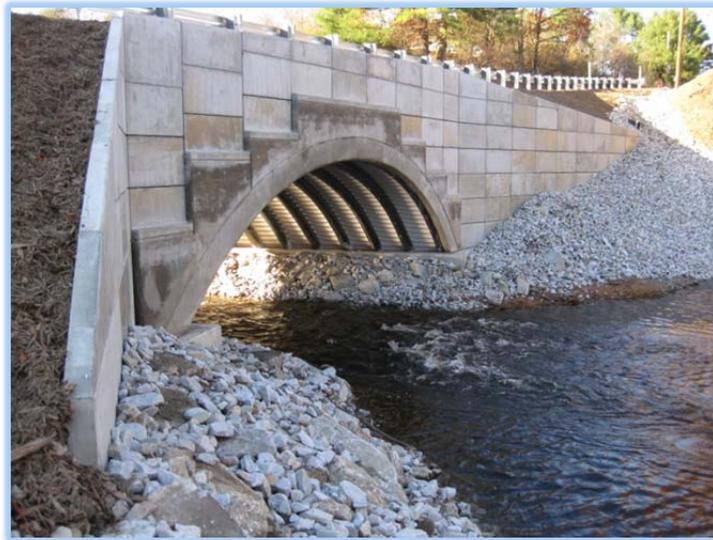




Transportation Research Division



Technical Report 15-05

Bridge-in-a-Backpack™

*Task 7: Investigation of Damage and Repairs for
Concrete Filled FRP Tubular Arches*

Final Report – April 2015

Technical Report Documentation Page

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<p>This report includes fulfillment of Task 7 of a multi-task contract to further enhance concrete filled FRP tubes, or the Bridge in a Backpack.</p> <p>Damage due to impact of the FRP shell of the concrete filled FRP tubular arch bridges has been and still is a concern for many engineers and administrators. This technology uses the exterior FRP shell for confinement, protection and longitudinal reinforcement of the reinforced concrete arch member. This report was commissioned to look at types of potential damage to these members, effects of varying levels of damage on flexural capacity and methods of repair to damaged sections.</p> <p>The 3-point bending strength of reinforced hybrid concrete beams was reduced by 36-47% by the presence of notches with widths between 0.5 and 2.8 inches. Measured percent reduction in bending capacity did not correlate well with measured notch size or predicted values using traditional methods of section loss. Reinforced hybrid concrete beams, broken and repaired by one particular method with triaxial broadgood, exhibited only 17-18% of their original strength. A hybrid concrete arch, tested to failure in 2009 at about 62,300 lb, was repaired by Kenway Corporation in March 2014 by generally following the guidance of Duong and Wang (2007). The resulting repair patch failed after 1.5 inches displacement at 43,041 lb (69%), after which the arch sustained an additional 6.0 inches of displacement until its shoulder ruptured at 60,321 lb.</p>			
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Bridge-in-a-Backpack™

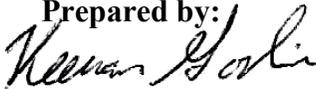
Task 7: Investigation of Damage and Repairs for Concrete Filled FRP Tubular Arches

Prepared for:

**Dale Peabody P.E.
Director Transportation Research
Maine Dept. of Transportation
16 State House Station
Augusta, ME 04333-0016**

**University of Maine's Advanced Structures and Composites Center
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April 1, 2015

Prepared by:

Keenan Goslin, P.E.
Structural Engineer

Reviewed by:

John Arimond, MSME
Business Development Manager

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BACKGROUND

Damage due to impact of the FRP shell of the concrete filled FRP tubular arch bridges has been and still is a concern for many engineers and administrators. This technology uses the exterior FRP shell for confinement, protection and longitudinal reinforcement of the reinforced concrete arch member. This report was commissioned to look at types of potential damage to these members, effects of varying levels of damage on flexural capacity and methods of repair to damaged sections.

BRIDGE DAMAGE

Bridge damage can be caused in many ways such as vehicle or equipment impact where traffic flows under the arch bridge, debris or ice impact for stream or river crossings, or vandalism. An example of collision damage is shown in Figure 1.



Figure 1. Example of collision damage to a reinforced concrete bridge

This project will focus on minor damage where the arch member's global geometry doesn't change and length of the shell's damage is limited to approximately the diameter of the tube.

COMPOSITES DAMAGE

Composite damage could include chips, cuts and cracks, delaminations, fractures, scratches and penetrations. These types of damage and imperfections are defined in ASTM D 2563. Another example of damage is shown in Figure 2 where a penetration is shown through the FRP shell.

Damage to the shell fibers versus the matrix or resin is more important for this technology for the short term strength of this technology due to the wrapping of the fibers around the tube in the braided fabric. Refer to NCHRP Report 564 and FHWA's Bridge Inspector's Manual (2012) for good background on composite materials, their manufacturing processes and components.



Figure 2. Penetration into tube

COMPOSITES REPAIR

There are several methods of composites repair available. This report will focus on single sided bonded repairs where a patch material is bonded to the structure to repair a hole, crack or other type of damage.

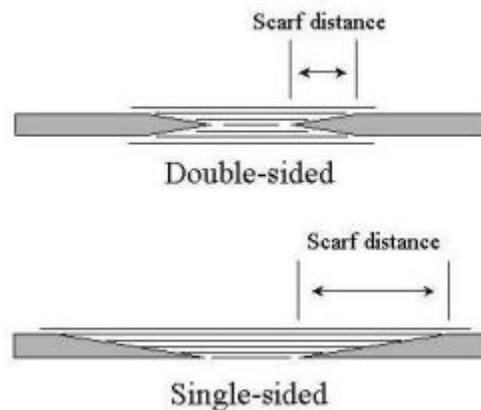


Figure 3. Schematic of single-sided repair (netcomposites.com)

The repair design process includes the design of the laminate for the repair including the critical design of the bond joint. This must include the analysis for peeling stresses, stresses due to moment due to eccentric loading of the single sided repair as well as shear stresses on the lap joint. The actual repair process includes the removal of damaged material, repair of the substrate, tapering of the substrate or scarf and priming of the surface prior to using one of several methods to bond the additional layers of material to the repair (Duong & Wang 2007).

