

**TESTING OF FULL-SIZE  
REINFORCED CONCRETE BEAMS  
STRENGTHENED WITH FRP COMPOSITES:  
EXPERIMENTAL RESULTS AND  
DESIGN METHODS VERIFICATION**

**Final Report**

**SPR 387**



*Oregon Department of Transportation*



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by

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| 16. Abstract<br><br>In 1997, a load rating of an historic reinforced concrete bridge in Oregon, Horsetail Creek Bridge, indicated substandard shear and moment capacities of the beams. As a result, the Bridge was strengthened with fiber reinforced polymer composites as a means of increasing load-carrying capacity while maintaining the historic appearance. Because composites were a relatively new construction material in infrastructure projects, subsequent tests were conducted to verify the design used on the Bridge. Four full-size beams were constructed to match the dimensions and strength capacity of the Bridge crossbeams as closely as possible. One of these beams was used as the control, while the other three beams were strengthened with various composite configurations including the same configuration used on the Bridge crossbeams. The beams were loaded in third point bending to determine their capacity. The beam strengthened with the same composite design used on the Bridge could not be broken with loading equipment used. Based on the maximum loads applied, the Bridge beams have at least a 50% increase in shear and a 99% increase in moment capacity over the unstrengthened condition. Design calculations show the Bridge beams now exceed the required shear and moment capacities. |  |  |  |   |           |
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## SI\* (MODERN METRIC) CONVERSION FACTORS

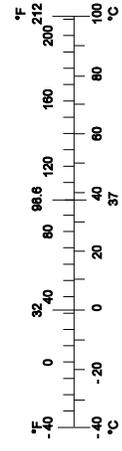
### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol          | When You Know          | Multiply By                       | To Find             | Symbol          |
|-----------------|------------------------|-----------------------------------|---------------------|-----------------|
|                 |                        | <b><u>LENGTH</u></b>              |                     |                 |
| In              | Inches                 | 25.4                              | millimeters         | mm              |
| Ft              | Feet                   | 0.305                             | meters              | m               |
| yd              | Yards                  | 0.914                             | meters              | m               |
| mi              | Miles                  | 1.61                              | kilometers          | km              |
|                 |                        | <b><u>AREA</u></b>                |                     |                 |
| in <sup>2</sup> | square inches          | 645.2                             | millimeters squared | mm <sup>2</sup> |
| ft <sup>2</sup> | square feet            | 0.093                             | meters squared      | m <sup>2</sup>  |
| yd <sup>2</sup> | square yards           | 0.836                             | meters squared      | m <sup>2</sup>  |
| ac              | Acres                  | 0.405                             | hectares            | ha              |
| mi <sup>2</sup> | square miles           | 2.59                              | kilometers squared  | km <sup>2</sup> |
|                 |                        | <b><u>VOLUME</u></b>              |                     |                 |
| fl oz           | fluid ounces           | 29.57                             | milliliters         | mL              |
| gal             | gallons                | 3.785                             | liters              | L               |
| ft <sup>3</sup> | cubic feet             | 0.028                             | meters cubed        | m <sup>3</sup>  |
| yd <sup>3</sup> | cubic yards            | 0.765                             | meters cubed        | m <sup>3</sup>  |
|                 |                        | <b><u>MASS</u></b>                |                     |                 |
| oz              | ounces                 | 28.35                             | grams               | g               |
| lb              | pounds                 | 0.454                             | kilograms           | kg              |
| T               | short tons (2000 lb)   | 0.907                             | megagrams           | Mg              |
|                 |                        | <b><u>TEMPERATURE (exact)</u></b> |                     |                 |
| °F              | Fahrenheit temperature | 5(F-32)/9                         | Celsius temperature | °C              |

NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>.

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol          | When You Know       | Multiply By                       | To Find              | Symbol          |
|-----------------|---------------------|-----------------------------------|----------------------|-----------------|
|                 |                     | <b><u>LENGTH</u></b>              |                      |                 |
| mm              | millimeters         | 0.039                             | inches               | in              |
| m               | meters              | 3.28                              | feet                 | ft              |
| m               | meters              | 1.09                              | yards                | yd              |
| km              | kilometers          | 0.621                             | miles                | mi              |
|                 |                     | <b><u>AREA</u></b>                |                      |                 |
| mm <sup>2</sup> | millimeters squared | 0.0016                            | square inches        | in <sup>2</sup> |
| m <sup>2</sup>  | meters squared      | 10.764                            | square feet          | ft <sup>2</sup> |
| ha              | hectares            | 2.47                              | acres                | ac              |
| km <sup>2</sup> | kilometers squared  | 0.386                             | square miles         | mi <sup>2</sup> |
|                 |                     | <b><u>VOLUME</u></b>              |                      |                 |
| mL              | milliliters         | 0.034                             | fluid ounces         | fl oz           |
| L               | liters              | 0.264                             | gallons              | gal             |
| m <sup>3</sup>  | meters cubed        | 35.315                            | cubic feet           | ft <sup>3</sup> |
| m <sup>3</sup>  | meters cubed        | 1.308                             | cubic yards          | yd <sup>3</sup> |
|                 |                     | <b><u>MASS</u></b>                |                      |                 |
| g               | grams               | 0.035                             | ounces               | oz              |
| kg              | kilograms           | 2.205                             | pounds               | lb              |
| Mg              | megagrams           | 1.102                             | short tons (2000 lb) | T               |
|                 |                     | <b><u>TEMPERATURE (exact)</u></b> |                      |                 |
| °C              | Celsius temperature | 1.8 + 32                          | Fahrenheit           | °F              |



\* SI is the symbol for the International System of Measurement

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# **1.0 INTRODUCTION**

## **1.1 SIGNIFICANCE OF THE RESEARCH**

Nearly 40 percent of the bridges in the United States and Canada are structurally deficient (Cooper 1991, FHWA 1993, Rizkalla & Labossiere 1999, FHWA 2000). Structural elements composed of concrete and reinforcing steel are frequently rated as inadequate due to load conditions beyond the capacity of the original designs. In addition, degradation such as corrosion and fatigue has reduced the capacity of many structures. External post-tensioning, addition of steel plating and total replacement have been the traditional methods used to meet the need for increased load capacity.

In recent years, fiber reinforced polymers (FRP) have been used to increase the capacity of reinforced concrete structural elements. Fiber reinforced polymers are typically comprised of high strength fibers (e.g. aramid, carbon, glass) impregnated with an epoxy, polyester, or vinyl ester resin (often termed the matrix). As this study showed, the addition of these materials can dramatically change the load capacity as well as the failure mechanism of reinforced concrete beams.

Experimental studies have been conducted using FRP reinforcing on both beams and columns. Field application of FRP is common, but a complete understanding of the behavior of reinforced concrete (RC) beams retrofitted with FRP is still lacking. This study investigated the bending behavior by way of strain and deflection of full-size beams in more detail than any previously known study.

## **1.2 HORSETAIL CREEK BRIDGE**

The Oregon Department of Transportation (ODOT) is currently undertaking an ongoing effort to load rate all state and local agency owned bridges. Bridge evaluation is required by the Federal Highway Administration, which partially funds state and local bridge construction projects.

