CLARKSON UNIVERSITY

LABORATORY TESTING OF FRP BEAMS

by

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ABSTRACT

The New York State Department of Transportation (NYSDOT) is planning to replace an existing bridge superstructure with a prefabricated Fiber Reinforced Polymeric (FRP) composite superstructure as part of their capital program. Due to the lack of experience regarding the strength and stiffness characteristics of this type of bridge, it was decided to load test two beams, through an independent testing/research facility, to obtain strength and stiffness characteristics in flexure and shear and investigate failure mechanisms. This report describes the load testing of two Fiber Reinforced Polymeric (FRP) beams and material testing conducted in the Clarkson University Structural Engineering Laboratory at the request of NYSDOT. It was found that the FRP beam tested under flexure configuration (Beam I) failed at a load of 330 kN by debonding of the top flange. Beam II, tested in shear, failed by crushing of the core under the single point load (512 kN) applied at midspan.
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CHAPTER 1

INTRODUCTION

The New York State Department of Transportation (NYSDOT) is planning to replace an existing bridge superstructure with a prefabricated Fiber Reinforced Polymeric (FRP) composite superstructure as part of their capital program. The FRP superstructure will be manufactured by Kansas Structural Composites (KSCI) using the wet-lay up process. NYSDOT has no experience regarding the strength and stiffness characteristics of this type of bridge. Thus, it was decided to load test two beams, through an independent testing/research facility (Clarkson University), to obtain strength and stiffness characteristics in flexure and shear and investigate failure mechanisms. The experimental results from this project will be used in the design of the superstructure.

This report describes the load testing of two Fiber Reinforced Polymeric (FRP) beams and material testing conducted in the Clarkson University Structural Engineering Laboratory at the request of NYSDOT.
CHAPTER 2
EXPERIMENTAL PROGRAM

2.1. Beam Manufacturing and Transportation

The two beams tested at Clarkson University were manufactured in Russell, Kansas, by Kansas Structural Composites (KSCI), Inc., under the direction of Dr. Jerry D. Plunkett. Both beams are of sandwich type construction with a vertical corrugated core and were manufactured using the wet-lay up method. Manufacturing beam dimensions were as follows:

Beam I: 9.8-m long, 0.79-m deep, and 0.30-m wide, weighing 530 kg
Beam II: 1.8-m long, 0.79-m deep, and 0.30-m wide, weighing 100 kg

Actual dimensions are indicated in Figures 2.1 and 2.2. Transportation of the beams was arranged by KSCI. Beam II was delivered on July 30th; beam I was delivered August 8th. Both beams were delivered inside of the Structural Laboratory and were placed on the strong floor area with the help of an overhead crane (Figure 2.3).

2.2. Parameters of Study

Beam I was tested under flexure load configuration and beam II was tested under shear load configuration. Parameters investigated were: strength and stiffness characteristics as well as failure mechanisms developed under flexure and shear loads.

The flexure test consisted of a two-point loading set-up with loads located at quarter span. The shear test consisted of a single point load applied at mid span. Load configurations are indicated in Figure 2.1.
2.3. Beam Configuration

Both beams are sandwich type construction with a 13 mm thick top and bottom FRP “flange” plate separated by a vertical corrugated core (with 4 mm thick alternate corrugated and flat thin plates). Figure 2.2 shows a typical cross section and core layout for both beams.

According to the manufacturer’s data, the top and bottom plates are composed of several layers of unidirectional, bi-directional and chopped E-glass fibers. The FRP plate lay-up is as follows (from exterior surface to core): 1 bi-directional (0/90) mesh of E-glass fiber, 9 unidirectional layers of E-glass fibers (continuous fibers running on the longitudinal direction), 1 bi-directional (0/90) mesh of E-glass fiber and 1 layer of chopped E-glass fibers. A vinyl ester resin is used as matrix (Vipel F0.10-TBN-35, AOL resin). The core is configured with thin plates (both corrugated and flat) with a thickness of 4 mm. These thin plates are composed of short glass fibers (chopped strand mat) and vinyl ester resin. Material properties for both types of plates were derived following ASTM specifications. Results are presented in Chapter 5.

2.4. Test Setup

The test setup consisted of a self-equilibrating structural steel testing frame. A hydraulic actuator with capacity of 1,100 kN was placed at midspan of the steel beam. A load cell and a magnetic position sensor were attached to the hydraulic actuator. A computer based data acquisition system was used to measure load and displacement from the actuator, as well as deflections and strains from specific locations in each FRP beam. Vertical and horizontal deflections for each beam were measured using external position transducers such as string pots and linear variable differential transducers (LVDT). Strain gages were attached to the surface of each FRP beam at different locations. A detailed description of the instrumentation layout is presented in Chapters 3 and 4. Both beams were supported on 19 mm thick square neoprene pads (305 mm width). The Fiberlast Isotropic randomly oriented fiber pads were purchased from Voss Engineering, Inc.
Note: dimensions in m.

Figure 2.1. Flexure and Shear Test Set-Ups

Figure 2.2. Typical Beam Configuration
Figure 2.3. Delivery of the FRP Beam I in the Structural Laboratory at Clarkson University
CHAPTER 3
FLEXURE TEST – BEAM I

3.1. Instrumentation Layout

For the flexure test of beam I, a 5.2 m long steel beam (W 21 x 182, grade 50) was used as spread beam to distribute the load from the hydraulic actuator into two point loads located 4.88 m apart. Stiffeners were welded at the midspan and both point loads locations to prevent web buckling during the test, see Figure 3.2. Steel rollers were placed under the spread beam, 4.88 m apart. Neoprene pads were placed between the rollers and the FRP beam to distribute the stress concentrations at these locations.

Four linear displacement transducers (LVDT) and three string pots were used to measure deflection of the FRP beam I. String pot #12 was attached to the bottom flange of the beam at midspan, string pot #13 and #11 were also attached to the bottom surface under the point loads on the right and left side respectively. LVDT #3 and #4 measured vertical deflection on both sides of the beam, at a section located 305 mm left from the midspan and 394 mm from the top surface. LVDT #2 and #1 were placed on the rear side of the beam. They measured top and bottom horizontal displacement respectively at a section located 51 mm right from the midspan (LVDT#2 was placed 29 mm from the top, LVDT #1 was placed 51 mm from the bottom). The layout for these displacement transducers is shown in Figure 3.1. A photograph of the flexure test set-up is shown in Figure 3.2. Two dial gages were installed on each end of the beam, close to the supports. They measured vertical deflection of the FRP beam I at the interior end of each support (35 mm from the end of the neoprene pads).
Fourteen strain gages were placed in different locations on all sides of beam I. Eight strain gages were located at midspan: two on the top surface (CT1, FT2), two on the bottom surface (BC9, BC10), two on the front side between the edge of the top flange and the core (FI7, FI8), and two on the rear side between the edge of the bottom flange and the core (RI5, RI6). Six strain gages were placed under the two point loads: two at the bottom surface on the left side (BL11, BL12), two at bottom right side (BR21, BR22), and two between the top flange and the core on the left side (RL13, RL14). Finally, two groups of three strain gages in rosette configuration (one on each side: RL15-17, RR18-20) were placed between the point load and the support (1,330 mm from the edge, 388 mm from the bottom). Strain gage layout is indicated in Figure 3.3.

