REPAIR OF CRACKED ALUMINUM OVERHEAD SIGN STRUCTURES WITH GFRP COMPOSITES

By Chris P. Pantelides[1] and Justin Nadauld[2]

Transportation departments have been using aluminum overhead sign structures since the early 1960's. It is well documented that cracks develop in the welds between diagonal and chord members, due to fatigue stresses by wind-induced vibration of slender members. The cracks propagate to complete failure of the members, which causes signs to fall and inflict injuries. The original design of overhead sign structures did not consider fatigue as a limit state. In addition, field welding of aluminum structures for any possible repairs is prohibited. A repair method for the cracked aluminum welded connections between diagonals and chord members using glass fiber reinforced polymer composites (GFRP) has been investigated. The static tensile load carrying capacity of the welded connection and the cracked connection repaired with GFRP composites were established. This article describes the surface preparation of the aluminum tubular members, the application of GFRP composites to repair the connection, and the experimental results from monotonic static tests. The experimental results of specimens from actual sign structures show that the GFRP repaired connection achieved 1.17 to 1.25 times the capacity of the uncracked aluminum welded connection. These results, along with the minimal traffic disruption anticipated in the application, make this repair method a good candidate for implementation.

INTRODUCTION

Aluminum overhead sign structures have been in use since the early 1960's. However, the design of the overhead sign structures does not consider fatigue as a limit state. Fatigue stresses caused by wind vibration of slender members cause cracks in the weld that propagate to complete failure of the connection. Consequently, a number of these aluminum structures have developed fatigue cracks in the welded connections between diagonal and chord members, as shown in Fig. 1. This connection was obtained from an actual sign structure in New York State by the New York State Department of Transportation (NYSDOT). Other instances of similar cracks have also been reported in other states (Sharp et al. 1996). Failure of the slender members has caused signs to fail and inflict injuries. Field welding of aluminum is prohibited, since it is difficult to maintain the gas enclosure over the arc in the wind (Sharp et al. 1996). On the other hand, removing the overhead sign structure and repairing the defective welds would be costly and time consuming. A practical and effective repair is needed, which can be undertaken with the overhead sign structure in service.

The use of FRP composites in civil structures is becoming economically feasible. This is especially true for bridges in urban areas, where reduced traffic control costs give FRP composite repair methods an advantage due to the limited disruption of traffic. High ultimate strength, relative ease and speed of application, and ability to conform to irregular surfaces, make FRP composites attractive alternatives for retrofitting existing structures. FRP composites exhibit excellent resistance to environmental and chemical corrosion, which makes them an excellent material for use in aggressive environments. FRP composites have been used in a variety of projects in civil engineering such as: composite decks, composite column wrapping, composite

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beams, composite wraps for reinforced concrete beams and joints, and external pre-stressing. These applications were part of either seismic retrofit, post-earthquake rehabilitation, or for flexural and shear strengthening.

The objective of this study is to investigate the effectiveness of FRP composites in the repair of aluminum overhead sign structures. Specifically, the monotonic static tensile load carrying capacity of the repaired connection with GFRP composites is established. The ultimate objective of this study is to develop a methodology for returning the cracked aluminum welded connections of overhead sign structures to their original or greater strength.

TEST SPECIMEN CONFIGURATION

Four connections of diagonal to chord truss members were repaired with GFRP composites and tested in monotonic static tension to failure. In addition, four tests were performed with GFRP composites only, in which four tack welds were used for each diagonal to chord connection to hold the diagonals in place for application of the GFRP composites; this simulates cracking along the whole length of the weld at impending failure of the connection. Finally, one test was carried out of a welded aluminum connection without any visible cracks to determine the as-is strength of the welded connection.

The test specimens consisted of two diagonal members of 63.5mm (2 ½ in.) diameter attached to a main chord of 101.6mm (4 in.) diameter; the diagonals were orientated at 48 degrees from the bottom chord as shown in Fig. 2. In order to apply a monotonic static tensile load, a triangular load frame was constructed such that one diagonal of the specimen could be positioned vertically, directly under the hydraulic actuator as illustrated in Fig. 2. The specimens were gripped using a tapered steel cylinder – chuck device.