The load rating process involves careful inspection and rating of each structural element in a bridge according to prescribed methods. The lowest rated bridge member determines the rating for the bridge. If the bridge is determined deficient, the bridge owner is required to either retrofit, replace, or post the bridge.

Horsetail Creek Bridge, shown in Figures 1.1 and 1.2, is located east of Portland, Oregon along the Historic Columbia River Highway. It was designed and constructed by K.S. Billner and opened to traffic in 1914. The structure is an 18.3 m (60 ft) long simple 3-span reinforced concrete slab-beam-column structure. The length and width of each span is 6.1 m (20 ft). A photograph of the original bridge is shown in Appendix A.

The Horsetail Creek Bridge beams were constructed without shear reinforcement (required by current standards and knowledge of RC beam behavior). Shear reinforcement inhibits the development of diagonal tension cracks (shear cracks). Once formed, these cracks can propagate quickly and result in a sudden failure before full flexural capacity of the beam is achieved. For this reason, a minimal amount of reinforcement (usually steel stirrups) must be provided (ACI 318-99). Adequate spacing in high shear regions enables the reinforcement to effectively mitigate diagonal tension cracking.

Load rating of Horsetail Creek Bridge identified flexural and shear Rating Factors of  $RF = 0.5$  and  $RF = 0.06$ , respectively (CH2M HILL, 1997). An RF value less than 1 indicates a deficient structure. The exceptionally low rating factor for shear was due to the lack of shear stirrups, which required the load-rating engineer to use only the concrete section to resist the induced shear forces. The details of the load rating, including selected calculations, are presented in Appendix B. It should be noted that visual inspection revealed minimal signs of distress or environmental degradation. Only a few locations of exposed steel under the bridge railing and curb were visible.



Figure 1.1: Horsetail Creek Bridge (1998, prior to retrofit)

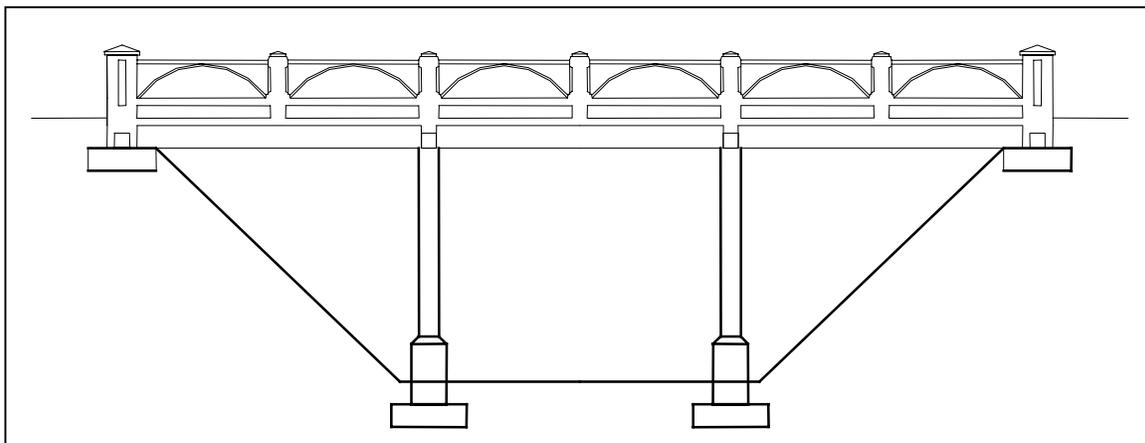


Figure 1.2: Elevation of Horsetail Creek Bridge (No. 04543)

As a consequence of the load rating, the Bridge was strengthened to an HS20 truck loading capacity using glass and carbon FRP. Of the strengthening options considered, FRP provided the required strength improvement and maintained the historic appearance of the Bridge.

### **1.3 PURPOSE OF THE STUDY**

This study examined the increased load capacity as the result of FRP added to inadequate RC beams. In addition, this study investigated the bending behavior of reinforced concrete beams retrofitted with FRP by examining deflection and strain as a function of load. Laboratory testing was conducted on full-size beams that closely represented the Horsetail Creek Bridge beams in order to accomplish the following:

- To verify that the retrofit scheme used to strengthen the Horsetail Creek Bridge was sufficient for the traffic loads; and
- To provide experimental data to validate finite element models being developed in another research project.

A secondary objective was to evaluate the effectiveness of a fiber optic strain sensing system for monitoring strain in FRP strengthened beams. Under a separate study, fiber optic strain sensors were installed on Horsetail Creek Bridge to monitor static, dynamic and long-term load response. This project was part of a continuing effort to use fiber optic sensors for structural health monitoring.



## 2.0 TEST SETUP

### 2.1 BEAM CONSTRUCTION AND PROPERTIES

Four full-scale beams with similar geometry and rebar placement as the Horsetail Creek Bridge crossbeams were constructed in the Oregon State University laboratories. Figure 2.1 shows the beam dimensions and the location of the rebar. There were three main flexural steel bars extending the full length and two bars that bent up to reinforce negative moment regions of the beam. Smaller diameter bars were positioned near the compression face of the beam.