Professor Guillermo Ramirez from the University of Kansas installed acoustic sensors on the top surface of the FRP beam I. Data from these sensors was analyzed by Prof. Ramirez and results are presented as an appendix of this report.

Due to the slenderness of beam I, it was feared that the possibility of lateral buckling would prevent the beam from reaching its flexural strength. Lateral supports were installed at both ends of the beam and ¼ span. A 15 mm gap was left between the lateral supports and the corresponding side of the FRP beam I. These lateral supports also reached the level of the spread beam. Two steel columns (one on each side) were placed at midspan to provided lateral support for the spread beam. Photographs of the flexure load set-up including the lateral supports are shown in Figure 3.2, 3.4, and 3.5.

3.2. Load Sequence

Beam I was loaded, in 22 kN increments, under displacement control. It followed a load sequence defined to optimize the information collected by the acoustic sensors: the beam was loaded and unloaded at selected load levels; at some of these load levels, the load was also held
(under displacement control) to allow the acoustic sensors to collect information. Data was collected at a rate of 5 samples per second. Load sequence for beam I is presented in Figure 3.6.

### 3.3. Strength and Stiffness Characteristics

All the transducers used to measure vertical deflection (LVDT #3 and #4, string pots #11, #12, and #13) showed a very stable behavior during the flexure test. The maximum vertical deflection of beam I at failure load (330 kN) was obtained at midspan (121 mm). As was expected from the two-point bending configuration, vertical deflections at both point loads were smaller than at midspan during the entire flexure test. Also, no major differences were observed between the deflection on the left side and the right side of the beam. Figure 3.7 shows the load vs. vertical deflection (midspan and point loads) curves for beam I.

From the shape of the three curves plotted in Figure 3.7 it can be inferred that the FRP beam I had a linear behavior up to failure. The beam was initially loaded up to 174 kN, and then unloaded to 89 kN. From this first load-unload loop, it can be observed that behavior of the beam is predominantly linear elastic with a residual deformation at 89 kN of 4 mm. The initial loading curve from string pot #12 was used to calculate the slope of the load vs. midspan deflection (2.83 kN/mm), which is related to the stiffness and cross sectional properties of the beam (EI). Considering that the beam remained linear elastic during the loading curve and the beam geometry didn’t change along the length of the beam, the overall stiffness characteristic for the FRP beam I (EI) was found to be equal to $3.32 \times 10^{10}$ kN-mm².

As indicated previously, two dial gages were installed on each end of the beam, 35 mm from the end of each neoprene pad. They measured vertical deflection of the FRP beam I at these locations. Readings were taken every 22 kN. At a load of 289 kN (last reading before failure) both dial gages indicated a deflection of 12 mm. If the supports were fully rigid, the theoretical deflection at this point will be 4 mm, therefore the remaining deflection of 8 mm corresponds to the compression of the neoprene pads at this load level. It can be concluded that the contraction
of the neoprene pads did not affect the readings of vertical deflection at both point loads or at midspan.

LVDT #3 and #4 registered vertical deformation of the core external plates on each side of the FRP beam I (front and rear) near the midspan. At failure load (330 kN), LVDT#4 (rear side) was 5 mm lower than LVDT#3 as shown in Figure 3.8. It can be concluded that there was no significant relative vertical deformation between both sides of the beam.

LVDT #1 went out of range during the first loading step and therefore failed to register any meaningful data. LVDT #2, on the other hand, was successful at registering horizontal displacements. It was removed during the holding step at 242 kN (time = 1:24:10) because it reached the top flange of the beam. The corresponding lateral displacement at that load level was 3.6 mm, as shown in Figure 3.9. Visual inspection of the lateral supports during the test indicated that none of them were in contact with the FRP beam I prior to the debonding of the top flange and total local buckling of the core under the right point load. After failure occurred, it was observed that the right end of the beam at the top had moved 15 mm toward the front and now the beam touched the right end lateral support as shown in Figure 3.22. Since this lateral movement was originated by the debonding of the top flange and the total local buckling of the core under the right point load it can be concluded that lateral stability of beam I was achieved during the entire test up to the failure point.

A total of eight strain gages were placed at midspan. Figure 3.10 shows a representation of the location of these strain gages in a cross section of the FRP beam I. FT-2 and CT-1 were placed on the surface of the top flange; BC-9 and BC-10 were placed on the surface of the bottom flange. Figure 3.11 shows the data obtained from these strain gages. It can be observed that BC-9 and BC-10 failed at a small load level. This can be attributed to possible malfunctioning of these gages. CT-1 failed at 157 kN during the first loading-unloading cycle. The maximum strain value at that load level was $2840 \times 10^{-6}$ (2840 µå). FT-2 did record strain data during the entire duration of the flexure test. From this load vs. strain curve it can be observed that the first disturbance occurred in the vicinity of 111 kN, associated with occurrence
of the first audible noise. Maximum strain achieved at failure load was 5000 µâ. The overall behavior of the curve shows a linear behavior up to failure.

Strain gages FI-7, FI-8, RI-5 and RI-6 measured strains at both sides of the interface between the core and the top and bottom flange respectively. RI-5 did not register any data, RI-6 failed at the same load level as the strain gage CT-1. Strain gages FI-7 and FI-8 did register data during the flexure test. Figure 3.12 shows load vs. strain curves for both strain gages. Maximum strain values were obtained at a load level of 322 kN, close to failure (4244 µâ and 3707µâ respectively). As expected, strain values for strain gage FI-7 were smaller than the ones obtained from the center of the top flange (FT-2). Load vs. strain curve for the strain gage FI-8 shows a progressive change in slope and a drop in the strain at a load of 280 kN. This disturbance could be interpreted as a redistribution of strains due to the partial debonding of the external plate of the core in the vicinity of this location.

All the strain gages installed under both point loads failed at a low value of load, only strain gage RL-14 did registered data. Same as with strain gage FI-8, the slope of the curve indicated a redistribution of strains at that location. A drop of strain can be observed at a load of 217 kN.

Finally, all the strain gages in rosette configuration worked well during the test. Figure 3.13 shows the plots of load vs. shear strain for both rosettes. Both rosettes registered a shear strain ($\bar{\gamma}_{xz}$) of 2080 µâ at failure load.

