ENDURANCE TESTING OF COMPOSITE REINFORCED WELDED ALUMINUM STRUCTURES

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ABSTRACT

Several states utilize welded aluminum structures to support freeway and throughway signage. In some cases the welds at the joints of these structures have either partially or fully cracked. The exact failure mechanism has not been isolated but the need to reinforce them is urgent. Air Logistics Corporation has developed and tested a field applied FRP repair system, which is currently in use to repair the cracked joint welds. Several joints with cracked welds were cut from dismantled sign structures and repaired with the FRP repair system. These samples were tested at the University of Utah in a series of tension tests and proved to be as strong as sound aluminum welds. A second series of endurance tests was also conducted. In this series, two test specimens were set up and subjected to long term cyclical loads. The first included a composite reinforcement over a failed weld. The second specimen was a sound weld with no defects. The final results were compared and it was determined that the composite reinforced welds performed as well as, or better than, a sound weld with no defects under a cyclical load.

KEY WORDS: Composite Materials, FRP, Aluminum Sign Structures

1. INTRODUCTION

Welded aluminum sign support structures are a typical element used on many of the nation's highway systems (Figure 1). The New York State Department of Transportation utilized this design extensively on their Interstate and Intrastate highways in both rural and metropolitan areas. The structures, constructed of 6061-T6 Aluminum, are normally a truss design utilizing chords (major horizontal elements) with aluminum cross members welded to these chords. These triangular truss elements are typically supported at each end with aluminum upright members. The cross members and chords are welded using a fitted butt joint with no hole bored into the chord. Within the past four to five years weld failures have been observed in a number of these structures, in some cases causing a structural failure (Figure 2). There have been several conventional methods, such as a steel cable sling or splice plates, employed to prevent collapse of the damaged structure, but there was no way to restore the original strength of the connection (Figure 3). During the past three years Air Logistics Corporation, in conjunction with the New York State Department of Transportation, Utah Department of Transportation, and the University of Utah, has developed an FRP repair system that can be used to bring the strength of a cracked connection back to its original design values and in some cases exceeding those original values.

Figure 1. Typical Sign Structure

Figure 2. Cracked Weld

Figure 3. Cable Repair

2. REVIEW OF THE PROBLEM

The focus of this paper is the repair of the cracked welds in the aluminum sign structure elements. The cause of these failures is an on-going investigation by The New York State Department of Transportation.

The welded joints crack at the connection between the interior chord and the main longitudinal chord (Figures 4 & 5). Typically, the crack follows the weld and remains completely within the weld pool or, due to poor penetration of the weld into the base metal, propagates along the interface between the weld and the base metal. Poor penetration of the weld into the base metal actually prevented some of the cracks from propagating into the base metal. In some isolated cases the cracks extend into the interior chord and, in extreme cases, can also extend into the main chord itself.

Figure 4. Typical Weld Failure

Figure 5. Severe Weld Separation

During the original construction of the sign structures the welded elements were not stress relieved. Also, the elements were not stress relieved during installation. Thus, they could have warped and caused a misalignment with the horizontal supports. This condition may have required the installation crew to pull, push, or torque the truss element into position, causing additional stress to be introduced into the system. These additional unforeseen stresses eventually lead to the crack development. In addition to this theory, it has been noted that fatigue design was not required in the NYSDOT Design Manual for Aluminum Overhead Sign Structures, 1968. Also, there was no shop inspection being conducted prior to 1999. However, all new designs, both span and cantilever type structures, account for fatigue. So, although construction problems may have had existed, there were also obvious quality control issues, as evidenced in the sloppy welds, as well as unanticipated fatigue considerations (Figure 6).

Figure 6. Poorly Welded Joint

3. MATERIALS

The system consists of a two-part polyurethane urethane adhesive, the polyurethane resin used in the prepreg, the fabric used in the prepreg, patching material, and various accessory items. The polyurethane adhesive is used for the primary bonding agent between the aluminum and the prepreg material.

The resin used in the prepreg is a specially formulated polyurethane system especially designed for this use. The fabrics are impregnated at the factory in a dry environment, cut to size, packaged in sealed pouches to protect it from atmospheric moisture, then packaged in a kit designed to repair one joint (Figures 7 & 8). The material packaging is designed in this manner to facilitate installation by Transportation Department Maintenance personnel as well as contractors.