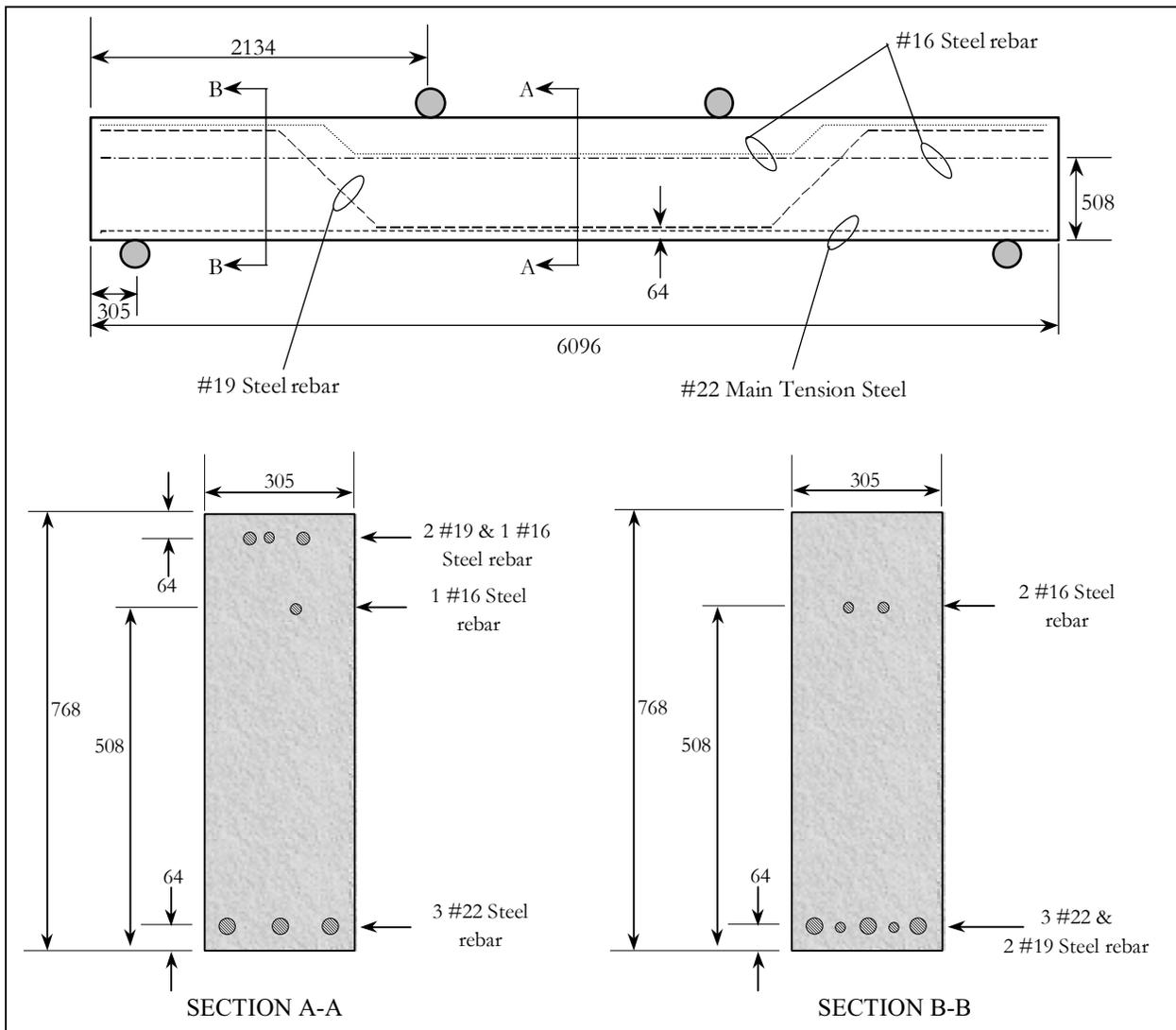


Figure 2.1: Position of steel reinforcement in all beams. Dimensions and rebar sizes are in mm.

The beams were designed to match the strength rather than the serviceability of the Horsetail Creek Bridge beams. For load rating purposes, AASHTO specifies the concrete strength of a bridge constructed before 1959 to be 2500 psi (17.2 MPa) and the steel yield stress to be 33,000 psi (228 MPa) (AASHTO, 1994). Concrete and steel are not readily available at these low strength levels. In an effort to construct beams with similar ultimate strength as the Horsetail Creek Bridge beams, reinforcement bars with smaller cross-sectional areas, Table 2.1, were used to account for the higher yield strength of today's steel. Design calculations for the beams are provided in Appendix B.

**Table 2.1: Steel reinforcement details**

| Standard Bar Size | Metric Bar Size | Steel Area                                     | Location of Reinforcement  |
|-------------------|-----------------|--|--|
| #5                | #16             | 0.31 in <sup>2</sup><br>(200 mm <sup>2</sup> ) | Straight and bent steel above elastic neutral axis. Derived from bridge deck reinforcement |
| #6                | #19             | 0.44 in <sup>2</sup><br>(280 mm <sup>2</sup> ) | Bent reinforcement used for positive and negative moment reinforcement.                    |
| #7                | #22             | 0.60 in <sup>2</sup><br>(390 mm <sup>2</sup> ) | Straight positive moment reinforcement bars present in all bridge beams.                   |

The four beams were cast and cured separately under similar conditions. Type I ready-mix concrete with nominal 28-day strength of 3000 psi (20.7 MPa) and 6 in (152 mm) slump was used. The beams were cast in the same form to ensure the dimensions were as similar as possible. Each beam was cured in a moist condition until removed from the form 7-14 days after pouring. Ambient conditions during casting and curing did not vary significantly from beam to beam.

After curing, three of the four full-size beams were strengthened with FRP. A description of each beam is given in Table 2.2, and the FRP configurations are shown in Figure 2.2. The Control, Flexure-Only, Shear-Only, and Shear and Flexure beams will be referred to as the Control Beam, F-Only Beam, S-Only Beam, and S&F Beam in this report. Table 2.3 shows the material properties used for analysis, which are based on established design values.

**Table 2.2: Experimental beam description<sup>1</sup>**

| Beam            | Description  |
|-----------------|--|
| Control         | Reinforced concrete beam with no shear stirrups and no FRP reinforcement |
| Flexure-only    | Control beam with added flexural carbon FRP reinforcement                |
| Shear-only      | Control beam with added shear glass FRP reinforcement                    |
| Shear & Flexure | Control beam with added shear and flexural reinforcement                 |

<sup>1</sup>See also Figure 2.2.

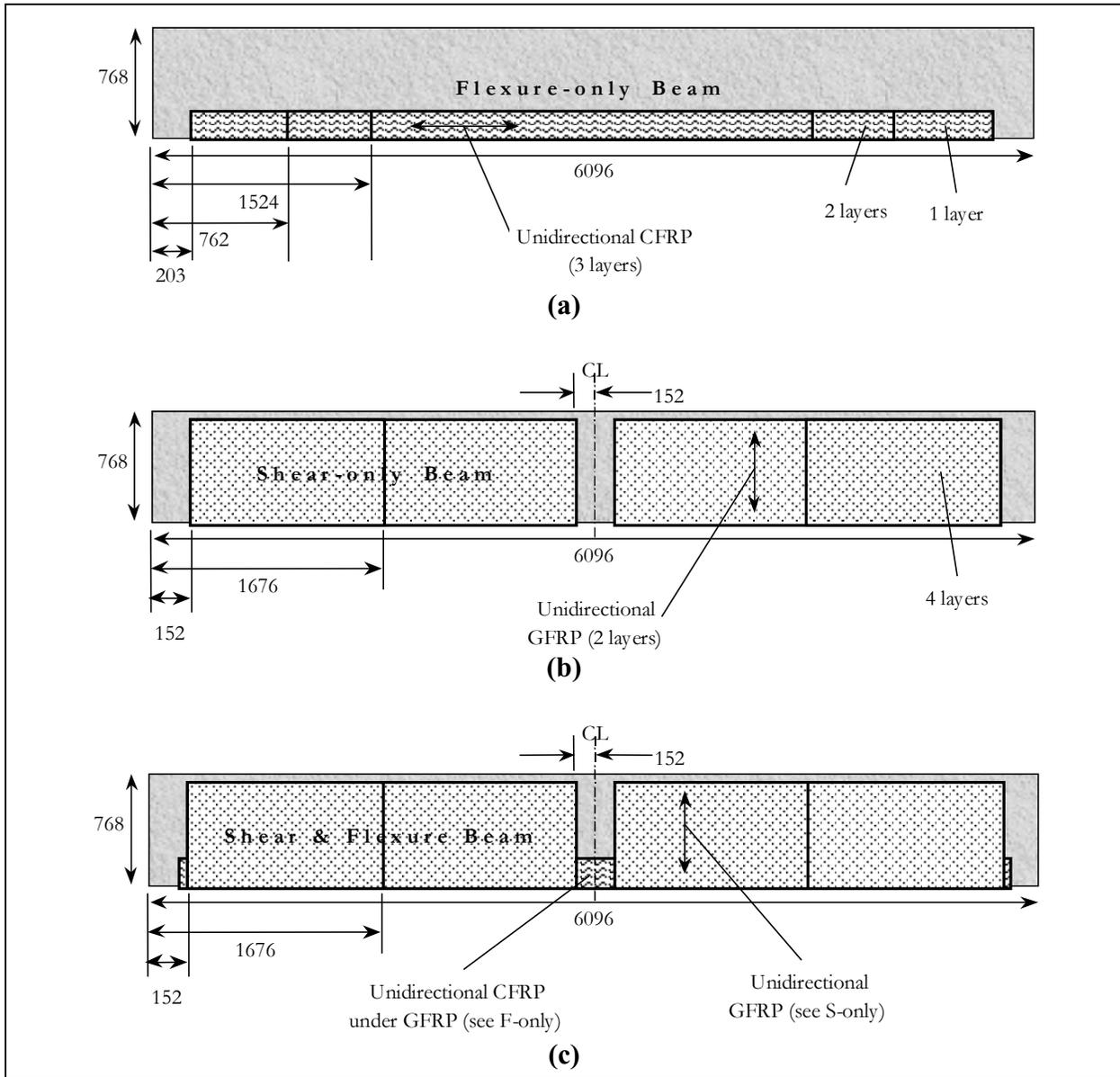


Figure 2.2: FRP-strengthened experimental beams. The flexural and shear FRP composites were wrapped continuously around the bottom of the beam. All dimensions in mm.