3.4. Failure Mechanisms

During the flexure test several types of damage (failure mechanisms) occurred. During the second loading step (108-174 kN) a first identified crack noise was heard at a load of 111 kN. It seemed to come from the midspan, inside the beam. Beam I was unloaded to 89 kN and then reloaded in two steps up to 219 kN. As the load increased it became evident that the source of the noise may be attributed to the debonding of the flat external thin plates in the web. This
debonding area developed on the right side of the beam, between the midspan and the point load. As the applied load increased the noise associated to the debonding process was more and more noticeable. At a load of 290 kN it was observed that this debonding process lead to local buckling of the exterior flat thin plate on the front side of the beam. A change in the color of the core delimited the buckled area. It was suspected that a similar debonding process was also occurring on the rear side.

Finally, at a load of 330 kN, 1 second after the loading was held, the top flange of the FRP beam I debonded. This type of failure was sudden and released a large amount of energy. The amount of energy released was evident by the amount of noise, heat and disturbance of the test setup (rollers, steel plates, and spread beam). This debonding at the interface started at the right point load and propagated through the interface between the top flange and the core up to the right end of the beam. The total debonded length was 7.5 ft. By loosing the contribution of the top flange to the strength of the beam, the core was subjected to larger loads and deformations that resulted in a well-defined local buckling failure of the core on both sides of the beam. Visual inspection of the debonded surface showed presence of loose fibers (no epoxy around them). It is suggested that a close study of the manufacturing process should be made to fully understand its effect on the failure mechanisms observed in this particular test.

Figure 3.14 shows a sketch of the debonded areas observed after completion of the flexure test. The locations where separation of the external plates from the core was observed have been drawn and tabulated. It should be pointed out that some of the strain gages were located in debonding areas (RL-13, RL-14, RI-5, RI-6). This may be the cause of the early damage of some of these strain gages. Figures 3.14 to 3.22 show a sequence of photographs corresponding to the flexure test of the FRP beam I.
Figure 3.1. Displacement Transducers Layout - Flexure Test of Beam I

Figure 3.2. Flexure Test Set-up
Figure 3.3. Strain Gage Layout – Beam I
Figure 3.4. Flexure Test of FRP Beam I

Figure 3.5 Details of Lateral Supports – Flexure Test of Beam I
<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Time(^{1}) (hh:mm:ss)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0:0:0</td>
<td>Start test</td>
</tr>
<tr>
<td>0-108</td>
<td>13:12</td>
<td>Loading</td>
</tr>
<tr>
<td>108</td>
<td>16:42</td>
<td>Hold - All the gages working OK.</td>
</tr>
<tr>
<td>108-174</td>
<td>26:04</td>
<td>Loading - First noise heard at around 111 kN</td>
</tr>
<tr>
<td>174</td>
<td>29:30</td>
<td>Hold</td>
</tr>
<tr>
<td>174-89</td>
<td>31:22</td>
<td>Unloading</td>
</tr>
<tr>
<td>89</td>
<td>33:05</td>
<td>Hold</td>
</tr>
<tr>
<td>89-174</td>
<td>37:49</td>
<td>Loading</td>
</tr>
<tr>
<td>174</td>
<td>40:31</td>
<td>Hold</td>
</tr>
<tr>
<td>174-219</td>
<td>44:06</td>
<td>Loading</td>
</tr>
<tr>
<td>219</td>
<td>51:35</td>
<td>Hold</td>
</tr>
<tr>
<td>219-240</td>
<td>52:54</td>
<td>Loading - Start buckling of the external sheet on core</td>
</tr>
<tr>
<td>240</td>
<td>58:55</td>
<td>Hold</td>
</tr>
<tr>
<td>240-188</td>
<td>1:01:17</td>
<td>Unloading</td>
</tr>
<tr>
<td>188</td>
<td>1:06:31</td>
<td>Hold</td>
</tr>
<tr>
<td>188-242</td>
<td>1:18:07</td>
<td>Loading</td>
</tr>
<tr>
<td>242</td>
<td>1:24:10</td>
<td>Hold - LVDT#2 removed</td>
</tr>
<tr>
<td>242-330</td>
<td>1:33:23</td>
<td>Loading - Well defined buckling in the core</td>
</tr>
<tr>
<td>330</td>
<td>1:33:33</td>
<td>Hold</td>
</tr>
<tr>
<td>328</td>
<td>1:33:34</td>
<td>Failure of the FRP beam – Debonding of the top flange</td>
</tr>
</tbody>
</table>

\(^{1}\) Time indicated corresponds to the end time of the respective step.

Figure 3.6. Load Sequence – Flexure Test
Figure 3.7. Load vs. Vertical Deflection (from String Pots) – Beam I

Figure 3.8. Load vs. Vertical Deflection (from LVDT) – Beam I
Figure 3.9. Load vs. Horizontal Displacement – Beam I

Figure 3.10. Location of Strain Gages at Midspan – Beam I
Figure 3.11. Load vs. Strain at Midspan – Beam I

Figure 3.12. Load vs. Interfacial Strains – Beam I
Figure 3.13. Load vs. Shear Strain – Beam I
Solid vertical lines indicate the locations where separation of the external plates from the core was observed. The debonded length is tabulated below. Buckling of the core on the right side of the beam started before failure of the FRP top flange.

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance x axis (mm)</th>
<th>Debonded length (mm)</th>
<th>Location</th>
<th>Distance x axis (mm)</th>
<th>Debonded length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1830</td>
<td>280</td>
<td>a'</td>
<td>990</td>
<td>Full</td>
</tr>
<tr>
<td>b</td>
<td>2380</td>
<td>76</td>
<td>b'</td>
<td>2280</td>
<td>508</td>
</tr>
<tr>
<td>cc</td>
<td>2480</td>
<td>76</td>
<td>c'</td>
<td>2480</td>
<td>76</td>
</tr>
<tr>
<td>d</td>
<td>3050</td>
<td>152</td>
<td>d'</td>
<td>2750</td>
<td>127</td>
</tr>
<tr>
<td>e</td>
<td>3380</td>
<td>254</td>
<td>e'</td>
<td>3460</td>
<td>127</td>
</tr>
<tr>
<td>f</td>
<td>3760</td>
<td>254</td>
<td>f'</td>
<td>4680</td>
<td>152</td>
</tr>
<tr>
<td>g</td>
<td>4680</td>
<td>Full</td>
<td>g'</td>
<td>4780</td>
<td>152</td>
</tr>
<tr>
<td>h</td>
<td>5900</td>
<td>Full</td>
<td>h'</td>
<td>6300</td>
<td>460</td>
</tr>
<tr>
<td>i</td>
<td>6400</td>
<td>305</td>
<td>i'</td>
<td>7080</td>
<td>690</td>
</tr>
<tr>
<td>j</td>
<td>6710</td>
<td>508</td>
<td>i''-j''</td>
<td>7080-7980</td>
<td>Full</td>
</tr>
<tr>
<td>k</td>
<td>6910</td>
<td>127</td>
<td>j'</td>
<td>7980</td>
<td>690</td>
</tr>
<tr>
<td>l</td>
<td>7180</td>
<td>662</td>
<td>k'</td>
<td>8080</td>
<td>460</td>
</tr>
<tr>
<td>l-m</td>
<td>7180-8575</td>
<td>Full</td>
<td>l'</td>
<td>8183</td>
<td>200</td>
</tr>
<tr>
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<td>8575</td>
<td>662</td>
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</tr>
<tr>
<td>n</td>
<td>8677</td>
<td>540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>o</td>
<td>8778</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.14. Location of the Debonded Region – Beam I
Figure 3.15. Meeting with DOT Personnel prior to the Flexure Test of Beam I

