeller@utulsa.edu, 918-631-3198*

For quarterly period ending: *October 9, 2016*

Business and Activity Section

(a) Generated Commitments - last quarter

There has been no change in project participants or other contracts.

Supplies	Cost
Testing Supplies and fittings	669.49
Pipe	144.27
Testing Supplies and fittings	816.68
Testing Supplies and fittings	14.09
Pump	985.23
Testing Supplies and fittings	216.63
pipe and testing supplies	122.22

Student in charge of following research: Omar Ramirez (M.S. – expected fall 2016 / spring 2017)

(b) Status Update of Past Quarter Activities

During the past year of this project we have completed the following research activities

1. Completed 2-layer straight pipe testing.
2. Submitted conference paper on this work to the Society for Experimental Mechanics.
3. Completed 4-layer straight pipe testing.
4. Developed new approach for elbow defect analysis.
5. Continued elbow testing.
6. Continued FEA analysis
7. Continued DIC analysis

Past year activities

For this annual report we will summarize the accomplishments of the last year before reporting on the activities of the last quarter.

Straight Pipe Testing

We have completed testing on straight pipe specimens for repairs that consisted of two layers and four layers of composite material. The results of the two-layer burst testing are shown in **Error! Reference source not found.** and Four-layer repair results are testing are shown Table 1.

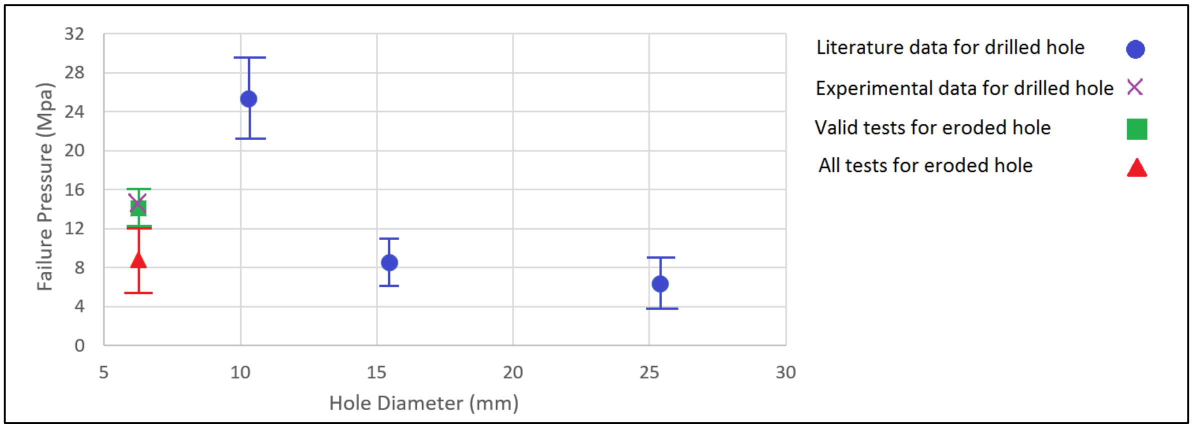

Figure 1: Comparison of failure pressures for two-layer repairs on drilled and eroded flaws.

Table 1: Hydrostatic burst test results for four layer repairs on a straight pipe with drilled and eroded flaws.

	1	2	3	4	Average	STD
Drilled	945	1084	650	1083	940.5	177
Eroded	1024	935	964	1827	1187.5	370

From these results we can conclude that the current design methodology for through-wall defects in PCC-2 is appropriate for flaws that have been produced from an erosion or corrosion type process in straight pipe geometry. This was concluded by observing that the valid tests for the eroded specimens for both 2 layer and 4 layer repairs had nearly identical failure pressures when compared to the drilled holes of the same diameter. However, there is one additional concern. We found that in the 2-layer testing, a significant number of through-wrap failures were experienced (triangles in Figure 1). While this failure mode can occur during drilled testing, it appears to occur more frequently in the eroded system. From this observation, we recommend that repairs performed on eroded or diffuse damage be evaluated for the potential for through-wrap failure and the repair thickness be increased to prevent this failure mode. We are exploring the stress and strain behavior of the composite using FEA to help provide more concrete guidance.

Elbow Testing and Flaw Characterization

In the last year we have been working to complete testing of elbows with drilled and eroded flaws. Based on our current results, eroded flaws do appear to have lower failure pressures when compared to drilled flaws. The current results of our pressure testing are shown in Table 2. We are working with FEA and additional testing to understand the causes of this performance difference. Our initial hypothesis is that the elliptical nature of the elbow flaws is causing the thinned region to buckle during pressure loading. This buckling dramatically increases stress and could lead to the observed reduction in failure pressure.