DAMAGED BEAM TESTING

The impact of damage to the shell of the exterior reinforced hybrid concrete section is important to determine the need for repairs. Analytical solutions for reductions in loss of capacity using transformed sections have been completed for various losses of exterior cross section. These solutions in Table 1 served as the basis for the design of damaged beam test specimens.

Table 1. Predicted Beam Capacities (Bannon 2012)

Percent Reduction	Target Capacity (in*kip)	Actual Capacity (in*kip)	Notch Width (in)	Predicted Test (kip-in)
0%	487	487	0	884.91
5%	462	466	1.36	846.91
10%	438	436	1.92	793.09
15%	414	416	2.35	756.91
20%	389	389	3.05	706.36

12inch diameter beams were manufactured similar to Dagher et al (2012). Three point bending was used with a span of ten feet. Digital image correlation, load and deflection of the load head were recorded. Digital image correlation using ARAMIS was used to collect strain data near the artificial damaged section and away from it on the tension face of the beam. A large mirror was used to protect the cameras and get an upward view of the beam's tension face as seen in Figure 4.

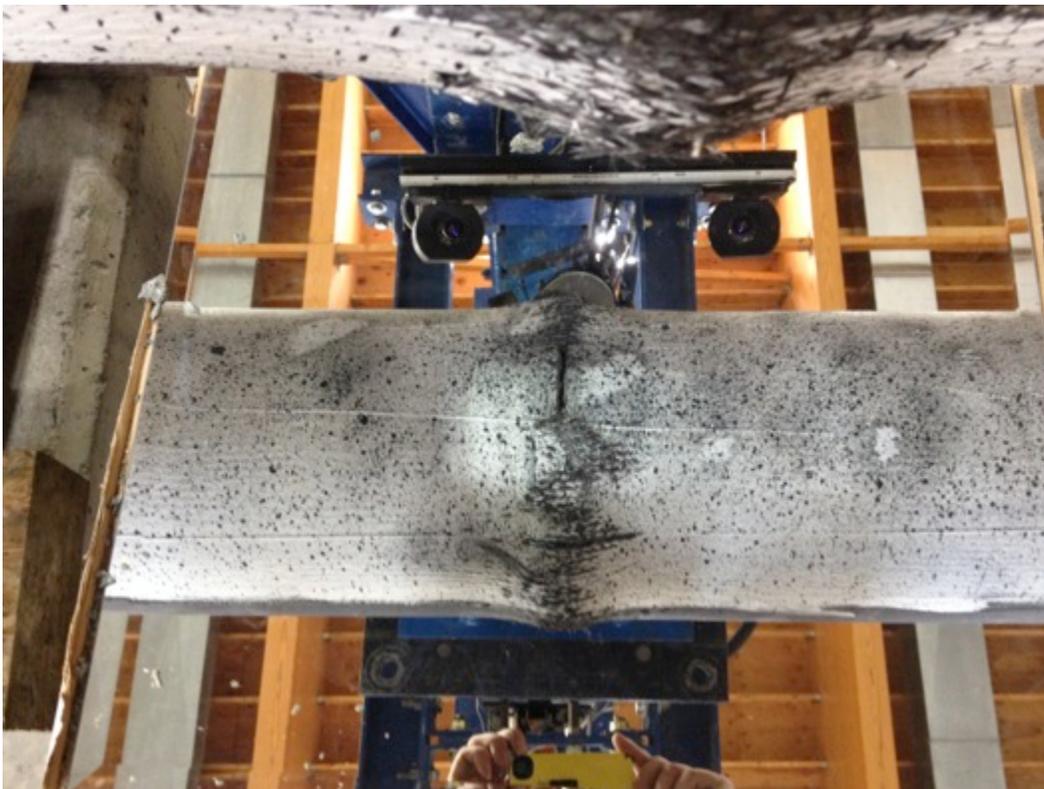


Figure 4. DIC cameras using mirror to collect image

RESULTS

All beams failed with rupture of the FRP in tension initiating at the precut section as seen in Figure 4.

Table 2. Summary of Damaged Beam Tests

Tubes	Outer (in)	Middle (in)	Inner (in)	Load (kips)	Span (inches)	Shear (kips)	Moment (kip-in)	Percent Reduction
A	1.773	0.972	0.582	38.44	120	19.22	1153	38.10%
B	1.511	1.009	0.53	39.7	120	19.85	1191	36.07%
C	NA	NA	NA	62.1	120	31.05	1863	0.00%
D	1.339	1.003	0.54	35.0	120	17.5	1050	43.64%
E	2.036	1.592	0.527	32.8	120	16.4	984	47.18%
F	2.087	1.124	0.526	37.4	120	18.7	1122	39.77%
G	2.12	1.07	0.54	32.8	120	16.4	984	47.18%
H	2.79	2.72	2.64	32.7	120	16.35	981	47.34%
I	Unk	Unk	Unk	57.9	120	28.95	1737	6.8%

Strain values from DIC were collected at each beam near and away from the precut section.

A typical plot of strain versus load can be seen in Figure 5 where strains near the cut are higher than away from the cut.