Figure 7. Surface Preparation Kit

Figure 8. Structural Material Repair Kit

When the user is ready to install the material the pouch is opened and the material applied. Water is applied between each layer to activate and cure the resin. The system is ANSI/NSF Standard 61 approved and has no VOC's, making it environmentally friendly. UV inhibitors can be added to the resin used in the final consolidating veil wrap. This eliminates the need to paint, and subsequently to maintain the paint in the future. The resin can also be colored gray to match the appearance of the weathered aluminum.

The glass fiber reinforced polymer (GFRP) material properties used for the repair and testing are presented in Table 1.

Table 1 - GFRP Composite Properties

Material (1)	Tensile Strength MPa (ksi) (2)	Modulus of Elasticity GPa (ksi) (3)
Fine Weave Tape (Veil)	414 (60)	26 (3800)
Woven Roving	310 (45)	19 (2800)
Tubular Weave Braid	207 (30)	21 (3100)
UD Tendons	517 (75)	31 (4500)

4. TEST ELEMENTS

The aluminum test elements for this study were field samples supplied by The New York State Department of Transportation. These elements were taken from sign structures that were taken down and replaced with new structures.

5. INSTALLATION PROCESS

5.1 Aluminum Preparation

Many of the structures that have developed cracks were installed as early as the 1960's. The structures have been exposed to freeze/thaw cycling, rain, wind, and long-term oxidation.

Prior to any preparation or application of the FRP material, the structures were inspected and the end points of the crack determined. Small holes were drilled at the crack end points to reduce the potential of further crack propagation.

Since the bond between the FRP repair and the aluminum base material is critical to the success of the repair, surface preparation of the aluminum is one of the most important details. Aerospace techniques were employed in this program to assure the aluminum was prepared properly. The first step in the process involves a caustic wash of the area to receive the composite material. Once the caustic process is completed the section is washed with water. This process is necessary to remove all oxidation.

Upon completion of the caustic washing process the section is dried and an acid etching solution is applied. This is left in place for a specified time, rinsed with water, and then dried. The acid etching process prepares the aluminum to accept a primer.

The primer used is Alodine. Alodine conditions the surface of the aluminum and provides a properly prepared area for the adhesive and the first layer of composite material. The Alodine is allowed to dry prior to the application of the adhesive. Since the failure mode is usually a tension failure, the bond area and bond strength per square inch are a major part of assuring a successful installation.

5.2 Composite Application

Once the surface has been prepared and the adhesive has been applied and allowed to become tacky, the polyurethane prepreg materials are applied in a systematic manner with alternating circumferential and longitudinal layers. The placement of the various types of weaves is also laid up according to a design. The design of the lay-up has been tested extensively in tension testing. Water is sprayed between the layers and then again to saturate the final repair. The entire wrapped area and approximately two inches beyond the end of the FRP is then wrapped with a proprietary, high-tensile strength stretch film and allowed to cure. The cure time for this system is usually one hour. Temperature has some effect on the cure rate of the system and it can be as long as one and one half hours. Once the material is cured the stretch film is removed and the surface is finished. If the installer has used a pigmented, UV resistant polyurethane resin system, this finishes the repair. If not, the material must be painted to protect it from UV degradation. The chosen color should match the structure for aesthetic purposes.

6. CYCLIC LOAD TESTING

All testing for this program was conducted to comply with AASHTO Standard Specification for Highway Luminaries and Traffic Signage, 1975 & 2001. All testing was conducted at the University of Utah utilizing their multi-axis load frames with MTS controlled hydraulic actuators. All data was recorded from strain gauges placed at various parts of the test element and also at various depths, including direct bonded strain gauges against the aluminum.

7. TESTING SET UP

The test element was attached to the welded I-beam frame using specially designed clamps. The angle of the fixture was determined by the test elements to insure that the force applied was an accurate replication of actual field conditions.

In some cases a steel bar was inserted into the chord (clamped) section of the tube. Tests were performed with and without the steel bar in order to determine and quantify any compliance of the frame or test element.

The clamping devices used to grip the tension member are collets designed and manufactured specifically for the test elements.

The following diagram illustrates the testing setup used for this study (Figure 9).