Table 2: Hydrostatic burst test results for four layer repairs on a repaired elbow with drilled and eroded flaws.

	1	2	3	4	Average	STD
Drilled	2299	3405	4000	4000	3426	694
Eroded	1245	1157	1464	2140	1501	385

Based on the elbow testing results shown in the Table 2, we have been focusing on our FEA models to help us understand the drivers for the lower failure pressures in elbows. Specifically, we are working on ensuring our FEA models are appropriately validated with DIC experimental data. Details of this validation, which was performed in the last quarter, will be discussed below.

Elbow Flaw Characterization

One potential area of concern is the exact size of the produced flaw in the elbow specimens. The approach of creating an epoxy mold has worked well with the straight flaws, but this approach has not been successful with the elbows due to the large size. We are experimenting with creating clay molds of the inside surface of the pipe. We then analyze these molds using DIC. Some initial results are shown in Figures 1 and 2 below. These initial experiments are very promising and we are working with this technique to improve our shape resolution.

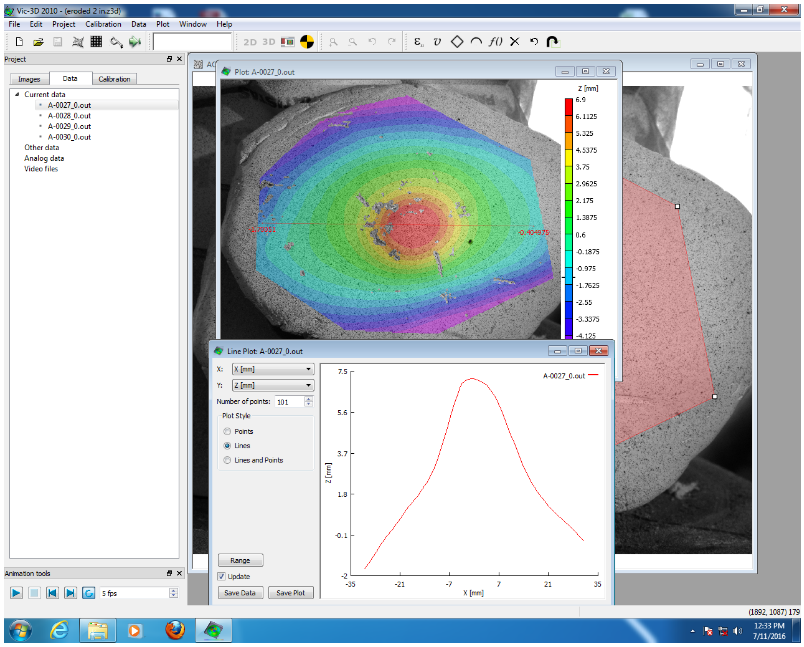

Figure 2: DIC result for the shape measurement of the clay mold for an eroded elbow. Inset line graph is the shape along an axial centerline.

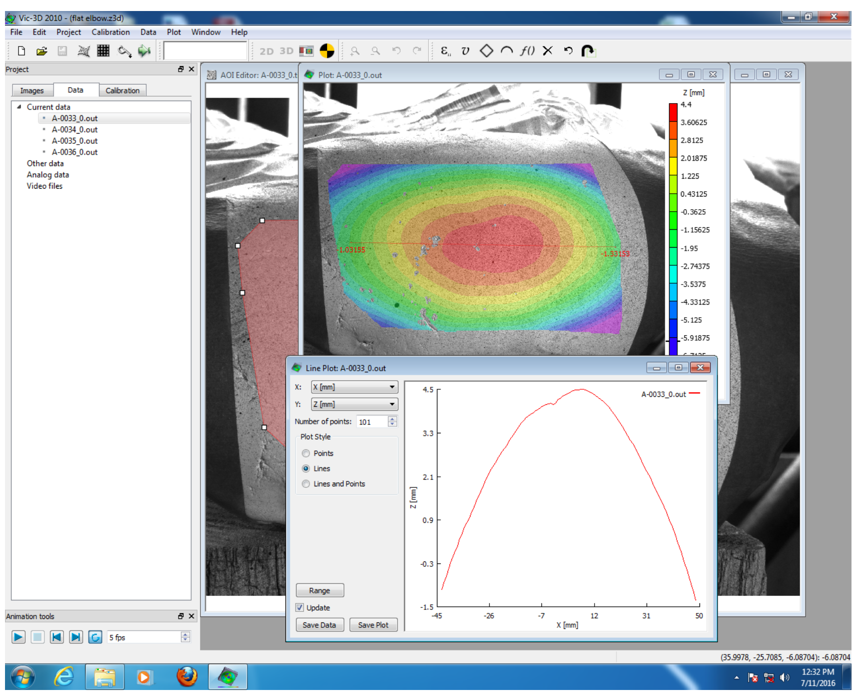

Figure 3: DIC shape measurement for a clay mold of an un-eroded elbow. Inset line graph is the shape along an axial centerline.