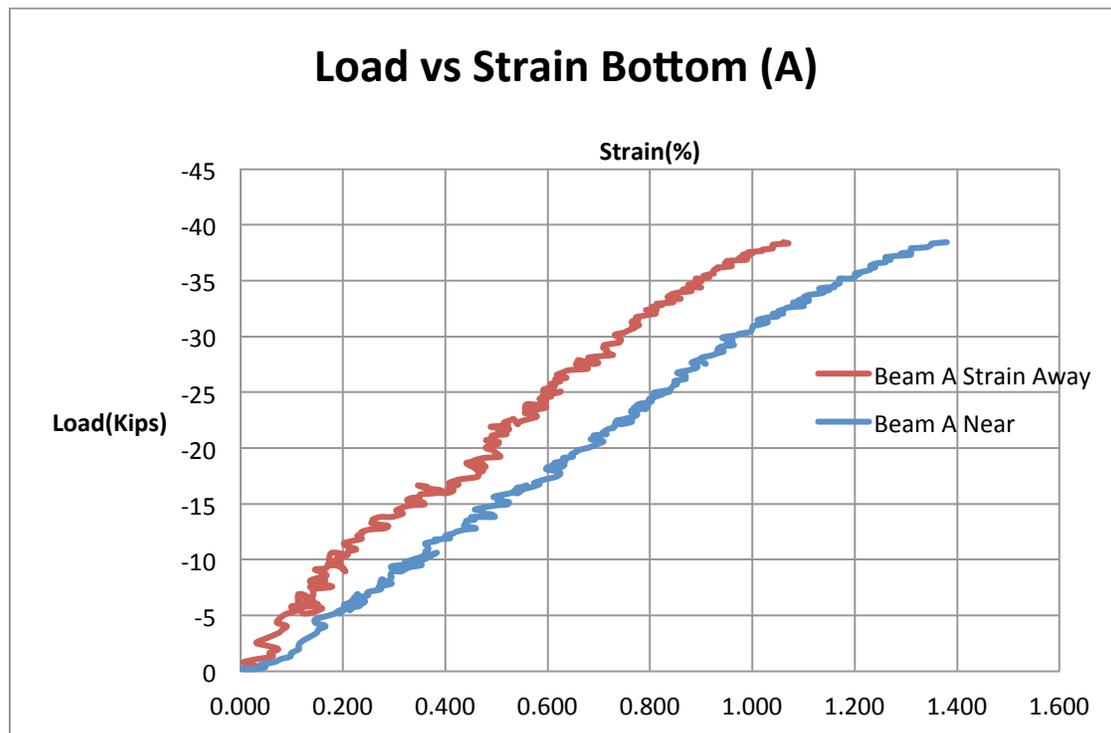


Figure 5. Strain in Beam A from DIC

DISCUSSION

Test values for control beams were higher than those predicted. Percent reductions are based on control values from beam C. In all cases, the percent reduction was greater than that predicted for the closest size notch size from Table 1. Percent reduction in bending capacity did not correlate well with notch size.

REPAIRED BEAM TESTING

REPAIRED SPECIMEN & SETUP DESCRIPTION

Two damaged beams (Beams H & I) from the first part of the project were repaired at the Advanced Structures and Composites Center using the method and materials in Appendix A. Three layers of triaxial broadgood with the same fiber architecture of the tube laminate were used to repair the ruptured laminate. Four point bending was used for these tests with the location of the supports and loading seen in Figure 6 and Figure 7. Three strain gages were used to investigate strain distribution from patch to main beam member during the testing. The beams were loaded from a 110 kip actuator moving at 0.75 inches per minute.

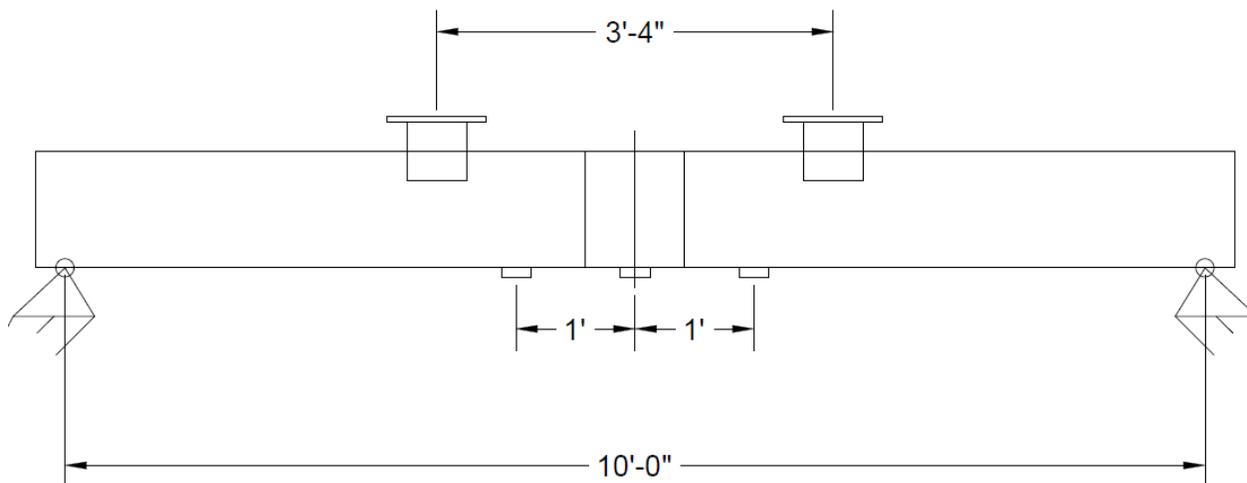


Figure 6. Damaged and Repaired beam test layout



Figure 7. Repaired beam test setup

RESULTS

Both beams failed at lower loads than they did in the damaged beam study (17.05 kip and 16.18 kip respectively for beam H & I). A failed beam can be seen in Figure 8 where the patch appeared to fail in or near the bondline. A summary of the resulting loading is given in Table 3.