Figure 3.16. Monitoring of the Status of the Transducers during the Test
Figure 3.17. Failure of the FRP Beam I

Figure 3.18. Details of the Debonding of the Top Flange
Buckling of the Core – Beam I

Figure 3.19. Buckling of the Core – Beam I
Figure 3.20. Close-up of the Core Buckling – Beam I

Figure 3.21. Debonded Area – Beam I
Right end of Beam I during flexure test.

Right end of Beam I after failure. Top front is in contact with the lateral support.

Figure 3.22. Lateral End Displacement – Beam I
CHAPTER 4
SHEAR TEST – BEAM II

4.1. Instrumentation Layout

An FRP beam (beam II) with the same cross section of beam I but with a shorter span (1.82 m) was tested under a single point load applied at midspan. This test configuration was selected because it provided a symmetrical shear loading. Due to this load configuration the instrumentation layout was optimized (e.g. strain gages in symmetrical locations could be used for comparison). A neoprene pad was placed between the point load and the surface of the FRP beam. For this shear test four linear displacement transducers (LVDT) and one string pot were used to measure deformation of the FRP beam. The only string pot was attached to the bottom flange of the beam at midspan. LVDT #3 and #4 measured vertical deflection. LVDT#4 was placed at a section located on the rear side of the beam at midspan, 394 mm from the top surface, whereas LVDT#3 measured displacement of the bottom surface at midspan, 29 mm from the edge. LVDT #2 and #1 measured top and bottom horizontal displacement respectively (both were placed 51 mm from the edge). Two dial gages were installed on each end of the beam, close to the supports. They measured vertical deflection of the FRP beam at the interior end of the support (20 mm from the end of the neoprene pads). The layout for these displacement transducers is shown in Figure 4.1.

Twenty strain gages were placed on the front and rear sides of beam II. Twelve strain gages in rosette configuration (total of four rosettes, two on each side) were placed between the point load and the support at 560 mm from the edge and 394 mm from the bottom (FL3-5, FR10-12, RR16-18, RL13-15). At the same section, strain gages were placed on the front side between
the top flange and the core (IL1 and IL2, IR8 and IR9) and between the bottom flange and the core (IL6 and IL7, IR19 and IR20). Strain gage layout is indicated in Figure 4.2. Due to the short span of this beam, it was determined that no lateral supports were needed during the shear test.

4.2. Load Sequence

The short FRP beam was tested in shear under displacement control. The beam was loaded in 22 kN increments with two unloading steps at 222 kN and 333 kN. After failure was determined (crushing of the core), this beam was reloaded several times to further investigate this failure mechanism. The load sequence for beam II is presented in Figure 4.3.

4.3. Strength and Stiffness Characteristics

All three transducers used to measure vertical deflection (string pot #11, LVDT #3 and LVDT#4) recorded data during the test. String pot #11 was able to follow the several reloading steps after failure. LVDT#3 and #4 showed a very stable behavior up to the failure load of 512 kN, see Figure 4.4. String pot #11 and LVDT #4 measured deflection of the bottom flange of the FRP beam; both curves had a linear behavior up to failure. Values of midspan deflection at failure load were 6.6 mm and 6.1 mm respectively. LVDT #3 measured vertical deflection of the core external plate on the rear side of the beam. The load vs. deflection curve for this LVDT follows the same trend than the other two curves up to a load of 30 kN. It then deviates with a different slope. It is expected that this difference in behavior reflects the difference in stiffness properties between the core and the top and bottom flanges.

LVDT #1 registered a maximum horizontal of deformation of 1.3 mm at failure load, as shown in Figure 4.5. LVDT #2 did not register meaningful data during the shear test.

All the strain gages in rosette configuration (FL3-5, FR10-12, RL13-15, and RR16-18) worked well during the entire duration of the shear test. From each rosette, shear strains ($\dot{\varepsilon}_{xz}$) were calculated. Figure 4.6 shows the load vs. shear strains for each one of these four rosettes.
Shear strains were plotted up to the failure load of 512 kN. Maximum shear strain values were 3533 μå, 2064 μå, 3190 μå, and 3440 μå respectively.

Figure 4.7 shows a plot of load vs. strain for strain gages placed between the top flange or bottom flange and the core. Strain gages IL1 and IL2 did not register any data. From all the other strain gages it can be observed that strain gages located on either the top or bottom flange register a larger strain than the corresponding strain gage located in the core. The largest difference was observed between strain gages IL6 and IL7. At failure load, they registered 300 μå and 1000 μå, respectively. The largest strain at the core level was registered by strain gage IR19 (1670 μå at failure load).

The shear specimen failed by crushing of the core under the midspan point load at a load level of 512 kN. Therefore crushing of the core occurred before the vertical shear capacity of beam could be reached. It can be concluded that the vertical shear capacity of the beam exceeds 256 kN.

4.4. Failure Mechanisms

Beam II was initially loaded in 22 kN increments with two unloading steps at 225 kN and 333 kN. No sign of damage or noise was evident during the first loading. The first sound was registered when the load reached 225 kN. After the unloading step, the beam experienced very small permanent deformation (1.5 mm) at a load of 134 kN. The beam was then reloaded up to a target load of 333 kN (failure load for beam I described in Chapter 3); a second crack was registered at a load of 225 kN. During the unloading step (333 kN – 267 kN) the beam had a very stable linear behavior. The beam was then loaded up to failure.

Evidence of permanent damage was reported near 450 kN (increase noise and slight drops in load were observed). At a load of 512 kN, it was evident that the failure mechanism for beam II was crushing of the core under the point load. The beam gradually decreased the load up to 400 kN as the crushed area developed. It was also noticed that the external flat plate of the
core on the rear side buckled under the point load. A drop at a load of 135 kN was observed as the buckling developed. It was decided to reload the beam several times to further investigate this failure mechanism. After several loading steps and corresponding drops in load, the crushing of the core under the point load was extensive and the test was stopped after one hour and twenty minutes of testing.