The members of the structure consisted of round aluminum tubing. The dimensions of the diagonal member were: outside diameter = 63.5mm (2 ½ in.), thickness = 6.35mm (1/4 in.); the dimensions of the chord member were: outside diameter = 101.6mm (4 in.), thickness = 6.35mm (1/4 in.). It should be noted that these sizes were identical for all the specimens and are typical for diagonal and chord members of overhead highway sign structures; however, depending on the span of the structure, truss depths ranging from 1.219m (4 ft) to 2.438m (8 ft), diagonals ranging from 38mm (1½ in.) to 127mm (5 in.) outside diameter and wall thicknesses ranging from 3mm (1/8 in.) to 6mm (¼ in.) are available (NYSDOT 1968).

MATERIAL PROPERTIES

Aluminum

The tubing material used in most existing overhead sign structures is aluminum alloy ASTM 6061-T6. This is a commonly used aluminum alloy in structural applications. The mechanical properties of aluminum alloy ASTM 6061-T6 determined according to ASTM Standards can be found in the *Aluminum Association Specifications* (1986), as follows: tensile yield strength = 240 MPa (35 ksi), tensile ultimate stress = 290 MPa (42 ksi), compressive yield strength = 240 MPa (35 ksi), and compressive modulus of elasticity = 70 GPa (10.1 Msi). The investigation was concerned with the strength of the connection between welded aluminum members and the strength of the connection with the GFRP composite repair. Table 1 shows the allowable stresses for welded tubes per *Aluminum Specifications* (1986) - *Allowable Stress for Bridge and Similar Structures*, and the allowable stress for welded tubes per NYSDOT *Design Criteria for Sign Structures* (1968). The slenderness ratio for 1.219m (4 ft) long members is given as L/r = 54.2, which is less than 66; therefore, according to the *Aluminum Association Specifications* (1986), the governing equation for L/r < 66 was used as:

$$\sigma_c = 17.9 - 0.112\left(\frac{L}{r}\right) \tag{1}$$

Note that (1) is in (ksi) units and results in a column allowable compressive stress of 11.85 ksi (81.7 MPa). The allowable stress governed by compression in terms of the walls of round tubes within 25mm (1 in.) of the weld is given by the *Aluminum Specification* (1986) as

$$\sigma_w = 12 - 0.44\sqrt{\frac{R}{t}} \tag{2}$$

Note that (2) is in (ksi) units, R is the mid-thickness radius equal to 1.1875 in. (30.16mm), and the tube thickness t = ¼ in. (6.35mm). Equation (2) gives an allowable strews equal to 11.04 ksi (76.1 MPa). According to the NYSDOT *Design Criteria for Sign Structures* (1968) the allowable stress in compression for 1.210m (4 ft) diagonals 63.55mm O.D. x 6.35mm (2½ in. O.D. x ¼ in.) is 68.6 MPa (9.95 ksi) and is governed by the capacity of the weld. The NYSDOT *Design Criteria* (1968) called for shop welding using an inert gas arc-welding process and 5356 or 5556 filler metal. The allowable stress in tension given by the *Aluminum Specifications* (1986) is 82.7 MPa (12 ksi). Since the tests carried out in this research were monotonic static tension tests, the latter value of 82.7 MPa (12 ksi) allowable tensile stress shall be compared with the test results.

GFRP Composite

Due to chemical interaction between carbon fiber composites and aluminum, a glass FRP composite rather than a carbon FRP composite jacket was used in this research. The properties of the GFRP composite used to wrap the NYSDOT sign structures are shown in Table 2. All of the fabrics were pre-impregnated with the same urethane resin. It should be noted that the modulus of elasticity of the various GFRP composite materials, which affects the stiffness of the connection directly, ranges from 28% to 45% the modulus of elasticity of the aluminum. The fine weave tape is used to generate the bond required for attaching the GFRP composite materials to the aluminum surface. The main tension-carrying member in the GFRP composite repair is the unidirectional (UD) tendon.