DIC and FEA Studies

As we begin to complete the experimental phase of this project, we have moved to validating our finite element modeling. This is a critical step as the most significant difference in the eroded and drilled behavior was found in the elbow specimens. To validate these computational models, we have used digital image correlation to extract full-field strain data from over the flaw region. Figure 4 shows an example DIC analysis with an extraction line running over the center of the flaw.

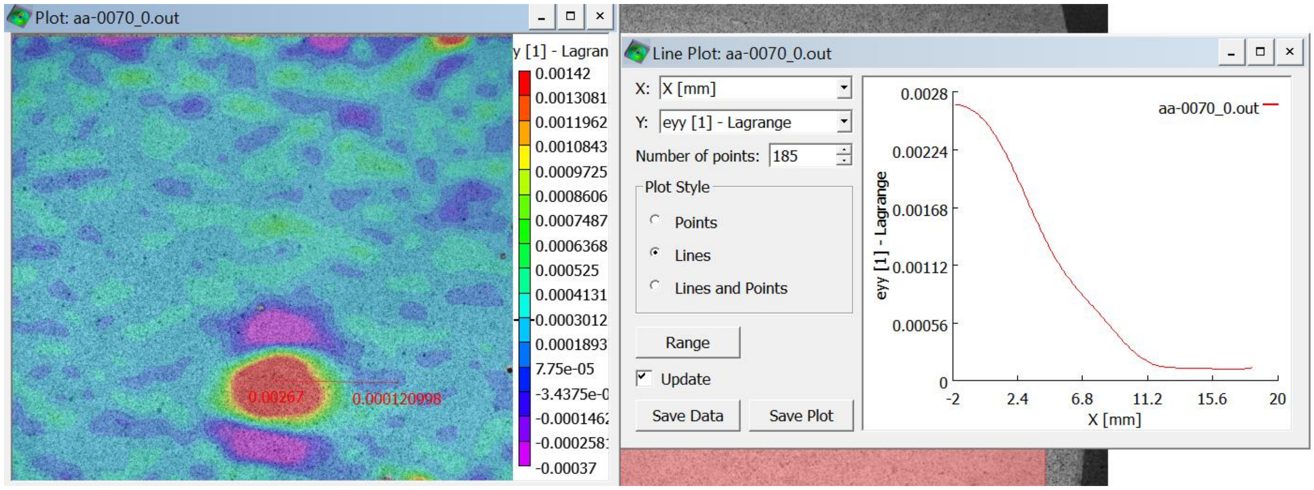

Figure 4: DIC strain field measured result for an experimental run showing extraction line.