Figure 4.8 shows a sketch of the debonded areas observed after completion of the shear test. The locations of core crushing and local buckling of the external rear plate from the core have been drawn and tabulated. Figures 4.9 to 4.13 show a sequence of photographs pertaining the crushing and local buckling of the core.
Figure 4.1. Test Set-Up and Displacement Transducers Layout – Shear Test of Beam II
Shear Test - Front View

Shear Test - Rear View

<table>
<thead>
<tr>
<th>Gage Label</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL1</td>
<td>559</td>
<td>0</td>
<td>778</td>
</tr>
<tr>
<td>IL2</td>
<td>559</td>
<td>0</td>
<td>775</td>
</tr>
<tr>
<td>FL3-5</td>
<td>559</td>
<td>0</td>
<td>394</td>
</tr>
<tr>
<td>IL6</td>
<td>559</td>
<td>0</td>
<td>51</td>
</tr>
<tr>
<td>IL7</td>
<td>559</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>IR8</td>
<td>1270</td>
<td>0</td>
<td>778</td>
</tr>
<tr>
<td>IR9</td>
<td>1270</td>
<td>0</td>
<td>775</td>
</tr>
<tr>
<td>FR10-12</td>
<td>1270</td>
<td>0</td>
<td>394</td>
</tr>
<tr>
<td>RL13-15</td>
<td>1270</td>
<td>333</td>
<td>394</td>
</tr>
<tr>
<td>RR16-18</td>
<td>559</td>
<td>333</td>
<td>394</td>
</tr>
<tr>
<td>IR19</td>
<td>559</td>
<td>333</td>
<td>51</td>
</tr>
<tr>
<td>IR20</td>
<td>559</td>
<td>333</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4.2. Strain Gage Layout – Beam II
<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Time(^1) (hh:mm:ss)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0:0:0</td>
<td>Start Test</td>
</tr>
<tr>
<td>0 - 225</td>
<td>10:58</td>
<td>Loading – No sign of damage</td>
</tr>
<tr>
<td>225 - 134</td>
<td>13:29</td>
<td>Unloading – First sound/noise at 225 kN</td>
</tr>
<tr>
<td>134</td>
<td>14:15</td>
<td>Hold</td>
</tr>
<tr>
<td>134 – 333</td>
<td>21:29</td>
<td>Second sound/noise at 225 kN</td>
</tr>
<tr>
<td>333 - 267</td>
<td>23:44</td>
<td>Unloading – Very stable behavior</td>
</tr>
<tr>
<td>267</td>
<td>24:29</td>
<td>Hold</td>
</tr>
<tr>
<td>267 - 512</td>
<td>35:22</td>
<td>Loading – Increasing noise around 450 kN</td>
</tr>
<tr>
<td>512-400</td>
<td>36:30</td>
<td>Crushing failure of the core</td>
</tr>
<tr>
<td>400 - 265</td>
<td>36:31</td>
<td>Drop in load</td>
</tr>
<tr>
<td>265 - 396</td>
<td>44:0</td>
<td>Loading</td>
</tr>
<tr>
<td>396-311</td>
<td>44:01</td>
<td>Drop in load</td>
</tr>
<tr>
<td>311</td>
<td>56:10</td>
<td>Hold</td>
</tr>
<tr>
<td>311 - 387</td>
<td>57:38</td>
<td>Loading</td>
</tr>
<tr>
<td>387 - 338</td>
<td>57:40</td>
<td>Drop in load</td>
</tr>
<tr>
<td>338-428</td>
<td>1:05:39</td>
<td>Loading – Crushing of the core well defined</td>
</tr>
<tr>
<td>428 - 324</td>
<td>1:05:50</td>
<td>Drop in load</td>
</tr>
<tr>
<td>324 - 378</td>
<td>1:13:38</td>
<td>Loading</td>
</tr>
<tr>
<td>378 - 212</td>
<td>1:16:38</td>
<td>Drop in load</td>
</tr>
<tr>
<td>212 - 0</td>
<td>1:20:53</td>
<td>Unloading and stop test</td>
</tr>
</tbody>
</table>

\(^1\) time indicated corresponds to the end time of the respective step.

Figure 4.3. Load Sequence – Shear Test
Figure 4.4. Load vs. Vertical Deflection – Beam II

Figure 4.5. Load vs. Horizontal Deformation – Beam II
Figure 4.6. Load vs. Shear Strain – Beam II

Figure 4.7. Load vs. Interfacial Strain – Shear Test
Solid vertical lines indicate the locations where separation of the rear flat plate from the core was observed. The debonded length is tabulated below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance x axis (mm)</th>
<th>Debonded length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>510</td>
<td>380</td>
</tr>
<tr>
<td>b</td>
<td>610</td>
<td>580</td>
</tr>
<tr>
<td>c</td>
<td>710</td>
<td>Full</td>
</tr>
<tr>
<td>d</td>
<td>810</td>
<td>580</td>
</tr>
<tr>
<td>e</td>
<td>1010</td>
<td>530</td>
</tr>
<tr>
<td>f</td>
<td>1110</td>
<td>280</td>
</tr>
<tr>
<td>g</td>
<td>1210</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.8. Location of the Debonded Region – Beam II
Figure 4.9. Shear Test Setup – Rear View Beam II

Figure 4.10. Crushing of the Core under Point Load – Beam II
Figure 4.11. Detail Strain Gages Near Top Interface – Beam II

Figure 4.12. Local Buckling Rear Core Plate – Beam II
Figure 4.13. Progressive Buckling Failure of the Core – Beam II
CHAPTER 5
MATERIAL TESTING

Material testing was conducted at Clarkson University to obtain material properties of the components of both FRP beams. Witness panels were provided by the manufacturer and coupons were manufactured at the machine shop of the School of Engineering. A list of requested ASTM test procedures was provided by the New York State Department of Transportation. Tests results are presented here.

5.1. Flexural Properties

ASTM C393-94 (Standard Test Method for Flexural Properties of Sandwich Constructions) covers determination of the properties of flat sandwich constructions. Both the flexure and shear tests described in Chapters 3 and 4 were used to determine the following properties according to this standard. Values of load and deflection at failure as well as material properties such as facing modulus and core shear modulus were used to determine the following values.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Beam I</th>
<th>Beam II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending stress (ó), MPa</td>
<td>115</td>
<td>24</td>
</tr>
<tr>
<td>Core shear stress (ô), MPa</td>
<td>0.64</td>
<td>0.99</td>
</tr>
<tr>
<td>Panel bending stiffness (D), kN-mm²</td>
<td></td>
<td>2.66 x10¹⁰</td>
</tr>
<tr>
<td>Panel shear rigidity, kN</td>
<td></td>
<td>6.84 x 10⁵</td>
</tr>
</tbody>
</table>
5.2. Tensile Properties

ASTM D3039M (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials) was followed to determine the in-plane tensile properties of test coupons corresponding to the “flange” and the core. Testing was conducted in the Geomechanics Laboratory at Clarkson University. An MTS universal testing machine with testing capacity of up to 89 kN was used. All the coupons were tested under displacement control (2 mm/min). Five coupons of each material were tested.