SURFACE PREPARATION

Surface preparation for the application of the GFRP composite is critical in order to obtain the bond strength required. The first two test specimens (TS1 and TS2) were prepared differently from the other specimens in two respects: (a) the aluminum surface was not roughened, and (b) a different aluminum preparation solution was used. The surface preparation procedure was improved through an evolutionary process developed in this research. Seven steps were used to get a good surface preparation, as outlined below: (P1) - Using a high alkaline wash cleaner the surface was scrubbed thoroughly to remove road film and dirt to prevent film and dirt from being forced into the aluminum in later steps. The surface was then rinsed with water and wiped dry; (P2) – an aircraft aluminum preparation compound was dubbed over all surfaces and allowed to set for at least three minutes; the surface was subsequently rinsed with water; (P3) – the surface of the aluminum was roughened using a "no-gray" sandpaper; (P4) - holes were drilled at the two ends of the crack using a drill bit at least three times larger than the crack width; (P5) - the surface was cleaned for a second time as in step (P2); (P6) – a two-part epoxy putty was then applied. The putty should be mixed until no streaks are present. The epoxy was applied to the joint to create a smooth transition from the chord member to the diagonal members; (P7) – a solution was then applied to the surface to convert the aluminum surface to a new compound that provides a stronger bond to the GFRP composite. The surface was finally rinsed with water and wiped clean and dry.

APPLICATION OF GFRP COMPOSITE

The GFRP composites used in this study were pre-impregnated with a urethane resin that starts curing when water is added to it. The four different GFRP composite materials were pre-packaged in aluminum foil so that they could be easily accessed and applied quickly. Once the water is added to the GFRP composite, it sets in approximately one hour. The following nine steps outline the method of application developed during this study, and the function of each layer of the GFRP composites. (A1) - The primer was brushed over the entire specimen and was allowed to set until it was tacky; (A2) - A bonding layer of fine weave tape GFRP composite was applied to the diagonal truss members, and curing was initiated; (A3) - One layer of bear tubular weave was applied to the joint structure. The tubular braid was molded to the curvature of the pipes and into the joint such that no gaps are present. The tubular braid consists of fibers orientated at ±45 degrees, forming an X shape, and its function is to resist shear forces; (A4) – The uni-directional (UD) GFRP composite tendons were then applied as shown in Fig. 3, which also shows the underlying tubular braid applied in step (A3); (A5) - Fine weave GFRP composite was used as bands at the following locations to hold the tendons in place: one near the top of each diagonal, one near the bottom of each diagonal, and one at the center of the main chord; (A6) - A second layer of tubular braid was applied as in step (A3); (A7) - One layer of heavy woven roving GFRP composite is applied to the bottom half of the main chord. This layer adds stiffness to the main chord and brings the system up to a more uniform thickness; (A8) - A fine weave GFRP composite was applied as in step (A2) but this time it was applied over the entire connection; GFRP composite pieces were cut to fit around the joints to create a smooth transition; and (A9) - Strictures banding, a high strength stretch film, was wrapped tightly around the entire connection to constrain the GFRP composite. Foam rope was also wrapped around the joints and was constrained with banding to ensure that the GFRP composite is tight around the joints. The stretch film and foam rope were subsequently removed after the composite had cured.

EXPERIMENTAL RESULTS

The results of the experiments were obtained using a 980 kN (220 kip) programmable actuator. All nine tests were carried out in monotonic tension at a constant rate of 89 kN/min (20 kip/min), and data was recorded at 0.1-second intervals. A data acquisition system was used to record the strain from strain gages placed on the specimens. Strain data were also recorded at 0.1-second intervals. The strain gage locations, all of which were attached to the GFRP composite, are shown in Fig. 4. A complete description of test procedures and results is given elsewhere (Pantelides and Nadauld 2001).

New Fabricated Specimens

Four of the specimens tested (TS1, TS2, TS4, and TS4-B) were newly fabricated specimens which were built using the same aluminum alloy ASTM 6061-T6 material, dimensions and configuration as for the field specimens. However, the new specimens were not welded with the details of the field specimens. The four new specimens were constructed by tack welding the diagonals in four spots to the main chord to hold them in place so that the GFRP composite could be applied. These specimens simulated the case when the weld would have been severed completely and the diagonals and chord would be completely separate members. For the first two specimens, TS1 and TS2, the wrap extended up the diagonals 305mm (12 in.) from the center of the chord; for TS4 and TS4-B the wrap extended 457mm (18 in.) from the center of the chord. Specimens TS1 and TS2 failed at a lower tensile load than TS4 and TS4-B as shown in Fig. 5. It is obvious from Fig. 5, that the specimens with the longer GFRP composite bond length performed better and resisted a load 1.46 times higher than the specimens with the shorter bond length. This suggests that the bond-dependent tensile capacity of the connection is proportional to the bond length. In addition, the maximum strain in the GFRP composite was increased by a factor of 2.0 in the chord (position #1 in Fig. 4), and in the diagonal (position # 2 in Fig. 4) for the specimens with the longer bond length. The displacement at peak load was increased by a factor of 2.6, which is desirable for giving warning of impending collapse.