Table 3. Summary of Repaired Beam Static Testing

Tubes	Load (kips)	Span (inches)	Shear (kips)	Moment (kip-in)	Percent of Control
H	17.05	120	0	341.0	18.3%
I	16.18	120	0	323.3	17.4%

Plots of load versus midspan deflection can be seen for both beams in Figure 9. It appears the string pots got hung up or bottomed out and did not move toward the end of the testing as shown by the vertical line for beam I. Capacities when comparing moments during the test were even lower than comparing the test loads.



Figure 8. Failed beam

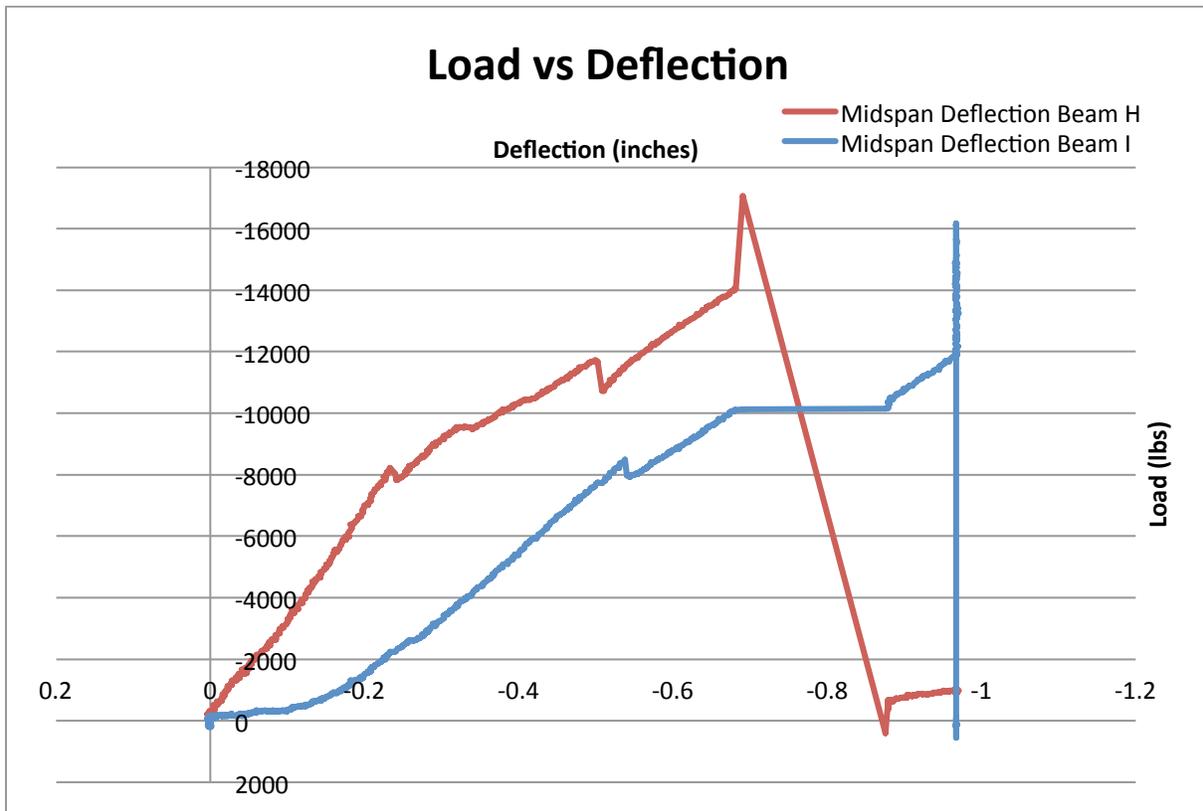


Figure 9. Load vs Deflection plot of repaired beams

DISCUSSION & RECOMMENDATIONS

Upon closer look, the patch fabric for both repaired beams appears to have been bonded with its strongest axis parallel rather than perpendicular to the beam crack, as was intended (Appendix A, step 19). More detailed analysis of the bondline and corrected fiber direction should be included if it's possible to repeat these tests. The process of substrate preparation and secondary bonding is a good example but unfortunately a successful repair was not shown in this test.

REPAIRED ARCH TESTING

SPECIMEN DESCRIPTION & TEST SETUP

Kenway Corporation was hired to repair an arch tested during the development of the hybrid composite arch bridge system. A composite arch tested to failure by Bannon in 2009 has been stored at the Composites Center awaiting repair and testing. This was the specimen designated Fatigue 2 in Dagher et al (2012). This arch has been stored inside and outside since its fabrication and testing in 2008. Kenway engineers designed the patch according to examples from Duong and Wang (2007) and came to the Center in March 2014 to repair the arch. A summary of the process and materials used to make the repair are given here.

SURFACE PREPARATION

The procedure for repairing the previously failed CFRP arch was begun by cutting away ruptured fibers from the damaged area. The fibers were cut back until only undamaged fibers still adhered to the concrete remained (Figure 10). The exposed area was then cut and shaped to remove any sharp corners, to minimize stress concentrations in the remaining material. The edges of the carbon material were then ground down to a taper of approximately 10:1 (e.g. 1 in. for a 0.1 in layer of carbon). An area 3 in. beyond the repair area was sanded down to remove resin and expose fiber, creating a good bonding surface and establishing the desired profile. The repair area was then thoroughly vacuumed then wiped down with 99.8% isopropyl alcohol wipes.