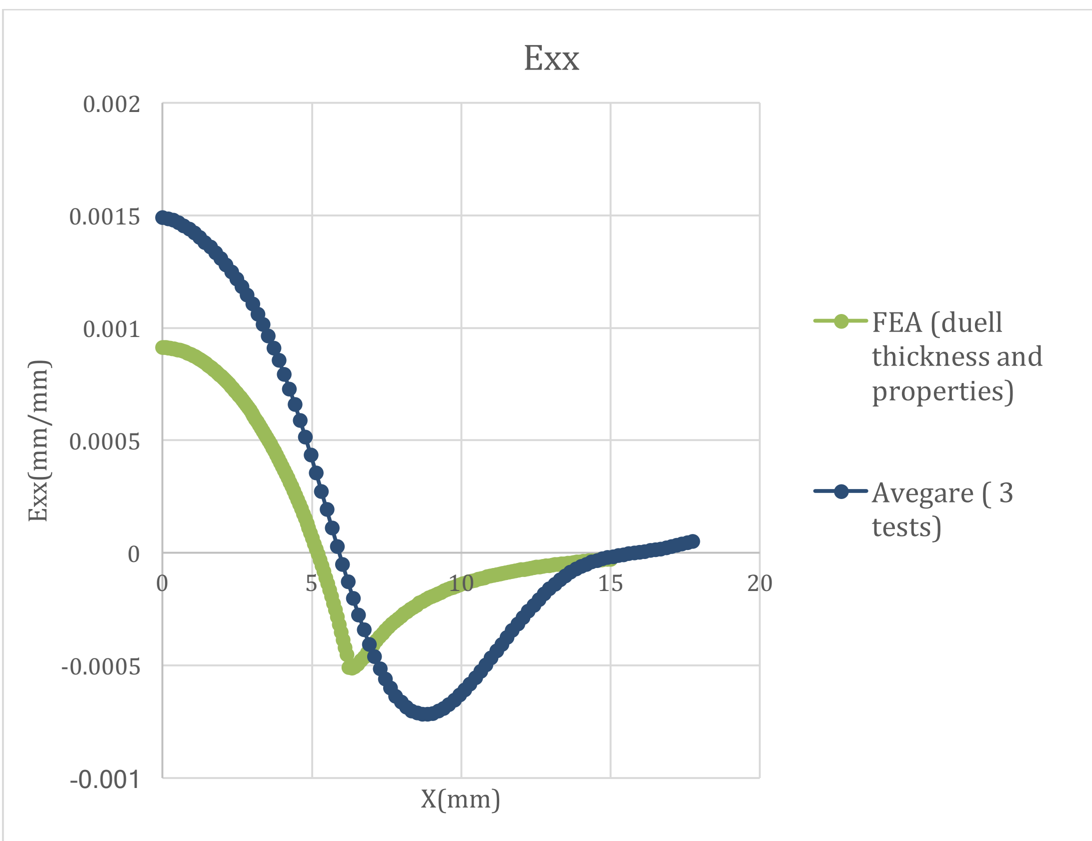

Figure 5: Axial strain measured at flaw midline compared to FEA predictions.

We are interested in three main quantities. Validating the strain values from the FEA to that of the DIC and measuring and comparing the out-of-plane displacement of the composite over the flaw with that of the FEA and the analytical model. Figure 5 shows the measured axial strain averaged from three experimental runs compared to FEA predictions. For this plot and all of the plots below zero on the x-axis represents the center of the flaw and so only one half of the curve is shown in all figures. FEA shows some agreement with the DIC measured values, but we are experiencing a discrepancy in this strain measurement. The FEA is currently under predicting strains. Investigating the hoop strains, shown in Figure 6, we see that the strains are also being under predicted, though by less than in the axial strains.

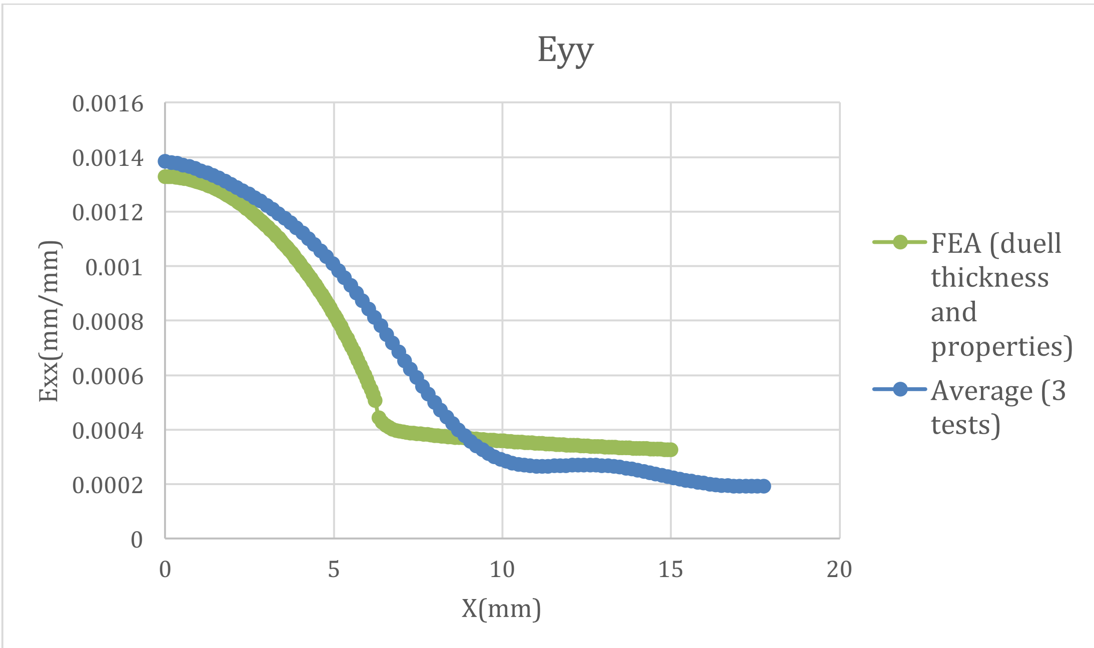

Figure 6: Hoop strain measured at flaw midline compared to FEA predictions.

