CFRP STRANDS FOR FLEXURAL STRENGTHENING OF STEEL BRIDGES

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ABSTRACT

This paper explores the use of Carbon fiber reinforced polymer (CFRP) material for strengthening of steel bridges. The research work includes an experimental program to study the effectiveness of using very small diameter CFRP strands, configured in a sheet format, for strengthening of steel structures. The experimental program includes scaled steel-concrete composite beams strengthened with this material at the bottom flange of the steel beams to increase the flexural capacity. The parameters that were considered in the experimental program were the type of CFRP, reinforcing ratio and type of loading. The two types of CFRP materials that were examined for strengthening are High Tensile CFRP and High Elastic Modulus CFRP material. The three types of loading investigated were Static, Cyclic and Fatigue loadings. Test results were used to determine the most effective strengthening system. The selected system was tested under fatigue and cyclic loading. This paper describes the experimental program, presents test results, including the failure modes, and provides guidelines for the design of flexural strengthening system for steel structures.

INTRODUCTION

Several researches have been reported recently on strengthening of steel structures using variety of methods (references 1, 2, 3 and 4). The goal of these researches was to explore the most efficient and effective strengthening system that can be used for steel structural members. Corrosion of steel structural members due to environmental conditions and increase in live loads are the main reasons for requirement of strengthening systems. Conventional strengthening systems such as using steel bars and plates as a reinforcement for steel members are common in current practice but these methods have several disadvantages including the heavy weight of steel plates which makes them hard to handle in addition to their low corrosion resistance. Recently, few researches explored the use of FRP materials for strengthening steel structures. FRP strengthening systems are light, easy to handle and have a relatively less tendency to corrode. Some of the researches have focused on key parameters that could affect the behavior of FRP strengthening systems for steel structural members. At North Carolina State University, two research programs were conducted to study the effect of externally bonded
CFRP laminates on the stiffness and the ultimate flexural strength of the steel-concrete composite beams. This paper explores a new type of carbon fiber reinforced polymer material for strengthening these types of beams. The new material provides solution to the problems related to the use of CFRP laminates in the earlier studies.

MATERIAL PROPERTIES

The CFRP material used for flexural strengthening is produced by Nippon Steel and Sumikin Materials Company, Japan. The two types of CFRP used for strengthening are High Tensile (HT) CFRP and Intermediate Modulus (IM) CFRP. Several tensile coupons were made from the strand sheets and were tested to evaluate the properties of CFRP materials. Table 1 presents the tensile properties of CFRP materials.

<table>
<thead>
<tr>
<th>CFRP Type</th>
<th>Strand Area</th>
<th>Ultimate Strain</th>
<th>Load Per Strand</th>
<th>Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Tension</td>
<td>1.0323 mm²</td>
<td>0.017 mm/mm</td>
<td>2362 N</td>
<td>134600 MPa</td>
</tr>
<tr>
<td>Intermediate Modulus</td>
<td>0.9548 mm²</td>
<td>0.0098 mm/mm</td>
<td>2117 N</td>
<td>226286 MPa</td>
</tr>
</tbody>
</table>

In order to evaluate the development length of the high tensile CFRP material, six double strap joints strengthened with one layer of the high tensile CFRP strands on each side were tested in tension using an MTS machine. The epoxy used for strengthening was “FB-E9” resin and hardener which was also provided by Nippon & Sumikin Steel Company. The measured ultimate load versus the bonded length relationships of the double strap joints are shown in Figure 1. Test results suggest that the development length of the high tensile CFRP strands is approximately of 280 mm.

![Figure 1: Ultimate Load versus the Bonded Length of the Double Strap Joints](image-url)
FLEXURAL TEST SPECIMENS

A total of eight specimens were tested under three types of loading in this research program. Figure 2 shows the typical cross section used for all of the specimens. All tested specimens were 3.35 m long, tested with a clear span of 3 m and subjected to two point loads at the mid span as shown in Figure 3. The fatigue test specimen was loaded using an actuator as shown in Figure 4. The fatigue test specimen was loaded with a frequency of 1.55 Hz using an 890 KN actuator. The minimum fatigue load was selected to be 10 percent of the ultimate load whereas the maximum fatigue load was selected to be the maximum of the yield load of the unstrengthened beam, $F_{yu}$, and 80 percent of the yield load of the strengthened beam, $F_{ys}$. The specimen was loaded up to two million cycles in fatigue testing then it was loaded statically to failure using same test setup.