Field Specimens

The other five specimens were supplied by the NYSDOT. These specimens were cut out of actual sign structures that had been taken out of service due to formation of fatigue cracks in the welds. Two of these specimens (TS3 and SS1-B) had no visible cracks in the weld. Specimen TS3 was tested as-is; specimen SS1-B was tested with the GFRP composite applied to the joint following the steps outlined above. The other three specimens all had visible cracks of varying length, similar to the one shown in Fig. 1, and GFRP composite was applied as a repair as outlined above. The details of the GFRP composite repair were identical to those of the uncracked specimen SS1-B.

Specimen TS3 was tested as-is to determine the actual tensile capacity of the welded aluminum connection obtained from the field. This tensile capacity was then compared to the allowable stress for welded tubular members. The experiment showed that specimen TS3 had a maximum tensile capacity of 110 kN (24.74 kip) at a displacement of 15mm (0.59 in.), as shown in Fig. 6. This corresponds to a tensile failure stress of 96.6 MPa (14 ksi), which is 1.16 times the allowable stress for welded tubes according to the *Aluminum Association Specifications* (1986).

Specimen SS1-B was the only specimen repaired with GFRP composite without any visible crack in the weld. This test had the highest tensile load of all tests, which was measured as 151 kN (33.93 kip) as shown in Fig. 7. This tensile load corresponds to a tensile failure stress of 132.4 MPa (19.2 ksi), which is 1.60 times the allowable stress for welded tubes according to the *Aluminum Association Specifications* (1986). It is evident from the strain gage data that the weld failed completely at a vertical displacement of 18 mm (0.708 in), as shown in Fig. 8. The strain in the GFRP composite at position #1 (Fig. 4), temporarily decreased after weld failure but subsequently it increased at the GFRP composite tensile failure point; compared to the previous peak at weld failure, the strain in the GFRP increased by a factor of 1.57. At that point, the GFRP composite carried the entire load until it failed in tension at a load of 151 kN (33.93 kip) and a vertical displacement of 20 mm (0.785 in) as shown in Fig. 7.

The repaired aluminum tube field specimens had cracks in the weld, induced by fatigue, which went all the way through the thickness of the weld, and varied in length. The length of the crack was measured around the circumference of the diagonal before application of the GFRP composite. Specimen SS1-A had a crack that was 140 mm (5.5 in.) long which corresponds to 52% of the total weld length; specimen SS2-A had a 64 mm (2.5 in.) long crack corresponding to 24% of the total weld length; and specimen SS2-B had a 178 mm (7.0 in.) long crack corresponding to 66% of the total weld length, as shown Fig. 1. The GFRP composite repair design details were the same for all repaired specimens as outlined in the section on GFRP composite application. It is interesting to note from the results, shown in Fig. 7, that all three repaired specimens (SS1A, SS2A, and SS2B) failed at similar loads regardless of the crack length. This demonstrates the effectiveness of the GFRP composite repair regardless of the crack length. The failure mode was similar to that of specimen SS1-B, which involved complete weld failure followed by tensile failure of the GFRP composite; as the weld began to fail, the GFRP composite took over and carried the load until the GFRP failed in tension. As in test SS1-B, before the weld completely failed, both the weld and the GFRP composite were carrying the load. This explains why the cracked welds failed at similar loads – even though the original crack lengths in the weld differ significantly. However, from Fig. 7 it can be observed that the specimen with the largest crack in the weld (SS2B) failed at the smallest applied displacement (16.9mm or 0.664 in.), and the specimen with the smallest crack (SS2A) failed at the largest vertical displacement (26.8mm or 1.055 in.).