Based on previous experience with FEA modeling of composite repairs, the discrepancy between the measured strains and the predicted strains are likely due to our uncertainty in the exact thickness and material properties of the applied repair. These repairs are installed such that the processing conditions are not perfectly controlled and there can be significant variation in final repair thickness from install to install. We are working on making some post-install measurements of repair thickness to help quantify the variation from our expected final repair thickness.

Finally, we have spent s significant amount of time trying to understand the relationship between the measured displacement and the predicted displacement. This relationship is critical as the PCC-2 design equations depend on the accuracy of the predicted out-of-plane displacement to predict repair failure pressures.

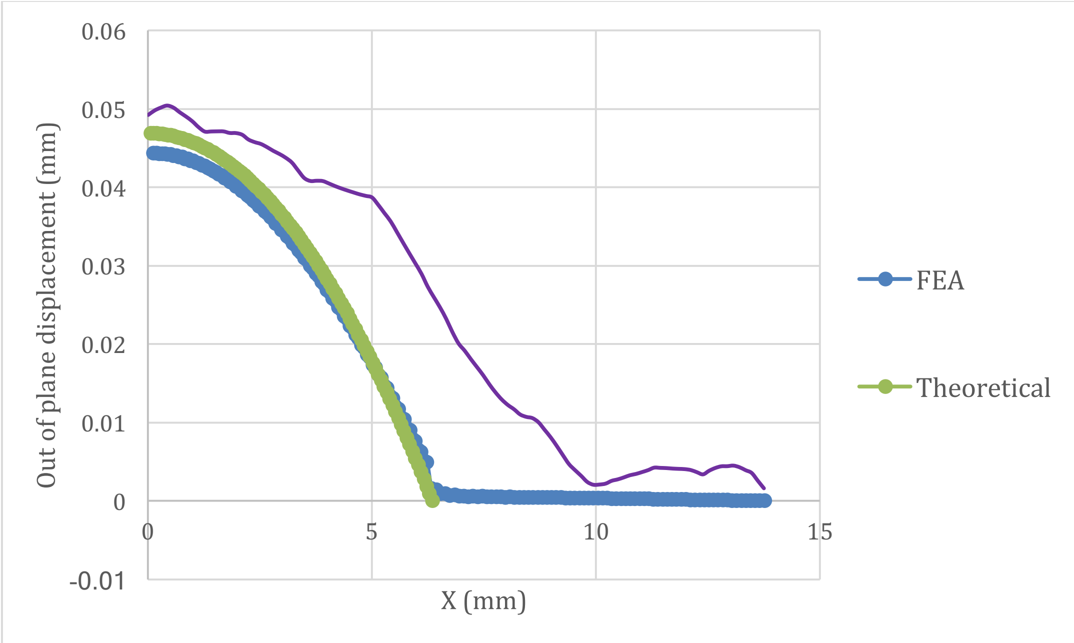

Figure 7: Out-of-plane displacement measured by DIC compared to analytical and FEA predictions.

As can be seen in Figure 7, the maximum of out of plane displacement matches quite well with both the FEA and the DIC. However, the volume of the measured displacement in DIC is larger, which would tend to increase the crack driving force. This implies that the design equations should be conservative. At the moment, we are observing that the eroded elbows fail at lower pressures than the drilled elbows when compared to the straight pipes. We believe that the underlying shape of the eroded region is playing a role in this behavior. We are planning on running some additional experiments where we introduce elongated damage in straight pipes that will approximate the geometry of the damage in the elbows. This should help untangle the impact of damage geometry and allow a cleaner comparison of interfacial fracture behavior. All of our tests on elongated damage have been performed in the context of an elbow geometry. Elbow testing adds an additional complication when attempting to understand the interplay of substrate geometry and damage on failure pressure since the curved geometry alters the expected composite deformation.

(c) Description of any Problems/Challenges

There were some minor testing delays as we shuffled pressure test equipment for the two related tests that are ongoing. This delay will not impact our current testing schedule.

***(d)* Planned Activities for the Next Quarter –**

Planned activities for the next quarter include the following

1. Continue testing and strain analysis using eroded specimens and digital image correlation.
2. Continue FEA modeling of the repair.
3. Develop understanding of the performance of elliptical flaw damage in elbows and straight specimens.