**Table 2.3: Design material properties**

| Material                  | Limiting Stress        | Limiting Strain | Limit State | Elastic Modulus                     |
|---------------------------|------------------------|-----------------|-------------|-------------------------------------|
| Concrete<br>(Compression) | 3000 psi<br>(20.7 MPa) | 0.003           | Crushing    | 3120 ksi <sup>1</sup><br>(21.5 GPa) |
| Steel<br>Reinforcement    | 60 ksi<br>(414 MPa)    | 0.002           | Yielding    | 29,000<br>(200 GPa)                 |
| Glass FRP                 | 60 ksi<br>(414 MPa)    | 0.02            | Rupture     | 3000 ksi<br>(20.7 GPa)              |
| Carbon FRP                | 110 ksi<br>(760 MPa)   | 0.012           | Rupture     | 9000 ksi<br>(62 GPa)                |

<sup>1</sup>Design elastic modulus from  $E_c=57,000(f_c')^{1/2}$ .

### 2.1.1 Concrete Modulus Determination

Efforts were made to accurately determine the actual elastic moduli of the beams so that a correct estimation of beam stiffness could be made. A correlation was made between pulse velocity and compressive elastic modulus (ASTM 1983, 1994). From this work, it was determined that each beam possessed a slightly different elastic modulus, as shown in Table 2.4. The elastic moduli calculated from cylinder strengths were too high in comparison to the elastic moduli determined from design 28-day strength and the pulse velocity measurements.

**Table 2.4: Elastic modulus results from pulse velocity correlation<sup>1</sup>**

| Beam            | Average Measured Pulse Velocity (km/s) | Elastic Modulus from Correlation |
|-----------------|--|----------------------------------|
| Control         | 3.72                                   | 2,810,000 psi<br>(19.3 GPa)      |
| Flexure-only    | 3.53                                   | 2,550,000 psi<br>(17.6 GPa)      |
| Shear-only      | 3.60                                   | 2,630,000 psi<br>(18.2 GPa)      |
| Shear & Flexure | 3.48                                   | 2,480,000 psi<br>(17.1 GPa)      |

<sup>1</sup> Correlation between ASTM C 469 and ASTM C 597 was conducted.

## 2.2 TESTING AND DATA COLLECTION

Details about data acquisition and the equipment used are found in Appendices C & D. A summary of the testing and data acquisition methods is presented below.

### 2.2.1 Beam Loading

All beams were tested in third-point bending as shown in Figure 2.3. No restraint was provided against rotation along any axis. Supports did not provide any fixity aside from friction due to normal forces. Thus, the beams could be analyzed as simply-supported beams. All beams spanned 18 ft (5.49 m) with a shear-span of 6 ft (1.83 m).

A 600 kip (2670 kN), internal-frame, hydraulic press with a load cell was used to load the beams. This machine was designed to compress test specimens by transferring all forces into its own frame. For beams that spanned beyond the frame of the machine (the situation for the beams in this project), the maximum applied force was limited to 160 kip (712 kN). This constraint was not known until after the project was initiated.

### 2.2.2 Data Collection

Deflection data were collected from three locations using direct current displacement transducers (DCDTs) as shown in Figure 2.3. A dial gauge was placed in the same longitudinal location as DCDT 2 to verify midspan deflection.

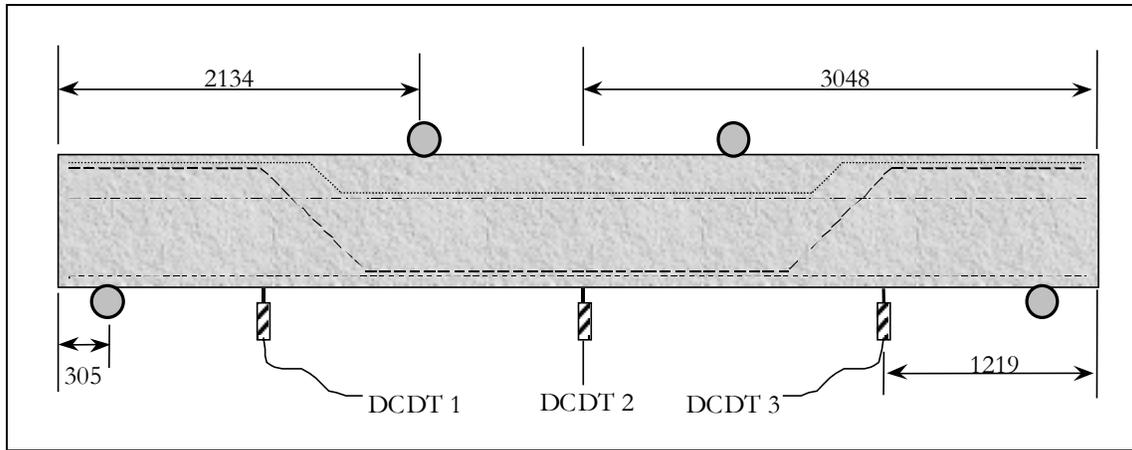


Figure 2.3: DCDT locations. Dimensions in mm.

Resistance strain gauges with a 2.36 in (60 mm) gauge length were placed at select sites throughout the beam. Strain data were collected at the midspan section and two sections in the shear zone as shown in Figure 2.4. Other important strains were collected as needed. Gauges were placed on the concrete surface, on the FRP surface, or inside the beam on the steel. Fiber optic gauges were installed only on the three FRP-reinforced beams in the positions shown in Figure 2.5. The fiber optic gauges were monitored by Blue Road Research<sup>1</sup> during the tests.

In order to ensure data collection systems were properly responding to applied loads, three cycles up to 15 kip (67 kN) were made. The load cycling helped to identify “noisy” and inadequate data collection channels in addition to providing more data for finite element models being developed under a separate project.