FAILURE MODES

The failure of the as-is welded specimen from the field (Specimen TS3) was a typical weld failure as can be seen in Figs. 6 and 8. As Fig. 6 shows, deterioration of the weld started approximately at a displacement of 2mm (0.08 in.); after a displacement of 5.6mm (0.22 in.) the load displacement curve became linear showing gradual degradation of the welded connection. The maximum strain measured at position #2 on the diagonal (Fig. 4) reached 0.19%, which is just under the offset strain of 0.2% corresponding to the expected minimum value of yield strength across a butt weld (ASCE Task Committee on Lightweight Alloys 1962).

The remaining eight specimens were all repaired with GFRP composites. Two distinct failure modes for these specimens were identified: (1) adhesive failure mode, and (2) weld failure and subsequent GFRP composite tensile failure. Failure mode (1), the adhesive failure mode, was observed for the four new fabricated specimens (TS1, TS2, TS4, and TS4-B). Even though these new fabricated specimens were built using the same aluminum alloy, ASTM 6061-T6, they were constructed by tack welding the diagonals in four spots to the main chord so that the GFRP composite repair could be applied. Therefore, only the GFRP composite held the connection together, which simulates a crack extending the total length of the weld. In all four specimens, the aluminum diagonal member was pulled out of the GFRP composite in an adhesive failure mode, as shown in Fig. 9. In all four tests there was a residual load developed due to the distance that the diagonal member had to pull out of the GFRP composite, as shown in Fig. 5. This is beneficial in a life-safety situation, since failure of the joint and possible collapse of a highway sign or truss substructure can be prevented if a residual strength can be maintained. Two of the specimens (TS1 and TS2) experienced this failure mode at low levels of load and displacement, as can be seen in Fig. 5, due to insufficient GFRP composite bond length. The same failure mode was observed even for the adequately prepared specimens (TS4 and TS4B) as shown in Fig. 5, with the exception that at the end of the test, tensile failure of the outer fine weave GFRP composite layer was observed at the far end of the diagonal; this occurred at an average tensile load 1.5 times that of specimens TS1 and TS2, an average displacement 2.6 times that of specimens TS1 and TS2, and a peak strain 2.0 times that of Specimens 1 and 2. In fact, specimens TS4 and TS4B experienced the highest strains in the GFRP composite of any of the tests carried out in this investigation.

Failure mode (2) was a combination of weld failure, which occurred first, and GFRP composite tensile failure shortly thereafter. This was the failure mode for all field specimens, SS1-A, SS1-B, SS2-A, and SS2-B, regardless of the existence of a crack in the weld or the length of the crack. In each of these tests, the GFRP composite started to share some of the tensile load as the crack initiated or propagated in the weld, until the weld failed completely. The load was then transferred entirely to the GFRP composite until it failed in tension, as shown in Fig. 10. This failure mode showed how the GFRP composite would behave at failure in the actual overhead aluminum sign structure, after the cracked welded connection had been repaired with the GFRP composites.

CONCLUSIONS

A repair method for cracked aluminum welded connections of overhead sign structures using GFRP composites has been investigated. The cracks in the welds can propagate to complete failure of the aluminum truss members, which can cause signs to fall and cause injuries. The tests performed in this investigation consisted of pulling the diagonal members from the chord member of the joint with in monotonic static tension. The as-is aluminum welded connection without any visible cracks was able to resist 110 kN (24.7 kip) or a stress of 96.6 MPa (14 ksi). This capacity is 1.16 times the allowable stress for welded tubes of the *Aluminum Association Specifications* (1986). The GFRP composite repaired connections were of two types: (a) field samples with or without cracks in the welds, and (b) new fabricated specimens tack welded only, in which the diagonal and chord were entirely separated to simulate a crack extending the total length of the weld; in this case the strength of the connection was entirely due to the GFRP composite.

The GFRP composite repaired field connections with cracks in the welds, which ranged from 24% to 66% of the total weld length, reached capacities from 129 to 137 kN (28.9 to 30.8 kip), or 1.17 to 1.25 times that of the as-is welded connection. One field connection with no visible cracks, which was retrofitted with the same GFRP composite procedure, reached a capacity of 151 kN (33.9 kip) or 1.37 times that of the as-is welded connection. The new fabricated connections were only tack welded, with the diagonals and chords entirely separated and held together only by the GFRP composite, simulating a crack extending the total length of the weld. By providing adequate surface preparation and GFRP composite bond length, which was identical to the repaired field samples, these connections reached capacities from 105 to 109 kN (23.5 to 24.5 kip) or 0.95 to 0.99 times that of the as-is welded connection. In addition, a residual capacity was left in the connection even after adhesive failure of the GFRP composite, which is a desirable life-safety property.