![Figure 2: Cross Sectional View of a Test Specimen](image-url)
STRENGTHENING PROCESS

The bottom surface of the tension flange for all of the steel beams was sand blasted and strengthened while the specimens were elevated to simulate field conditions. The length of the first layer of strand sheets was 2.9 m long while the length of each additional CFRP sheet was shortened by 152.5 mm from both sides to avoid possible stress concentrations as shown in Figure 5. Details of the tested beams are given in Table 2.
### Table 2: Test Specimens Details

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Number of Layers</th>
<th>CFRP Type</th>
<th>Loading Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0-C</td>
<td>-</td>
<td>-</td>
<td>Static</td>
</tr>
<tr>
<td>S3-HT</td>
<td>3</td>
<td>High Tensile</td>
<td>Static</td>
</tr>
<tr>
<td>S4-HT</td>
<td>4</td>
<td>High Tensile</td>
<td>Static</td>
</tr>
<tr>
<td>S3-IM</td>
<td>3</td>
<td>Intermediate Modulus</td>
<td>Static</td>
</tr>
<tr>
<td>S4-IM</td>
<td>4</td>
<td>Intermediate Modulus</td>
<td>Static</td>
</tr>
<tr>
<td>S4-HT-IM</td>
<td>3,4</td>
<td>HT &amp; IM</td>
<td>Static</td>
</tr>
<tr>
<td>S4-HT-C</td>
<td>4</td>
<td>High Tensile</td>
<td>Cyclic</td>
</tr>
<tr>
<td>S4-HT-F</td>
<td>4</td>
<td>High Tensile</td>
<td>Fatigue</td>
</tr>
</tbody>
</table>

### TEST RESULTS

The load-deflection behaviors of all tested specimens tested under static loading are shown in Figure 6. All strengthened specimens showed a significant increase of the flexural strength in comparison to the control specimen. Results show that the test specimens strengthened with the high tensile CFRP strands have higher deflection at failure in comparison to the beams strengthened with the intermediate modulus CFRP strands.

![Figure 6: Load-Deflection Comparisons of Specimens Tested under Static Loading at Mid-span](image)

Test results show that the specimens strengthened with the intermediate modulus CFRP strands have a higher flexural stiffness compared to the ones strengthened with the high tensile CFRP strands.

The percentage increase of the measured ultimate flexural capacity in comparison to the control specimen is shown in Figure 7.
Strengthening with Intermediate modulus CFRP strands provided more increase in the pre-yielding and the post-yielding flexural stiffness due to their relatively higher elastic modulus. However, the failure mode for these specimens (S3-IM, S4-IM & S4-HT-IM) was brittle in nature. Specimens S3-HT and S4-HT, strengthened with high tensile CFRP, showed ductile behaviors. Adding the intermediate modulus CFRP strand sheets to the web of specimen S4-HT-IM did not significantly improve the behavior considering the high strengthening ratio used for specimen S4-HT-IM.

Examining the behavior of all tested Specimens, it was clear that the strengthening system used for Specimen S4-HT was the optimal system since it provided a significant increase in the flexural strength while showing a ductile behavior. The failure mode was crushing of the concrete slab which is the desired failure mode for typical steel-concrete composite beams. As a result, specimen S4-HT was selected to be tested under cyclic and fatigue loading.

The load-deflection behaviors of specimens S4-HT & S4-HT-C, tested under cycling loading, are shown in Figure 8. The load-deflection behavior indicates that specimen S4-HT-C has approximately the same behavior as specimen S4-HT, tested under static loading. The slight differences in the behavior could be attributed to possible creep of the concrete slab due to the cycling loading. In general, test results indicated that the selected HT-CFRP strengthening system was effective for cyclic loading.
The load-Deflection behaviors of specimen S4-HT-F, subjected to fatigue loading, and specimen S4-HT, tested under static loading, are shown in Figure 9. The difference in the behaviors could be due also to the fatigue creep in the concrete slab. Test results indicated that the selected strengthening system was effective also for fatigue loading.