Figure 10. Damaged arch surface preparation (ruptured carbon FRP removed)

Any cracks, voids, or sharp transitions were filled with KCR structural putty. Once the putty had cured, the area was given a final sanding. The repair area was primed with a light coat of M1002 toughened epoxy resin and allowed to cure until tack free. The area was then wetted with a heavy coat of resin and the first of the 7 layers of the carbon fiber patch were placed. Any entrapped air pockets were pressed out by hand. The 6 subsequent layers were then placed in a similar manner. The patch was allowed to cure at room temperature for 15 hours (Figure 11). Then, the patch was heated to 140°F and held for 8 hours.



Figure 11. Repaired arch patch

INSTRUMENTATION

9 strain gages were applied to the arch: 4 on the carbon patch, 3 circumferentially around the arch 1' -7" from the centerline just off the patch, and 3 circumferentially around the arch at 5' 6" from the centerline. Their locations can be seen in Figure 12.

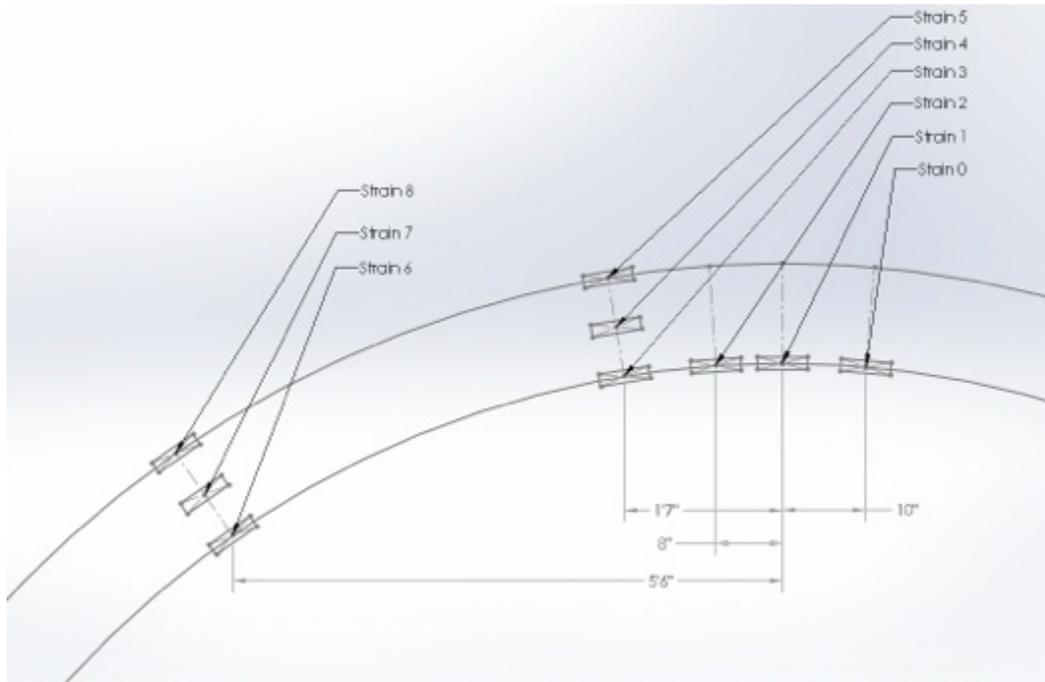


Figure 12. Strain gage locations on repaired arch

String Potentiometers

7 string pots were placed at key points along the arch. One was placed at each of the footings to measure the angular displacement of the footings, one was placed at mid-span to measure vertical displacement, and two were placed in a triangular arrangement at both quarter-span points to measure vertical and horizontal displacement. These two string pots were screwed to a piece of 2x4 a fixed distance apart. This was then mounted on a steel stanchion. An adhesive tab was placed on the side of the arch. The string pots were then tied to the tab using fishing line. The distances for both the north and south quarter-span string pot arrangements were recorded as in Figure 133.

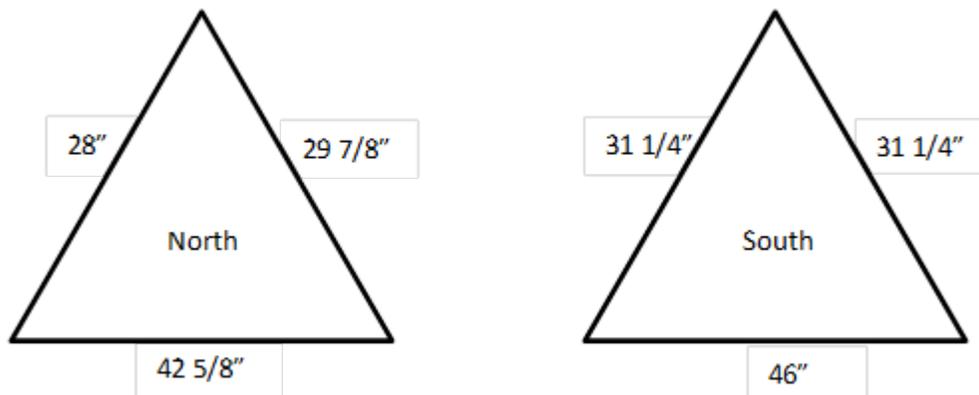


Figure 13. String pot initial lengths

The tip of each triangle corresponds to the tabs on the arch. The vertical and horizontal displacements will be calculated using the law of cosines:

$$a^2 = b^2 + c^2 - 2bc \cos \alpha$$

Rearranged to:

$$\cos \alpha = \frac{b^2 + c^2 - a^2}{2bc}$$

The horizontal displacement will be calculated using:

$$x = b \cos \alpha$$

And vertical displacement:

$$y = b\sqrt{1 - \cos^2 \alpha}$$

The angular displacement of the footings was calculated by measuring the distance from the pivot point of the tilt tables to the footing string pots, taking the displacement data from said string pots, and taking the arc tangent of the ratio of these measurements:

$$\theta = \tan^{-1}\left(\frac{\text{string pot readings}}{\text{distance from footings}}\right)$$

RESULTS

The arch test reached a peak load of 43,041 pounds prior to the repair failure. An ultimate load of 60,321 lbs was seen when the arch shoulder ruptured. The repair failed in the bondline of the patch as seen in Figure 14. Load versus deflection at the crown of the arch can be seen in Figure 155.