The experimental results have demonstrated that the method presented in this article is a viable repair method of the cracked welded connections of aluminum sign structures. The ease of application of the GFRP composite system used in this study, and the anticipated minimal disruption of traffic required for application of the GFRP composite, make this method a good candidate for such repair applications.

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REFERENCES

Aluminum Association Inc. (1986) *Aluminum Construction Manual*, Section 1 – Specifications for Aluminum Structures, 5th Ed., Washington, D.C.

ASCE Task Committee on Lightweight Alloys (1962). "Suggested specifications for structures of aluminum alloys 6061-T6 and 6062-T6." *J. Structural Division,* ASCE, 88(ST6), 1-45.

Pantelides, C.P., and Nadauld, J. (2001). "Repair of cracked aluminum overhead sign structures with fiber reinforced polymer composites." *Research Report CVEEN-01/01,* Dept. of Civil & Environmental Engineering, Univ. of Utah, April, Salt Lake City, UT.

Sharp, M.L., Nordmark, G.E., and Menzemer, C.C. (1996). *Fatigue Design of Aluminum Components & Structures.* McGraw-Hill, New York, NY.

State of New York Department of Transportation (1968). *Design Criteria for Sign Structures with Tables and Charts*. Division of Construction, Albany, NY.

Table 1. Allowable Stresses for Welded Tubes

Property	Allowable Stress MPa (ksi)
All columns in compression	81.7 (11.85)*
Compression walls of round tubes within 25mm (1in.) of weld	76.1 (11.04)*
Tension walls of round tubes within 25mm (1 in.) of weld	82.7 (12.0)*
Compression for 1.210m (4 ft) diagonals 64mm O.D. x 6mm (2 ½ in. O.D. x ¼ in.)	68.6 (9.95)+

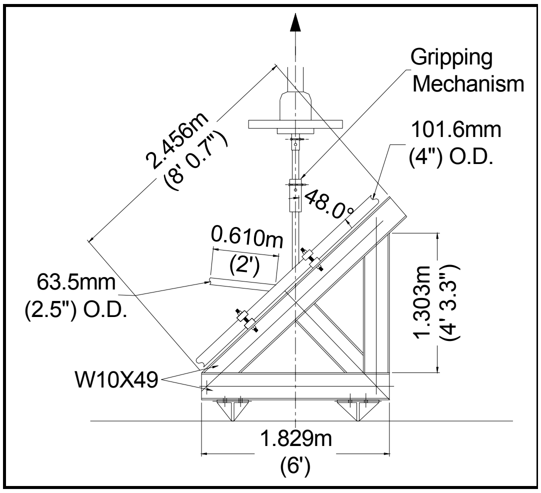
* *Aluminum Association Specifications (1986)*

\+ NYSDOT *Design Criteria for Sign Structures (1968)*

Table 2. GFRP Composite Properties

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

Fig. 1. Cracked welded connection: (a) overhead sign structure, (b) fatigue crack in welded connection of specimen SS2-B with a crack 66% of total weld length



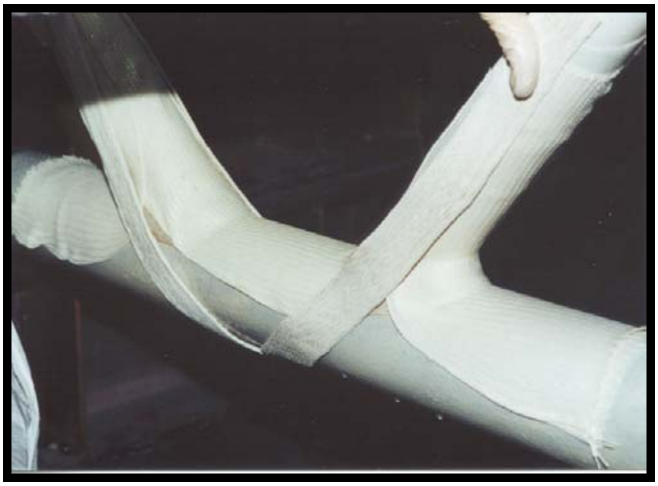


Fig. 2. Support frame and test configuration Fig. 3. Application of unidirectional GFRP tendons