Coupon dimensions: 25 mm x 178 mm x thickness (4 mm core, 13 mm flange)

Ply orientation: core, random fiber orientation. Flange: length of specimen follows unidirectional layers of E-glass fiber. Figure 5.1 shows the tensile test setup.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Core Specimens</th>
<th>Flange Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>112.79</td>
<td>326.18</td>
</tr>
<tr>
<td>Apparent tensile strain* (µå)</td>
<td>14267</td>
<td>16641</td>
</tr>
<tr>
<td>Modulus of elasticity (E, GPa)</td>
<td>7.99</td>
<td>19.6</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
<td>0.58</td>
</tr>
<tr>
<td>Failure mode</td>
<td>LAT, LWB, LGM</td>
<td>LAT, SMM,</td>
</tr>
</tbody>
</table>

* back calculated using the values of tensile strength and Modulus of Elasticity

5.3. Shear Properties

ASTM D5379 (Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method) determines the shear properties of composite materials reinforced by high-modulus fibers. Testing was conducted in the Geomechanics Laboratory at Clarkson University. An MTS universal testing machine with testing capacity of up to 89 kN was used. All
the coupons were tested under displacement control (2 mm/min). Five coupons of each material were tested.

Coupon dimensions: 20 mm x 76 mm x thickness (4 mm core, 13 mm flange)

Ply orientation: core, random fiber orientation. Flange: length of specimen follows unidirectional layers of E-glass fiber. Notch is located at midspan, perpendicular to the longitudinal direction. Figure 5.2 shows a photograph of the test setup.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Core Specimens</th>
<th>Flange Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (MPa)</td>
<td>68</td>
<td>95</td>
</tr>
<tr>
<td>Shear strain at failure (µå)*</td>
<td>26000</td>
<td>19000</td>
</tr>
<tr>
<td>Shear modulus (G, GPa)</td>
<td>2.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Location of failure</td>
<td>v-notch</td>
<td>v-notch</td>
</tr>
</tbody>
</table>

* back calculated using the values of shear strength and shear modulus

5.4. Interlaminar Shear Strength

ASTM D2344 (Standard Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method) covers the determination of the apparent interlaminar shear strength of parallel fiber reinforced plastics. Testing was conducted in the Geomechanics Laboratory at Clarkson University. An MTS universal testing machine with testing capacity of up to 89 kN was used. All the coupons were tested under displacement control (1.3 mm/min). Ten coupons from the flange panel were tested.

Ply orientation: Length of specimen follows unidirectional layers of E-glass fiber. Five coupons were tested with the layer of chopped E-glass fibers on the compressive zone; five specimens were tested with the layer of chopped fibers on the tension zone.
Specimens 1,3,4,5, and 6 failed by delamination (horizontal shear) starting from the midspan point load up to the end of one of the supports. The average value for the horizontal shear strength was found to be 33.65 N/mm² (0.89 N/mm², std. dev.)

Specimens 2’, 7’, 8’, 8’, 9’, and 10’ failure initiated by delamination (horizontal shear) on one of the edge of the specimen, then a tensile failure was observed at midspan. Finally, partial delamination occurred at the same level as the initial horizontal shear failure and total delamination occurred above the end of the chopped fibers layer. The average value for the horizontal shear strength was found to be 27.10 N/mm² (0.89 N/mm², std. dev.). Figures 5.3 and 5.4 show test setup and failure modes for this test.

5.5. Fiber Content

ASTM D3171 (Standard Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion) covers the determination of the fiber content of resin-matrix composites by
digesting the matrix using chemical reaction. Several problems were encountered while following this standard test method: in order to allow for a complete digestion, the specimen size was so small that it was not representative of the material tested. Also, it was not possible to achieve full digestion of the matrix by any of the three methods suggested in this standard. After several unsuccessful attempts, an alternative method (recommended by the manufacturer) was followed:

Specimen dimensions were selected so the width and length was representative of the fiber matrix. Weights were recorded prior to placing them into an oven at 1000°C. After 30 minutes, the resin matrix was completely dissolved and only the fibers remained. After a cooling period, final weights were recorded. Weight fiber content was determined as a % of the initial weight of each specimen.

<table>
<thead>
<tr>
<th></th>
<th>Initial weight (g)</th>
<th>Fiber weight (g)</th>
<th>Resin weight (g)</th>
<th>W. Fiber Content, %</th>
<th>Average</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.0682</td>
<td>0.6308</td>
<td>1.4374</td>
<td>30.49995</td>
<td>31.05291</td>
<td>0.7528</td>
</tr>
<tr>
<td>2</td>
<td>2.1601</td>
<td>0.6642</td>
<td>1.4959</td>
<td>30.74858</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.7286</td>
<td>0.5516</td>
<td>1.177</td>
<td>31.91022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flange</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10.0863</td>
<td>5.4081</td>
<td>4.6782</td>
<td>53.61827</td>
<td>53.76232</td>
<td>0.1928</td>
</tr>
<tr>
<td>2</td>
<td>12.8324</td>
<td>6.9271</td>
<td>5.9053</td>
<td>53.98133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10.9523</td>
<td>5.88</td>
<td>5.0723</td>
<td>53.68735</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.6. Density

ASTM D792 (Standard Test Method for Density and Specific Gravity of Plastics by Displacement) describes the determination of the specific gravity and density of solid plastics. Test Method A for testing solid plastics in water was used.
<table>
<thead>
<tr>
<th></th>
<th>Specific Gravity</th>
<th>Average, (Std. Dev.)</th>
<th>Density, kg/m³</th>
<th>Average (Std. Dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.280</td>
<td>1.39, (0.057)</td>
<td>1277</td>
<td>1390, (57.12)</td>
</tr>
<tr>
<td>2</td>
<td>1.400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.390</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.394</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flange</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.581</td>
<td>1.59, (0.013)</td>
<td>1577</td>
<td>1587, (13.22)</td>
</tr>
<tr>
<td>2</td>
<td>1.610</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.588</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.584</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.1. Tensile Test Setup

Figure 5.2. Shear Test Setup
Figure 5.3. Apparent Shear Strength Setup

Figure 5.4. Failure Modes – Apparent Shear Strength Test

Delamination, chopped fibers on compression

Delamination, Tension failure, chopped fibers on tension
CHAPTER 6
CONCLUSIONS

The load test of two FRP beams (beam I and II) described in this report provided important information regarding the strength, stiffness and failure modes characteristics of this wet-lay up composite system. Material testing performed also provided information regarding the mechanical properties of the core and flange laminates. The results from this project will be used by NYSDOT in the design of a prefabricated FRP bridge superstructure. Main conclusions from this research project are presented next.