Figure 14. Bondline failure of repaired arch

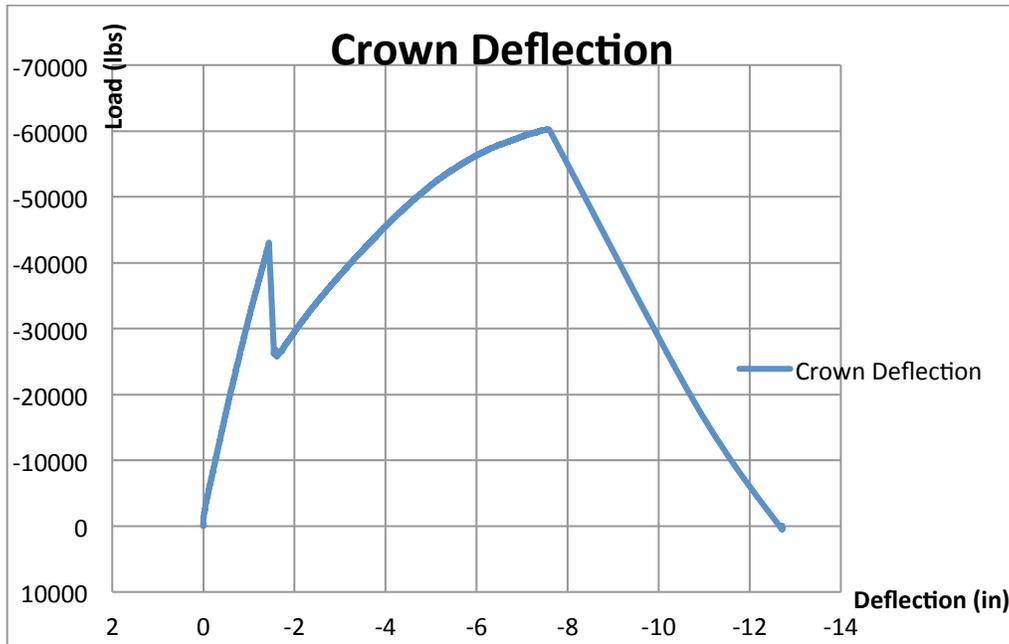


Figure 15. Plot of cross head load versus vertical deflection

Deflection of the shoulders in the vertical and horizontal directions is shown up until repair failure in Figure 166. As seen there, the vertical deflections on the shoulder on each side of the arch match up well but there appears to be some side sway as indicated by the difference in the X-direction deflections.

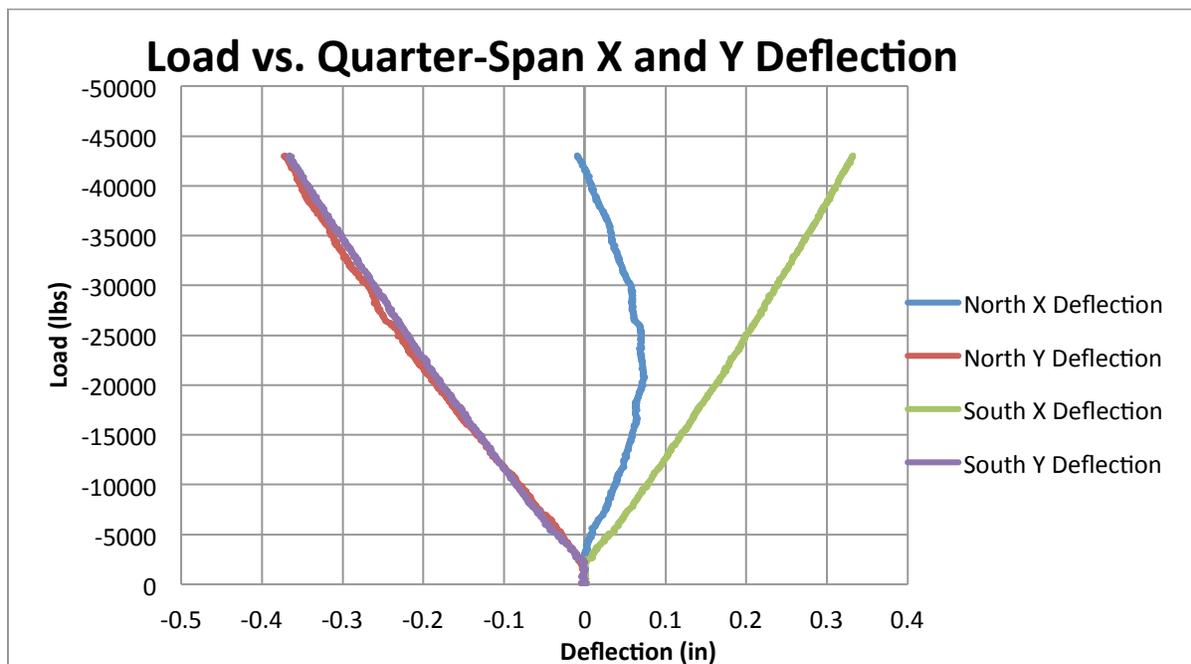


Figure 16. Plot of vertical and horizontal deflections at shoulders

Strain is shown in Figure 17. Peak strains are shown with the gages under the load head at midspan (Strain 1) as expected where peak moments exist. Strain 0 and 2 are close as they should be in symmetric locations about midspan. Cross-sectional curvatures can be found using strains at the shoulder cross section and upper cross section by plotting each strain triplet (6,7,8 & 3,4,5) for each load value.