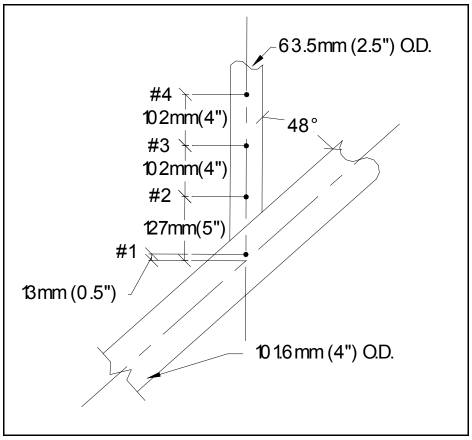


Figure 4. Strain gage positions

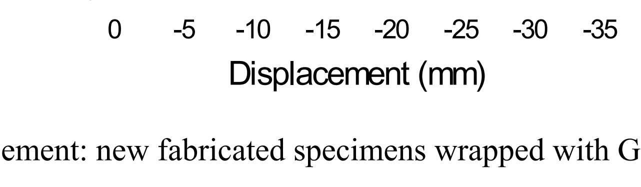


Fig. 5. Load vs. displacement: new fabricated specimens wrapped with GFRP composite

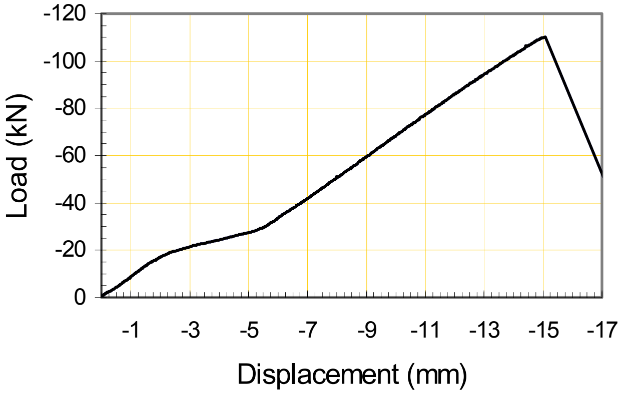


Fig. 6. Load vs. displacement for welded connection without visible crack – specimen TS3

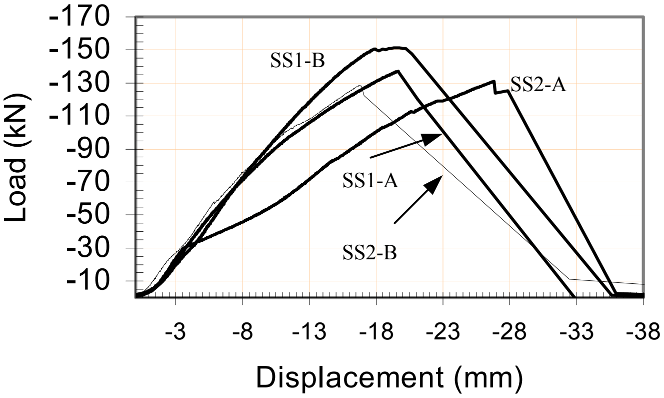


Fig. 7. Load vs. displacement: tests SS1-A, SS1-B, and SS2-B

Fig. 8. Close-up of weld failure of specimen TS3

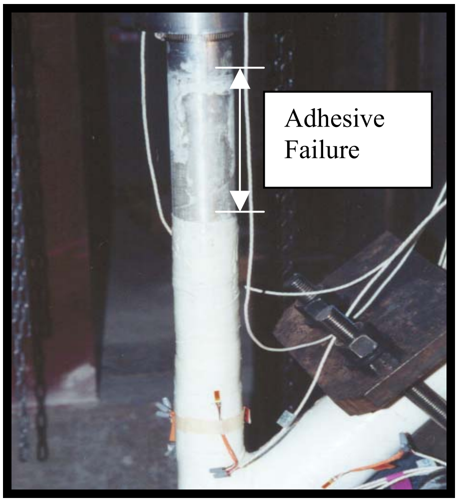


Fig. 9. Adhesive failure mode for specimen TS4

(a) (b)

Fig. 10. GFRP composite tensile failure after weld failure: (a) entire joint, and (b) end of diagonal