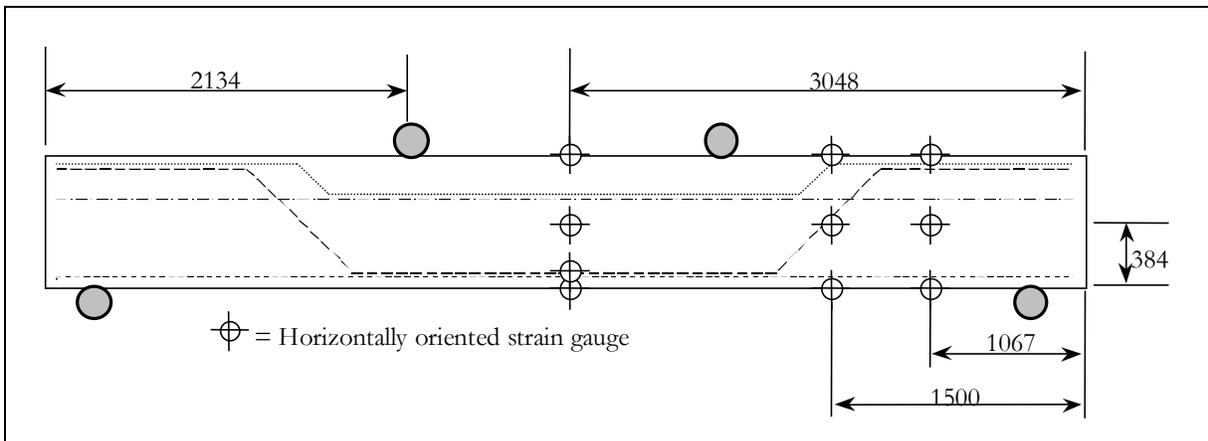


Figure 2.4: Typical locations of resistance strain gauges. Dimensions in mm.

<sup>1</sup> 2555 NE 205<sup>th</sup> Avenue, Fairview, Oregon 97024. See: [www.bluerr.com](http://www.bluerr.com)

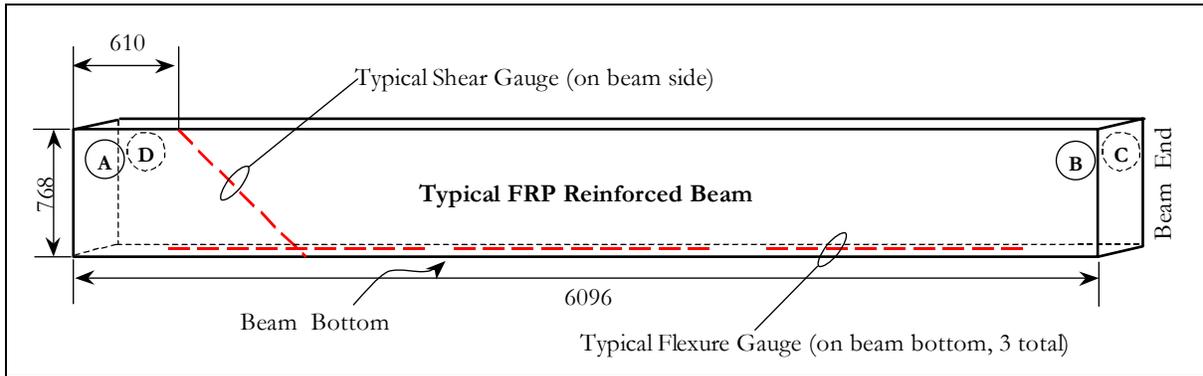


Figure 2.5: Locations of fiber optic strain gauges. Dimensions in mm.

Cracking was documented during the testing. Only the Control Beam and to a lesser degree, the F-Only Beam, provided a good map of the cracks because the S-Only and S&F Beams were wrapped with FRP laminates on the sides. Appendix C gives a complete description of visible cracking patterns. For this experimental study, crack widths were not measured.

## 3.0 EXPERIMENTAL RESULTS

### 3.1 SUMMARY OF LOAD AND DEFLECTION

The Control, F-Only and S-Only beams were loaded to failure. The failure modes are shown in Table 3.1. The S&F Beam was loaded to 160 kip (712 kN), the capacity of the testing equipment, and held for several minutes without failing. The S&F Beam was reloaded to 160 kip (712 kN) with the load points positioned 2 ft (51 mm) apart to increase the applied moment and again held at this load for several minutes. There was no indication of imminent failure.

**Table 3.1: Beam failure modes**

| Beam            | Failure Mode   |
|-----------------|--|
| Control         | Diagonal tension crack (shear failure)   |
| Flexure-only    | Diagonal tension crack (shear failure)   |
| Shear-only      | Yielding of tension steel followed by crushing of compression concrete after extended deflections  |
| Shear & Flexure | No failure observed. Believed to be yielding of tension steel followed by crushing of the concrete. FRP rupture might occur after significant deflections due to failure of the concrete |

A summary of the capacity and deflection results is presented in Table 3.2. A load of 15 kip (67 kN) was selected for comparing deflection, and hence stiffness, before first significant cracking. First significant cracking is indicated by the sudden change in slope at approximately 20 kip. Stiffness after first significant cracking was calculated from the slope of the load-deflection curve after cracking.

Figures 3.1 to 3.4 show the load vs. deflection plots for the four beams. Midspan deflection for the S-Only Beam went beyond the range of the DCDT2. Consequently, part of the plot is shown as an extrapolated line. For all plots used in this study, the applied moment at the midspan in kip-ft is always three times the applied load in kip based on the relationship  $M=PL/3$  where P is  $\frac{1}{2}$  the total applied load and L is the span length. The applied moment in kN-m is 0.914 times the load in kN. The applied shear is  $\frac{1}{2}$  the applied load.

**Table 3.2: Summary of load and deflection**

| <b>Item</b>   | <b>Control</b>             | <b>Flexure-Only</b>       | <b>Shear-Only</b>                | <b>Shear &amp; Flexure</b>            |
|---|----------------------------|---------------------------|----------------------------------|---------------------------------------|
| Midspan Deflection at 15 kip (67 kN)                    | 0.0465 in<br>(1.18 mm)     | 0.0480 in<br>(1.22 mm)    | 0.0489 in<br>(1.24 mm)           | 0.0435 in<br>(1.10 mm)                |
| Stiffness After First Significant Cracking <sup>1</sup> | 115 kip/in<br>(20.1 kN/mm) | 139 kip/in<br>(24.3 kN/m) | 134 kip/in<br>(23.5 kN/m)        | 150 kip/in<br>(26.3 kN/m)             |
| Midspan Deflection at Steel Yield <sup>2</sup>          | Did Not Yield              | Did Not Yield             | 0.896 in<br>(23 mm)              | Did Not Yield                         |
| Maximum Observed Deflection                             | 0.963 in<br>(24.5 mm)      | 1.193 in<br>(30.3 mm)     | 1.390 in<br>(35 mm) <sup>3</sup> | 1.000 in<br>(25 mm)                   |
| Midspan Deflection at Failure                           | 0.963 in<br>(24.5 mm)      | 1.193 in<br>(30.3 mm)     | 2.00 in<br>(51 mm) <sup>3</sup>  | Did Not Fail <sup>4</sup>             |
| Load at First Significant Cracking <sup>1</sup>         | 17.6 kip<br>(78.3 kN)      | 21.7 kip<br>(96.5 kN)     | 19.7 kip<br>(87.6 kN)            | 21.6 kip<br>(96.1 kN)                 |
| Load at Failure   | 107 kip<br>(476 kN)        | 155 kip<br>(689 kN)       | 155 kip<br>(689 kN)              | Did Not Fail <sup>4</sup>             |
| Applied Moment at Yield <sup>2</sup>                    | Did Not Yield              | Did Not Yield             | 360 kip-ft<br>(488 kN-m)         | Did Not Yield                         |
| Maximum Applied Moment <sup>4</sup>                     | 321 kip-ft<br>(435 kN-m)   | 465 kip-ft<br>(630 kN-m)  | 465 kip-ft<br>(630 kN-m)         | 480 kip-ft<br>(651 kN-m) <sup>5</sup> |
| Maximum Applied Shear                                   | 53.5 kip<br>(234 kN)       | 77.5 kip<br>(345 kN)      | 77.5 kip<br>(345 kN)             | 80.0 kip<br>(356 kN)                  |

<sup>1</sup>First significant cracking is indicated by the first slope change of the load-deflection plot.