6.1. Flexure Test of Beam I

- The FRP beam tested under flexure configuration (Beam I) failed at a load of 330 kN by debonding of the top flange. At this load level, the maximum vertical deflection was obtained at midspan (121 mm). No major differences were observed between the deflection on the left side and the right side of the beam.
- The overall shape of the load vs. deflection and load vs. strain curves indicated that beam I had a linear behavior up to failure. The overall flexural stiffness (EI) of the FRP beam was found to be equal to $3.32 \times 10^{10}$ kN-mm$^2$.
- The contraction of the neoprene pads at the supports was less than 7% the midspan deflection at failure load. Therefore it did not affect the readings of vertical deflection for beam I.
- Lateral stability of beam I was achieved during the entire test up to failure. Displacement transducers did not register significant horizontal displacement neither significant relative vertical deformation at midspan.
- Maximum strains were recorded on the top flange at midspan. At the failure load of 330 kN the strain value was 5000 µå (only 30% the tensile strength of the flange laminate). The overall behavior of the curve shows a linear behavior up to failure. Strain gages placed at both sides of the interface between the core and the top flange at midspan registered maximum strain values of 3707 µå and 4244 µå respectively. At failure load, strain gages in rosette configuration registered shear strains ($\tilde{\alpha}_{xz}$) of 2080 µå for beam I. All the strain gage readings were lower than the corresponding material failure strain.

- Two types of failure mechanisms were observed in the flexure test of beam I. First, debonding of the external flat plate in the core was observed with increasing applied loads. This debonding process lead to local buckling of the plate near the right point load. The second failure mechanism determined the strength capacity of the FRP beam: the top flange debonded (starting from the right point load and propagating to the right end of the beam) from the interface and caused the entire core to buckle on both sides of the beam under the right point load. This type of failure was sudden and released a large amount of energy.

- It can be concluded that the failure mechanism of the debonding of the top flange is a brittle failure and it occurred before other failure mechanisms (such as tensile failure) could be triggered. Further study of this brittle type of failure is recommended.

6.2. Shear Test of Beam II

- Beam II failed by crushing of the core under the single point load (512 kN) applied at midspan. At this load level the corresponding average value of midspan deflection was 6.4 mm.

- At failure load, strain gages in rosette configuration registered shear strains values ($\tilde{\alpha}_{xz}$) between 2064 µå and 3533 µå for beam II well below the corresponding material shear failure strain.
• The overall shape of the load vs. strain curves indicated that beam II had a linear behavior up to failure.
• It was determined that strain gages located on either the top or bottom flange registered a larger strain than the corresponding strain gage located in the core.
• The controlling failure mechanism for beam II was crushing of the core under the point load. It was also noticed that the external flat plate of the core on the rear side buckled under the point load.
• It can be concluded that the vertical shear capacity of beam II exceeds its crushing core capacity. It is recommended that a new specimen should be designed and tested to determine the vertical shear capacity of the FRP beam. However, a conservative value of 256 kN could be assumed for design purposes.

6.3. Material Testing

• The value of the panel flexural stiffness determined following ASTM C393-4 (2.66x10^{10} \text{kN-mm}^2) was 80\% the one found from the experimental test of beam I (3.32x10^{10} \text{kN-mm}^2).
• The value of the panel shear rigidity (following ASTM C393-4) was 6.85 \times 10^5 \text{kN}.
• Both the core and the flange laminate tensile coupons exhibited linear elastic behavior up to failure.
ACOUSTIC EMISSION MONITORING RESULTS

INTRODUCTION

Acoustic emission (AE) is widely used in the monitoring of several different types of fiber reinforced plastic (FRP) structures. Its main advantage lies in the broad coverage of the method and the ability of creating evaluation and monitoring schemes based on the standard load profile of the structure. Other applications include pre-selected loading profiles to be implemented on the new or, in service structure in order to determine not only its current condition, but also the likelihood of impending failure. Newer developments in AE have been associated with the location of the damage area in the structure and the identification of damage type based on the digital record of the AE signals. These are still in the research/development cycle, but results and implementations are beginning to appear in the field [1].

In its most common form, AE has been mostly a statistical comparison tool. Comparing levels of emission of a healthy structure against those of damaged ones and extracting differences in their signatures for later use as evaluation benchmarks. Figure A.1 shows the most common parameters used in the evaluation of AE records. Of particular interest in most standards are the maximum amplitude of the signal, the duration of the wave and the signal strength. Other elements of the wave have lost implementation in the process as the result of being too dependent on the sensor more than the material. The two most common applications are in the area of pressure vessels and railroad tank cars. In both cases, the evaluations are made based on statistical comparisons of the level of emissions recorded during a particular type of test. These emissions are then evaluated against the benchmarks and the structure is deemed worthy of continued service or selected for suspension and further inspection.

Because of this implementation, results from single tests cannot be conclusive. A larger number of tests are required to build the benchmarks that are to be used in the inspection of a particular structure. Nevertheless, general trends that will be part of further monitoring of the same type of structure can be identified from one test.

EXPERIMENTAL SETUP

The test was a simple supported four point bending test of a deep FRP beam, as shown in the figure. Because of the unique nature of the test and the specimen, a predetermined loading profile was utilized for the AE monitoring. This loading profile was as shown in Figure A.2. In the figure, the darker like indicated the load as actually recorded from the load cells in the test. The lighter line indicated the corrected loading profile that will be used in the analysis of the data. Another point of interest is the note stating “system disconnect”. During the tests, the AE system was accidentally shut down, and although no data was lost, a system reboot was necessary creating false time compression as it is shown in the figure. The time window during the reboot was small enough that no correction was judged necessary to the data and the plot.
As it is noticeable in the plot, the loading profile contained a series of load holds and load drops during the test. These were selected for identification of features in the AE signature such as the Felicity Effect and Felicity Ratio as described by Fowler et al [2].

\[
\text{Felicity ratio} = \frac{\text{load at which AE is first observed on reloading}}{\text{previously applied maximum load}}
\]

The calculation of the Felicity Effect and its derivative, the Felicity Ratio allows for identification of the significance of the permanent damage generated in the structure as the result of loading. The load holds also permit the identification of permanent damage being generated in the form of emission during the load hold. The intensity of this emission during the load hold has been proved and accepted, as a clear indication of permanent damage generation. As we will see in the test results it does provide with some meaningful insight to the behavior of the FRP beam. Maximum load as recorded in one of the two load cells at the loading points was about 75 kips.