**SHEAR LAG PHENOMENA**

Typical load-strain behavior of the steel bottom flange versus the high tensile CFRP material is shown in Figure 10. Typical load-strain behavior of the steel bottom flange versus the Intermediate Modulus CFRP material is
shown in Figure 11. Detailed information of all tested beams is given in reference (5). No shear lag was observed for the specimens that were strengthened with the high tensile CFRP material. However, the behavior clearly indicates that there is a shear lag between intermediate modulus CFRP material and steel after yielding of the steel, due to the difference in the drastic modules of the CFRP and the steel. No shear lag was observed under the effect of cyclic and fatigue loading since HT-CFRP was used for these tests as shown in Figure 12 and Figure 13, during fatigue testing followed by static testing to failure, respectively.

Figure 10: Load-Strain Diagram of Steel Bottom Flange and CFRP Strands of Specimen S3-HT

Figure 11: Load-Strain Diagram of the Steel Bottom Flange and the CFRP Strands of Specimen S3-IM
FAILURE MODES

Failure mode for the beams strengthened with HT-CFRP strengthening system was crushing of the concrete slab, which is the favorable failure mode for reinforced concrete structures, as shown in Figure 14. However, the beams strengthened with IM-CFRP material failed due to rupture of the CFRP strands as shown in Figure 15.
Primarily, moment-curvature analyses were adopted for the analysis of each specimen. In order to perform moment-curvature analyses, the following assumptions were made:

- Plain sections remain plain after deformation therefore the strain profile of the section is linear for all loading stages
- The CFRP material is perfectly elastic material with a linear stress-strain relationship up to failure
- The steel is elastic-plastic material
• The thickness of the CFRP materials is relatively small compared to the overall dimensions of the section; therefore its effect in increasing the moment of inertia of the strengthened section is neglected
• The CFRP tensile force is assumed to be applied at bottom surface of the flange of the cross section

The load-deflection behavior of the specimens was calculated based on the predicted moment-curvature behavior for each specimen. The predicted load-deflection behaviors versus the measured load-deflection behaviors of specimens are provided in Figure 16 and Figure 17 for beams strengthened with high tensile CFRP and Intermediate Modulus CFRP, respectively. It is clear that the analysis is not valid for the specimens strengthened with the intermediate modulus CFRP strands due to the presence of shear lags after yielding of the steel bottom flange as shown in Figure 17. The strain profile of a typical specimen strengthened with HT-CFRP is shown in Figure 18 which is linear up to failure. The strain profile of a typical specimen strengthened with Intermediate Modulus CFRP material is shown in Figure 19 which shows clearly the shear lag after yielding of the steel bottom flange.

![Figure 16: Load-Deflection Diagram for Specimens S3-HT & S4-HT](image-url)
SUMMARY AND CONCLUSIONS

This paper presents an innovative strengthening system for steel structures and bridges. The proposed system includes a new material and new configuration of a carbon fiber reinforced polymer, CFRP, which is believed to have quite an advantage over current strengthening techniques and materials presented in the literature. The research findings are based on an experimental program conducted on eight scaled typical steel-concrete composite sections used for bridges. Configuration of the CFRP material used in this research consists of small diameter strands provided in a sheet format to simplify the installation process. Based on the measured results, the most effective strengthening system was the high tensile CFRP strengthening system. The main findings of the research program are summarized below:

1. Proper design of HT-CFRP material lead to crushing of the concrete in the compressive zone which is the most favorable mode of failure
2. Using an appropriate design, debonding of the CFRP material can be totally eliminated
3. Intermediate and high elastic modulus of CFRP material can cause shear lag after yielding of the steel, due to the significant difference of its elastic modulus in comparison steel.
4. Use of CFRP strengthening systems delays the yielding of steel to higher load levels.

Figure 17: Load-Deflection Diagram of Specimens S3-IM & S4-IM

Figure 18: Strain Profile of S3-HT

Figure 19: Strain Profile of S3-IM
5. No shear lag was observed for high tensile CFRP strengthening system under the effect of cyclic and fatigue loadings.

REFERENCES