<sup>2</sup>Primary tension reinforcement only yielded in the S-Only Beam.

<sup>3</sup>Extrapolated.

<sup>4</sup>S&F Beam was not loaded to failure due to equipment limitations.

<sup>5</sup>A second loading of the S&F Beam achieved a total applied moment of 640 kip-ft (868 kN-m).

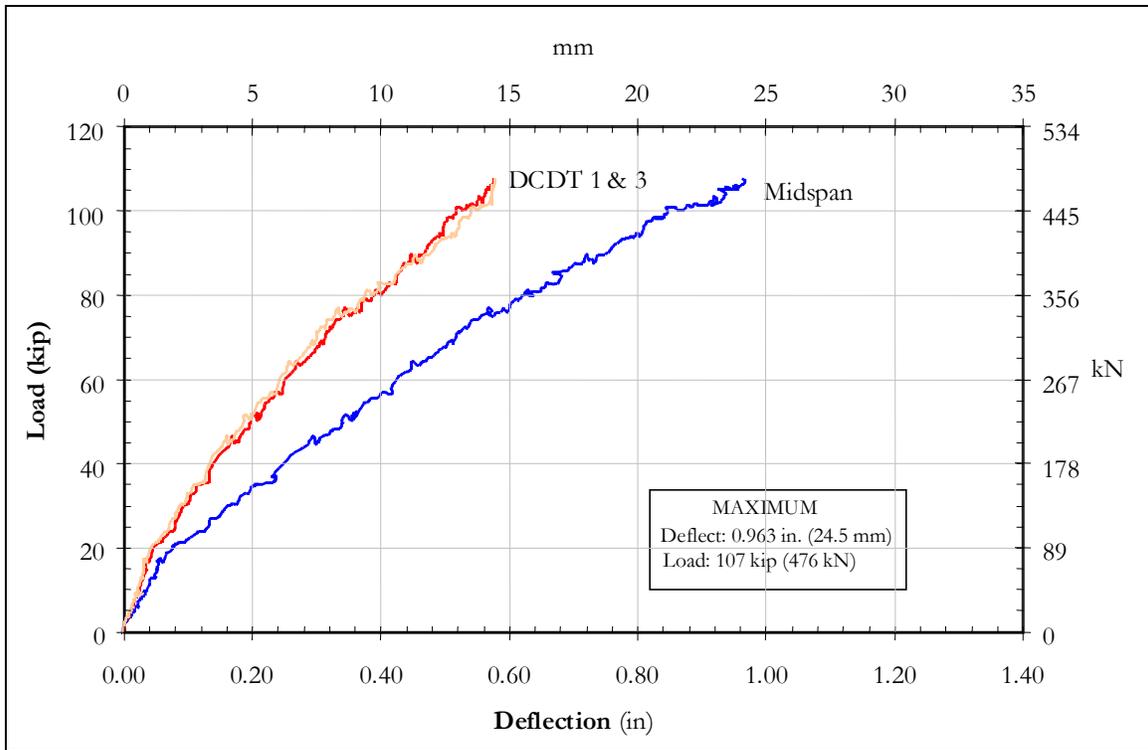


Figure 3.1: Load vs. deflection for the Control Beam

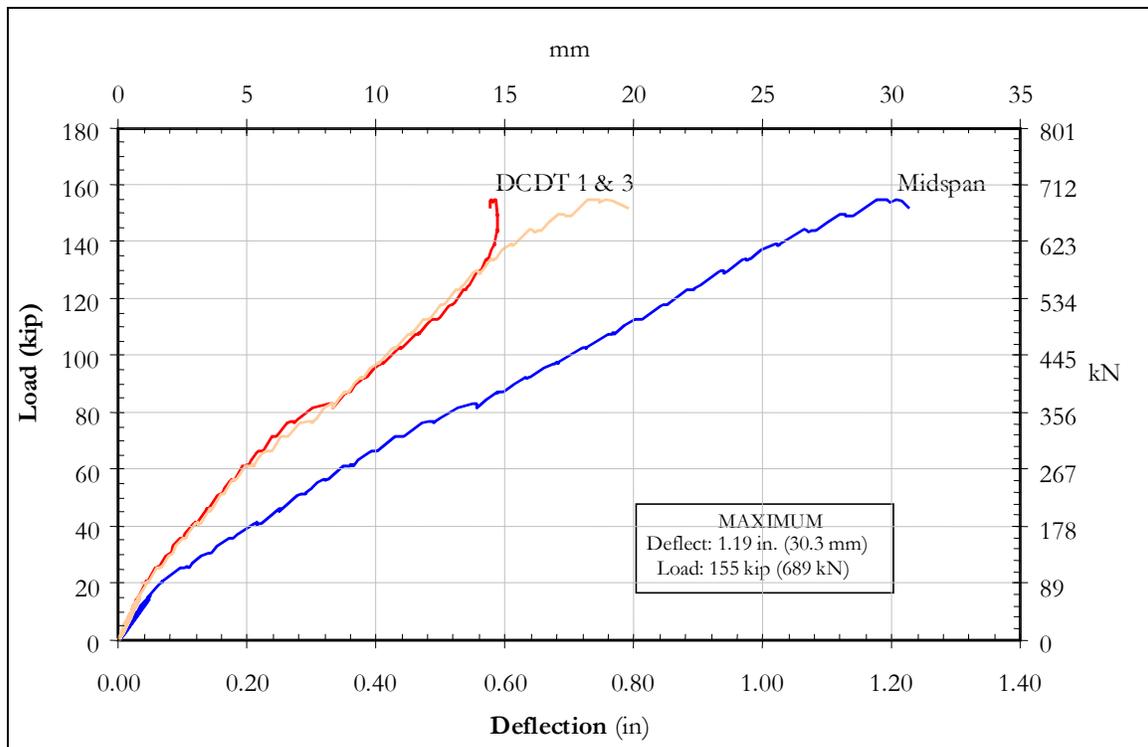


Figure 3.2: Load vs. deflection for the Flexure-Only Beam

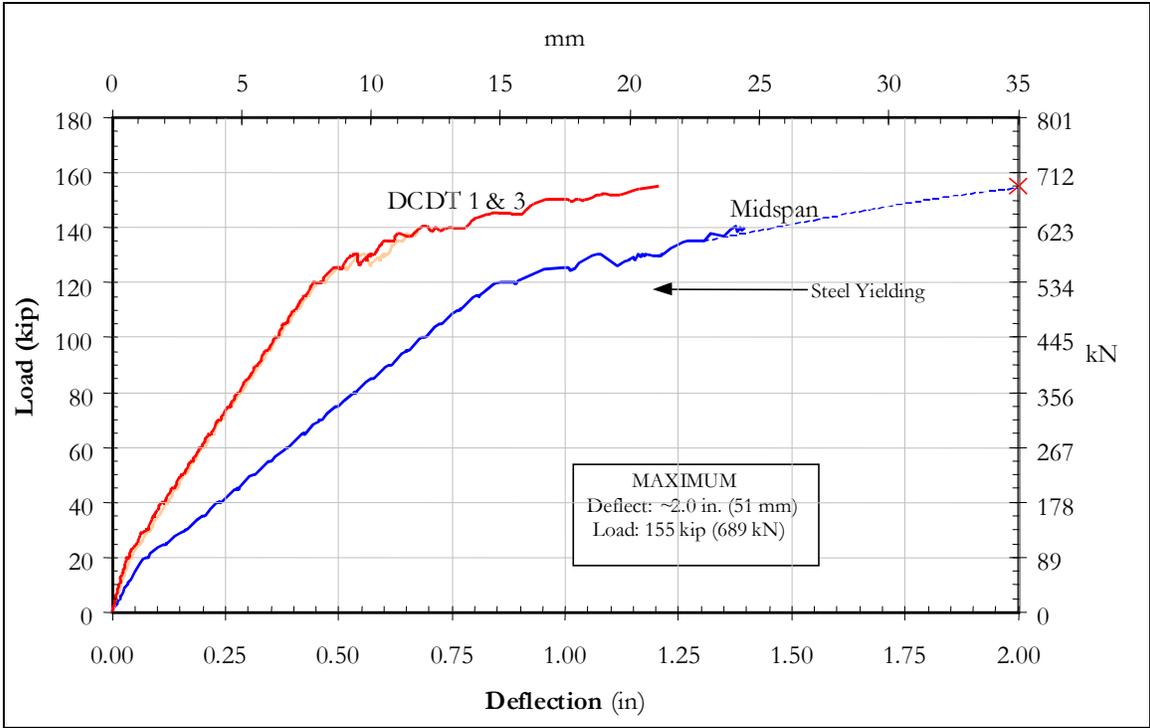


Figure 3.3: Load vs. deflection for the Shear-Only Beam