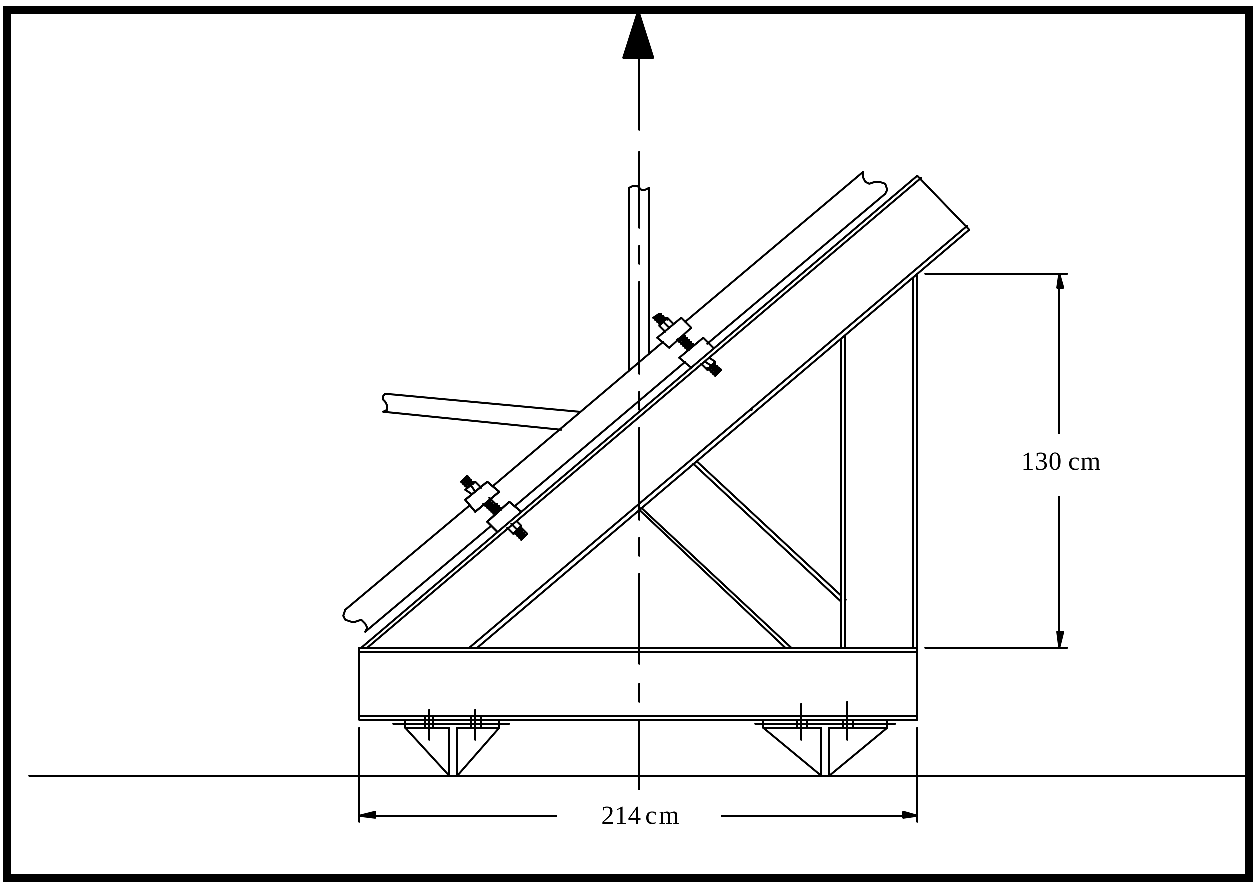

Figure 9. Diagram of Test Specimen and Test Stand

8. RESULTS

Three series of tests were conducted. The first series was to determine the baseline strength of the as-is welded aluminum connection with no visible cracks. The samples provided were in-service elements.

Following is an illustration of how the test specimen appears when attached to the test apparatus (Figure 10). Note the placement of the strain gauges that are placed near the suspected failure area. A typical failure mode of the test specimen is also shown (Figure 11).

Figure 10. Illustration of test setup and strain gauge placement.