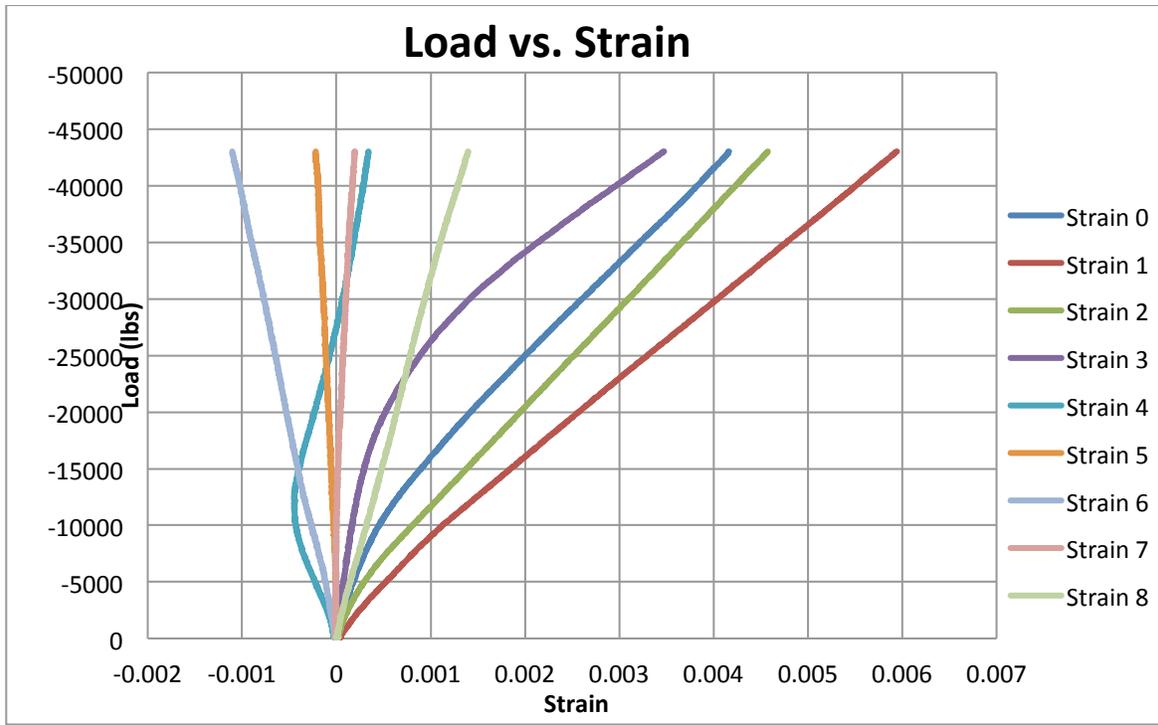


Figure 17. Plot of strain measurements from arch test

DISCUSSION

The arch failed at a load lower than the original capacity of the member which was 62.3 kips (Nagy et al 2009). Additional bondline width or strength could be designed in future applications however it is expected that the moment gradients seen in this test with the single point load at the crown contributed to unrealistic peeling stresses for in-service bridges. Repair methods and professionals are available should there be a need for these services.

DISCUSSION OF REPAIR GUIDELINES

Among the several available methods of repair, single sided, bonded repairs with scarf joints may be the most aesthetically pleasing. Design methods such as that in Duong and Wang provide reasonable solutions for repairs for many situations, but with limited results for the test specimens here. As the particular repair method used on beams H and I has not been shown to be effective, other potential repair methods for reinforced hybrid concrete beams should be developed and tested. These need to emphasize the bondline design and potentially use additional factors of safety where peeling stresses due to the geometry may be greater than predicted with the linear cross section design. Surface preparation and curing are also very important to the quality of the repair and should be considered and discussed when repairs are needed.

CONCLUSIONS AND RECOMMENDATIONS

The 3-point bending strength of reinforced hybrid concrete beams was reduced by 36-47% by the presence of notches with widths between 0.5 and 2.8 inches. Measured percent reduction in bending capacity did not correlate well with measured notch size or predicted values using traditional methods of section loss.

Reinforced hybrid concrete beams, broken and repaired by one particular method with triaxial broadgood, exhibited only 17-18% of their original strength.

A hybrid concrete arch, tested to failure in 2009 at about 62,300 lb, was repaired by Kenway Corporation in March 2014 by generally following the guidance of Duong and Wang (2007). The resulting repair patch failed after 1.5 inches displacement at 43,041 lb (69%), after which the arch sustained an additional 6.0 inches of displacement until its shoulder ruptured at 60,321 lb.