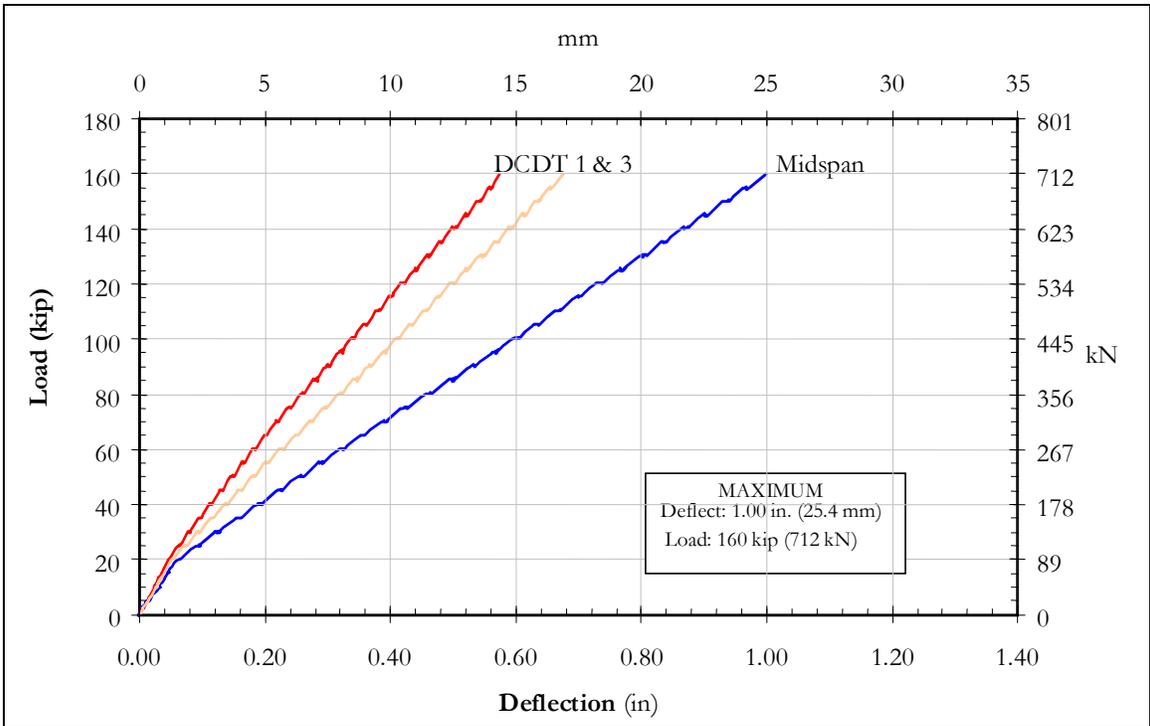


Figure 3.4: Load vs. deflection for the S&F Beam (beam did not fail)

### 3.2 STRAIN DATA

Appendix C presents the load vs. strain data. Figures 3.5 to 3.8 provide midspan strain as a function of load for the four beams. The steel yielding in the S-Only Beam is indicated in Figure 3.7. Figure 3.8 shows the strain in the tension steel reinforcement of the S&F Beam had just exceeded the design limit strain of 0.002. Consequently, the anticipated failure mode for the S&F Beam was flexural failure characterized by steel yielding followed by concrete crushing.