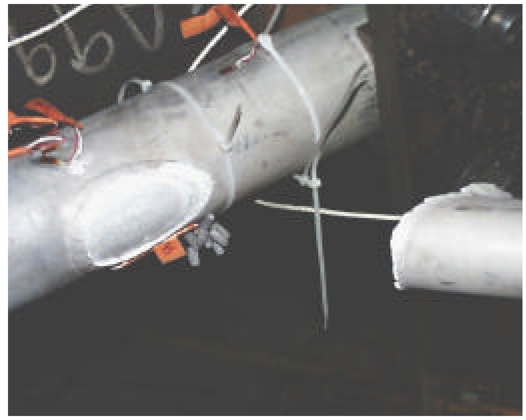

Figure 11. Typical aluminum connection failure during testing.

Listed below are the results for the three series of tests that were performed.

Series I: Test Results for Static Tests of As-is Welded Aluminum Connections with no visible cracks.

- **= No pipe in the chord**

Specimen	Failure	Maximum Load
I-a*	Weld & Base	28.81 kips
I-b*	Weld & Base	28.26 kips

Series II tests were done using the same setup as shown above. Cyclic loading was applied and the results of the as-is aluminum connection were established. Note that R is the stress ratio.

Series II: Test Results for Fatigue Tests of As-is Welded Aluminum Connections with no visible cracks.

- **= No pipe in the chord**

Specimen	Failure	Maximum Load	R	Number of Cycles
II-a (1)*	Weld	21 kips	0.190	5,690
II-a (2)	Weld & Base	21 kips	0.190	14,448
II-b (1)*	Weld & Base	15 kips	0.267	28,491
II-b (2)	Weld & Base	15 kips	0.267	48,096
II-c	Weld & Base	10 kips	0.200	320,829

Series III are the test results for the fatigue test of cracked aluminum connections repaired using Air Logistics Corporation's FRP repair system (Figures 12 & 13).

Series III: Test Results for Fatigue Tests of Cracked Aluminum Connections from the field repaired with GFRP.

Specimen	Failure	Maximum Load	R	Number of Cycles
III-a	Weld, Base, & FRP	21 kips	0.190	6,763
III-b	Weld, Base, & FRP	15 kips	0.267	69,194
III-c	Weld, Base, & FRP	10 kips	0.200	1,000,000 Static 21 kips

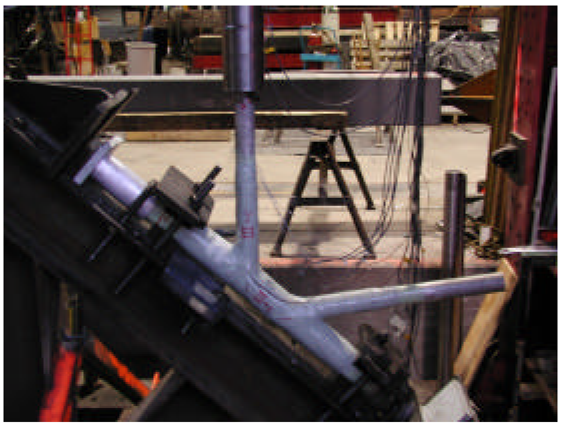

Figure 12. Fatigue test in progress.

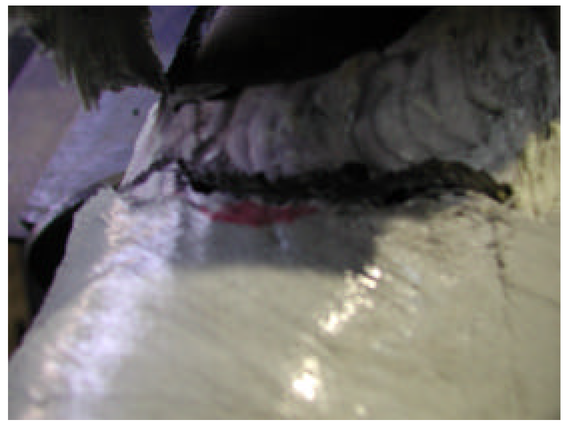

Figure 13. Typical Fatigue Fracture

9. CONCLUSIONS

This paper has served to describe another practical use for FRP materials in infrastructure applications. When FRP materials are properly selected and applied, the results will be successful. Using the correct design and installation guidelines is essential to this type of repair. This study has proven that FRP materials, specifically Aquawrap® in many of its forms, can provide a successful solution to an existing problem. The methodology used provided a repair method that met, and in many cases exceeded, original design specifications. It also provided the customer with a cost effective solution to an existing problem.

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