RECOMMENDATIONS

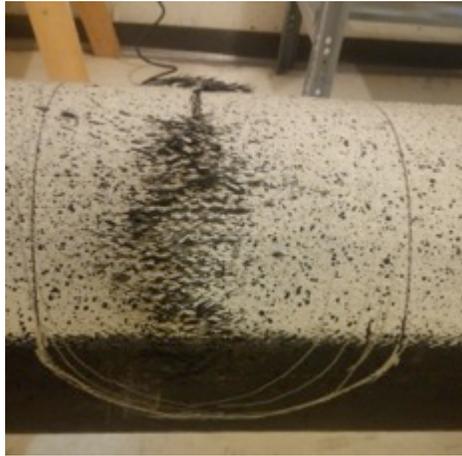
Assessment of section capacities with damage should be continued based on the non-linear results with more sophisticated analyses. Continued work should include an investigation into fracture mechanics as well as more structural testing.

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APPENDIX A - FRP CONCRETE FILLED BEAM REPAIR PROCEDURE USED FOR TESTED BEAMS H AND I

1. Locate damaged fiber and mark out around the damaged area 3” away from visible damage. An oval or circular shape is preferable. It makes it easier to cut out fabric for the repair



2. Cut the marked out straight line with skill saw using Remigrit blade adjusted to the depth of the carbon fiber only and cut the curved line with angle grinder with metal cut off disc assuring to cut only the carbon fiber and not the concrete. Removed the damaged carbon fiber.



3. Remove any bag, flow media, feed line, and remove any debris from the crack using air nozzle and shop vacuum.



4. Use Emecole 302 to attach the Emecole 101 feed ports over the crack 4” to 5” apart from each other.



- a. Let epoxy hardened for 4 minutes.
- b. Use the Emecole 302 application gun to run ¼” bead over crack and around the ports.



- c. Use spreader over Emecole 302 bead to completely seal the crack and completely cover the port bases. The Emecole 302 **(It is important that it is sealed well so that Emecole 101 will not leak out after it is introduced through the ports.)**

5. Use Emecole 101 in Jake gun with static mixer to fill bottom port until epoxy is visible in the next port.



6. Remove static mixer and quickly cap the port. Repeat step 6 and 7 on opposite bottom port.



7. Place static mixer in port above capped port and fill until epoxy is visible in next port, cap, and repeat on opposite side.

8. Wait for air to escape through top port, and then fill top port.
9. Let Cure overnight.
10. Remove the ports and use Paint Buster disc on angle grinder to sand the Emecole 302 sealer flush to concrete.



11. Mark 2" back around the cut away area using a scribe/compass.



12. Use random orbital sander with 120 grit sandpaper to fair back the fiber from the concrete to the 2” line.
13. Prepare the indent due to feed line by sanding with 60 grit sandpaper then thoroughly clean with acetone.
14. Fill the indent with fiberglass reinforced bondo. Let cure.



15. Sand bondo flush to surrounding concrete and carbon fiber.



16. Place clear plastic over the cut away area and trace the cut line.



17. Remove plastic and place on flat work surface.

- a. Place another piece of clear plastic over the plastic with tracing on it.
- b. Adjust scribe/compass to 2"
- c. Trace along marked out line on plastic with pointed end and marker along the outside of marked out line.



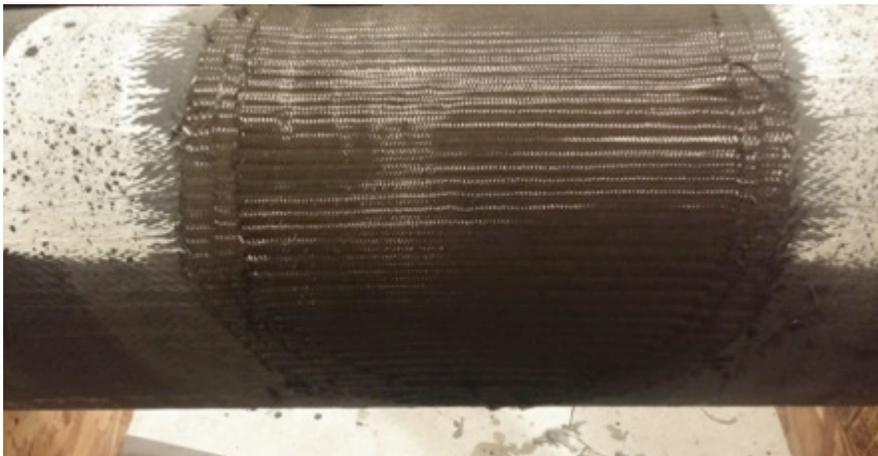
18. Remove plastic and repeat step 18 a.-c. but adjust compass to $1 \frac{5}{8}$ ". Then repeat once more with compass adjusted to $1 \frac{1}{4}$ ".
19. Place individual sheets of plastic(except the initial piece used on beam) on 52" W +/- 60 Carbon Triaxial Broad Good 4.14 FT/LB 8 OZ/SQ YD 271 GSB so the orientation of the fibers match that cut away carbon fiber. Then use lines to cut out the carbon fiber.



20. Thoroughly clean the surface of the beam with acetone.
21. Place larger piece of carbon fiber on area to be repaired and lightly spray tack in place.



22. Then spray tack in next larger piece and then the smaller piece.



23. 6” back from each side of tacked carbon fiber wrap tacky tape around the circumference of the beam.

24. Wrap the entire area inside the tacky tape with peel ply.



25. Wrap 3/8" coil wrap around the beam 2" back from the carbon fiber on both side.
26. Insert 3/8" tee's in center of both coils.
27. Place flow media over 1 coil so the tee protrudes out and cut flow media 1" back from carbon fiber on opposite side.



28. Cover the over coil with peel ply.
29. Bag the part using vacuum bag.
30. Attach feed line to flow media coil and clamp line
31. Attach vacuum line to peel ply coil and attach to vacuum pump.
32. Apply vacuum.
33. Check part for leaks.
34. Infuse using Derakane 610 C vinyl ester resin