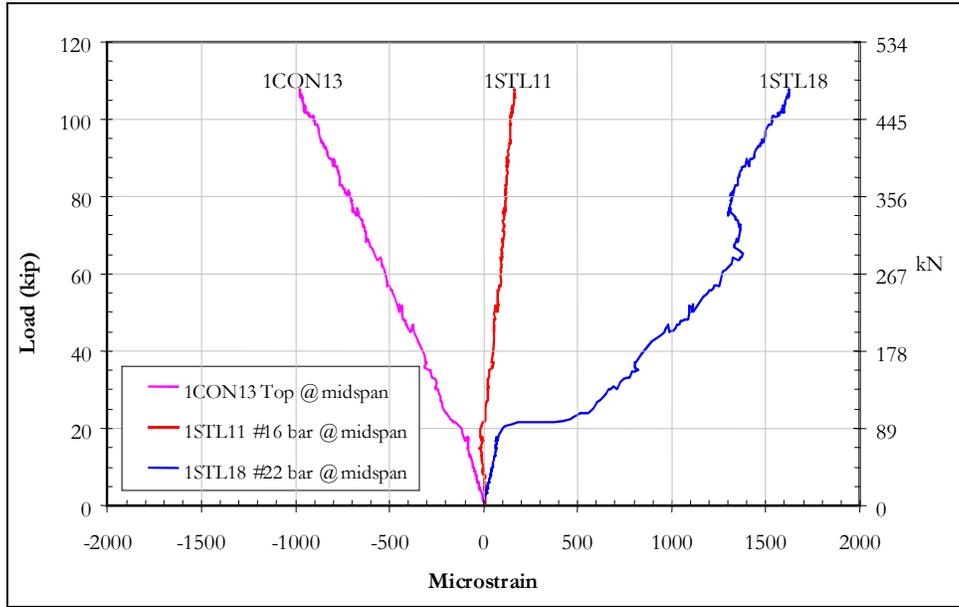


Figure 3.5: Control Beam load vs. strain at midspan

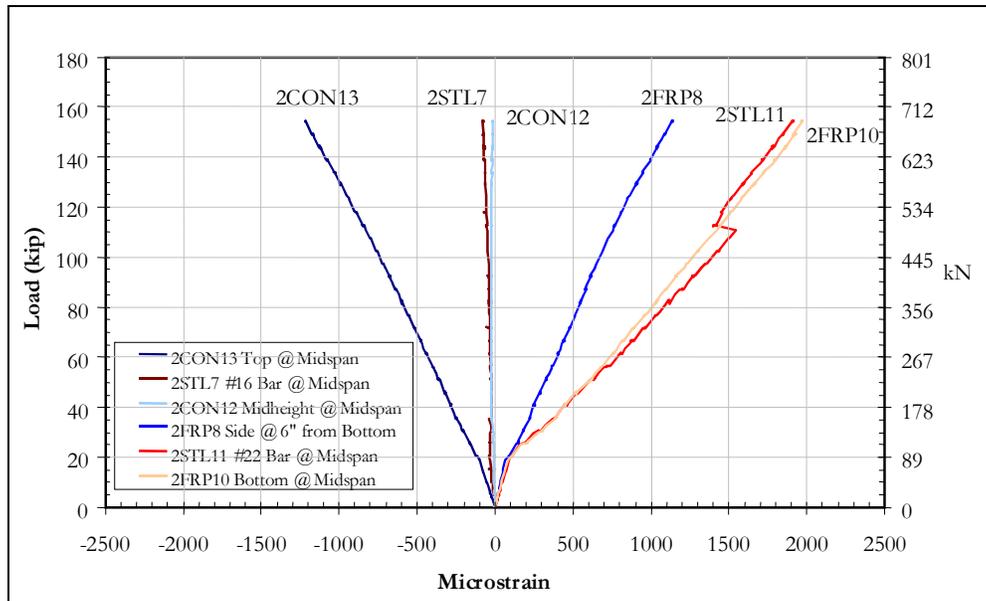


Figure 3.6: F-Only Beam load vs. strain at midspan

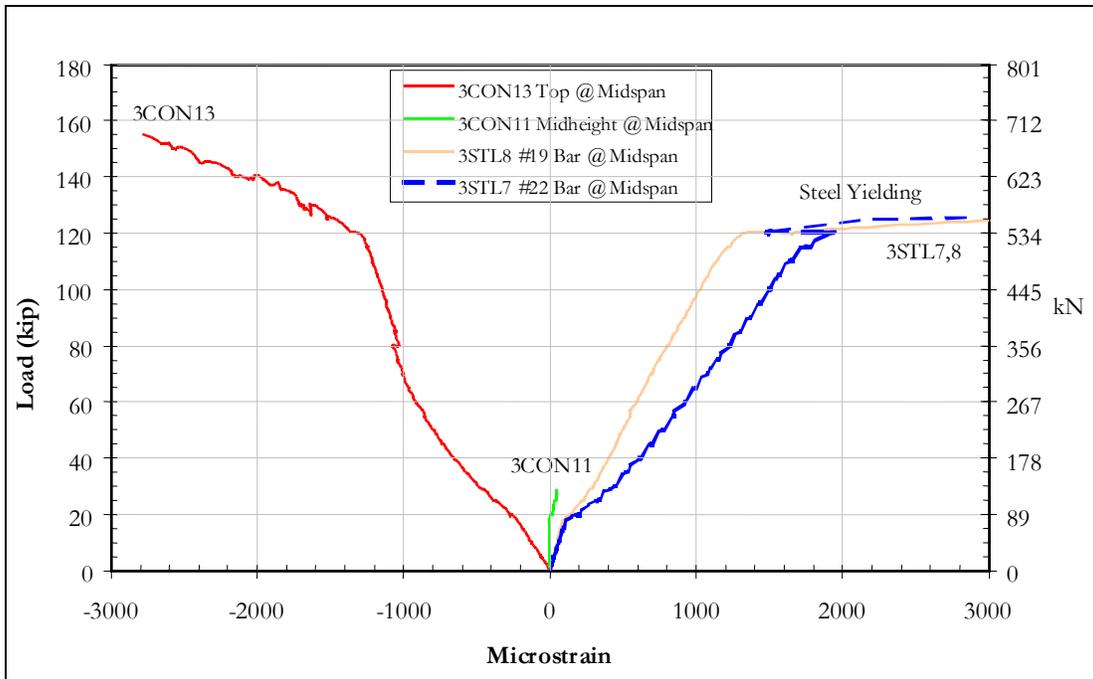


Figure 3.7: S-Only Beam load vs. strain at midspan

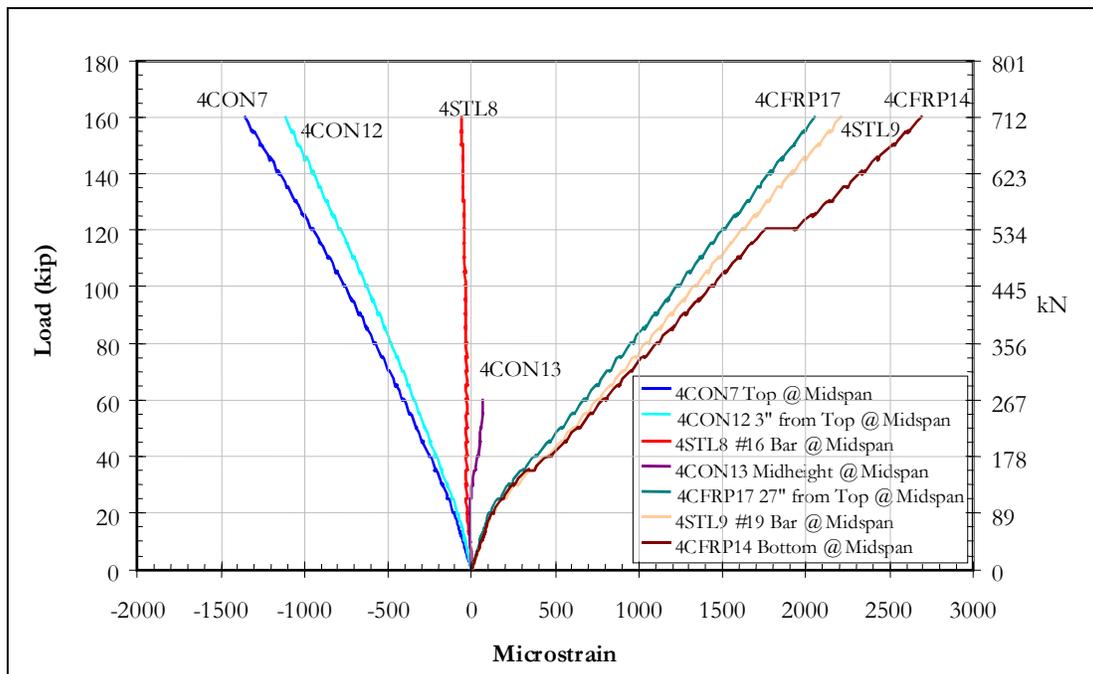


Figure 3.8: S&F Beam load vs. strain at midspan

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