The equipment used was a Physical Acoustics Mistras AE-DAQ system. The system is capable of digitizing up to 8 channels of AE data simultaneously. The number of channels used for this test were 5 total. Sensors used were 2 resonant sensor at 150 kHz and 3 broadband sensors with flat response between 100 and 2100 kHz. The signals were preamplified with a single amplifier for each channel with a setting of 40dB. The placement of the sensors was as shown in Figure A.3. As seen in Figure A.3, a total of five sensors were used in the monitoring of the specimen. The location of the sensors was based on the most likely areas of failure based on the load and geometry. No sensors were placed in the bottom flange of the beam because of the expected brittle nature of the failure and the need to protect the integrity of the equipment. The locations were also non symmetrical with respect of the midspan to facilitate source location as required in the analysis. In addition, the sensors numbered 4 and 5 were placed in the web and not in the top flange since the expected failure at this location would be separation of web with respect to the flange. The sensors located in the top flange were the broadband piezoelectric, while those in the sides were the resonant sensors as described in the beginning of this section.

**TEST RESULTS**

Load, deflection and strain data collected by the University of Clarkson research team is shown in Figures 3.7 and 3.11 with permission from Dr. Maria del Mar Lopez at Clarkson. The strain records referenced here are for comparison purposes only and no inference is made to their significance. The reader is advised to go to the prior sections of this report by Clarkson for more information on this area.

It is clear that the behavior of the specimen was mostly linear throughout the loading history. This is of no surprise for specimens built with composite materials where connections to other structures are either non-critical or non-existing. This is not to say that the internal connections between components in the element do not play a role, but their degradation is not as apparent as in the case of element connections. As it was observed in the tests, this internal connection degradation was the main cause of failure but was not apparent in the strain or deflection records as seen in this plot.

**ACOUSTIC EMISSION DATA**

The records from all the sensors used in the monitoring of the FRP beam are presented here. Figure A.4 shows the amplitude vs. time plot while Figure A.5 shows the calculated energy under the curve. In addition, it should be indicated the order in which the data is plotted. As indicated in the diagram of Figure A.3, the ends represented by channels 4 and 5 are referred to as right and left respectively. This
was the orientation as seen standing with the rest of the attendance to the test and not with the AE system location. Conversely, the middle right and left location were represented by sensor 3 and 4 respectively. Sensor one was located at midspan of the specimen and is referred to as middle sensor.

During the tests several audible indications were noted from the specimen. These were later confirmed to be associated with separation of the side web skins from the corrugations forming the web. These delaminations, or separations, occurred at load increases and were not typically noted during the load holds required for the AE. In addition to the overall records on amplitude and signal strength, isolated records for signal strength from each of the sensors is presented here (Figure A.6)

ANALYSIS AND CONCLUSIONS

The analysis of the data at this point is somewhat limited by the fact that only one specimen was tested at the site. In the case of fiberglass composites not to mention acoustic emission testing, it is necessary to have repeated specimens in order to minimize the random and irregular nature of the material. However, interesting trends were observed during the testing of this specimen and in the AE results obtained.

It is worth of note to review the nature of the failure recorded in the specimen. Deformation records during the test at midspan and in strain gages placed through the specimen showed little indication of imminent failure when compared to previous readings. The deformation profile as shown in the Clarkson report, shows a very linear behavior until failure and so does the strain record at midspan provided by Dr. Lopez in Clarkson and shown in this report.

From Figures A.4 and A.5, we can note a gradual increase of the acoustic emission starting at the recorded load of 40 kips. This is important because in tests performed by this researcher, it has been noted that the load of first emissions during load hold is typically associated with fatigue endurance limits for undamaged systems. This trend, although common in fiberglass systems tested by the researcher, cannot be verified here without fatigue tests performed in similar systems. Figure A.4 shows a very “quiet” system until the load of 40 kips was reached and at the same time emission during load holds were recorded. Although, immediate records during load holds after first emission is not a very typical trend in FRP systems, it does not mean that the structural system was defective in any way. In the records, a heavy concentration of emissions is observed during the load increase sequences, and progressively increasing emission during load hold at each subsequent load hold. The lack of emissions observed during the first two load drops and holds, are indications that, in those cases, permanent damage had no been created. In contrast, at the their load drop and hold, after 70 kips, some emission is apparent during the hold. This is a clear indication of permanent damage been created in the structure in the previous loading levels.

Felicity ratio for this specimen is difficult to define because of some mechanical rubbing between the lateral skin and the ribs forming the web. This obscured emission during the load increases after the drops making it difficult to extract the information. Additional analysis is underway in an effort to eliminate the noise. However, the increase of the energy of the emission is apparent at the level of 70 kips in both the amplitude and the energy plots. It can be confirmed visually that, the energy increase, or slope of the signal strength plot, dramatically increased at 70 kips when compared to the previous load of 65 kips. This rate of change could be an indication of imminent failure for this system that can be verified with additional tests and monitoring in similar specimens.

Finally, from plots in Figures A.7 and A.8, it is noticeable that most of the signatures and emissions came from an area between the loading point and the right of the specimen. This agrees with the final
location of the failure zone. In addition, it indicates that no separation was apparent between web and flange at the ends of the structure. This would seem to indicate that the final failure was initiated by buckling of the web in the middle right area of the beam and followed by the separation of the flange from the web, also at the right end. The five separate signal strength plots in Figure A.6 also support this observation.

CONCLUSIONS

From the records of a single specimen is difficult and not advisable to draw definite conclusion in terms of AE signatures. However, general trends were observed that support observations made during and after the test of the beam. The most useful observations were in terms of load at first emission and change in signal strength as maximum load was approached. The possibility of determining an endurance load level for the system was also noted.

The AE records appear to support the conclusion that the failure zone originated in the middle right section of the specimen and propagated to the end from there. It also supports the possibility that failure was initiated by buckling of the web ribs followed by the separation of the flange to the web.

Additional studies are necessary in order to determine benchmarks that would be useful in the life monitoring of the bridge using AE based system. With the development of such benchmarks, it would be a simple task to develop a field-monitoring program for determination of structural condition during service. This is a step that is advisable due to the innovative nature of the project and the need of keeping complete records of its short and long term performance in the field.

REFERENCES

**Figure A.1 Common AE Evaluation terms**

- **Voltage**
- **Time**
- **First Threshold Crossing**
- **Duration**
- **Last Threshold Crossing**
- **Rise Time**
- **Positive Threshold**
- **Negative Threshold**
- **Area under “Envelope” = Signal Strength**

Approx. 6.7µsec for 150 kHz

- **First Threshold Crossing**
- **Last Threshold Crossing**
- **Amplitude**
- **Rise Time**
- **Duration**
- **Each Threshold Crossing = One Count**

**Figure A.2 Loading Profile**

- **Load Profile**
- **Rounded Profile**
- **System disconnect**
Figure A.3 Sensor Location

Figure A.4 Amplitude vs. Time plot for all sensors
**Figure A.5** Signal Strength plot for all channels

**Figure A.6** Signal Strength Plot per Location
Figure A.7 AE Records for both End Sections

Figure A.8 AE Records for Middle Sections
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