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ENHANCING PLASTIC HINGE BEHAVIOR IN STEEL FLEXURAL MEMBERS USING CFRP WRAPS

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SUMMARY

Carbon fiber reinforced polymer (CFRP) composites have been shown to be particularly well suited for external strengthening of reinforced concrete members. However, there is limited information about how they can be used to strengthen steel structures. This paper presents test results of four steel flexural specimens subjected to reversed cyclic loading, two of which are wrapped with CFRP in the plastic hinge region. The main variables investigated are fiber orientation and wrapping scheme. Test results show that application of CFRP can significantly improve overall structural behavior and suggest that CFRP wrapping can be used in new construction or to effectively upgrade existing structures in regions of high seismic risk.

INTRODUCTION

The use of carbon fiber reinforced polymers (CFRP) for repair and strengthening of concrete structures has been gaining in popularity over the past two decades. Extensive research has shown that externally bonded CFRP material in the form of sheets or plates is particularly well suited for flexural and shear strengthening of deficient reinforced concrete (RC) girders and confinement of RC columns. CFRP plates are attached to the bottom surface of beams while CFRP sheets are usually attached to the bottom surface or wrapped around the stem of RC beams using epoxy adhesives. For columns, the sheets are generally wrapped around critical areas to improve confinement and hence strength and ductility for seismic applications. Sheets are preferable to plates because they are easier to handle, and they do not peel off at the edges as easily when compared to the more rigid plates.

Studies that have been conducted to date have focused on the effect of CFRP rehabilitation on the stiffness, strength, ductility, mode of failure, long term performance and reliability of RC girders strengthened with CFRP (e.g. Ritchie [1], Saadatmanesh [2], Jones [3], Triantafillou [4], Shahawy [5], Arduini [6], Shahawy [7], El-Tawil [8], and Okeil [9]). The benefits of using CFRP to confine and improve the seismic behavior of RC columns, connections, slabs and walls (including masonry walls) are

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well documented in numerous papers, including Pantelides [10], Belarabi [11], Pantelides [12], Spoelstra [13], Lau [14], Mirmiran [15], Sadaatmanesh [16], etc. The results from these and other previous and ongoing studies are currently being crystallized into formal design procedures in the US through the efforts of ACI-440 Committee (ACI [17]). Some countries have recently published comprehensive design provisions for fiber reinforced polymer structures. Most prominent among these are the provisions in Section 16 of the Canadian Highway Bridge Design Code (CHBDC [18]) and the FRP Design Manual of the Japan Society of Civil Engineers (JSCE [19]).

In contrast to the extensive research focus placed on CFRP/concrete applications, there has been little research on the use of CFRP to strengthen steel and composite steel-concrete structures. Three recent studies have shown that FRP plates can be used to successfully strengthen steel girders in flexure (Sen [20], Miller [21], and Tavakkolizadeh [22]. In these studies, CFRP plates were attached to the bottom surface of steel girders to improve flexural strength. The rehabilitated girders showed a substantial increase in strength and stiffness, demonstrating the effectiveness of the method. Mosallam [23] investigated the use of CFRP T-sections to strengthen steel moment connections in seismic zones. They used the CFRP components in a haunch-like configuration but did not observe good performance because of early debonding at the steel/CFRP interface.

This paper presents the results of a study conducted to investigate whether the reversed cyclic response of steel plastic hinges can be improved by using CFRP. There are a number of important advantages offered by this type of strengthening technique. First, CFRP components are light, and can be easily positioned and then attached using epoxy adhesives. They are also resistant to corrosion, and thus they do not need extensive maintenance. Most importantly, field welding is not required, which avoids a host of associated problems, including 1) weld quality control; 2) difficulty of welding in tight locations; 3) introduction of unknown residual stresses; 4) weld cracking in the heat-affected zone; 5) significant reduction in low-cycle and high-cycles fatigue life, and 6) high cost. Other motivating factors for the study include: the use of CFRP reinforcement in the plastic hinge region of steel members can lead to relaxation in the stringent local slenderness and lateral torsional buckling limits that are imposed on members of special moment resisting frames; and the technology has the potential to be used in new construction as well as for seismic upgrading of existing structures.

In the experimental study discussed in this paper, the plastic hinge regions in two large-scale steel flexural members are wrapped with CFRP and the specimens are tested under reversed cyclic loading. The main variable investigated is the orientation and wrapping scheme of carbon fiber sheets. By comparing the behavior of the wrapped specimens to the response of control (i.e. unwrapped) steel specimens, conclusions are drawn about the effectiveness of CFRP strengthening. This paper describes the experimental program, presents experimental observations, and discusses the benefits of using CFRP to rehabilitate steel structures in regions of high seismic risk.

EXPERIMENTAL PORGRAM

Test Specimens

Two double channel built-up members with CFRP wraps in the plastic hinge region were tested to failure under reversed cyclic loading. The specimens were identical to two ‘baseline’ specimens tested by Kim [24] in a previous investigation at the University of Michigan. These latter specimens were unwrapped and serve as control specimens. Built-up double channel members are often used in seismic resistant steel structures, such as in braced frames or truss moment frames (Figure 1), where they can be subjected to large ductility demands.

Each of the four specimens discussed in this paper consisted of a reusable base beam made of two tube sections welded together, a gusset plate (254-mm x 610-mm x 32-mm), and a double channel built-up cantilever member (Figure 1). Each test specimen is representative of a truss chord in the special segment of a truss moment frame as shown in Figure 1. The cantilever member was connected to the base beam through a gusset plate fillet welded to the base beam tubes. As shown in Figures 1 and 2, the bottom parts of the channel webs were cut out to permit more extensive fillet welding in the connection region. Kim [24] observed that such a connection detail reduced demands in the connection region and improved cyclic performance. The dimensions for the test specimens are shown in Figure 1.

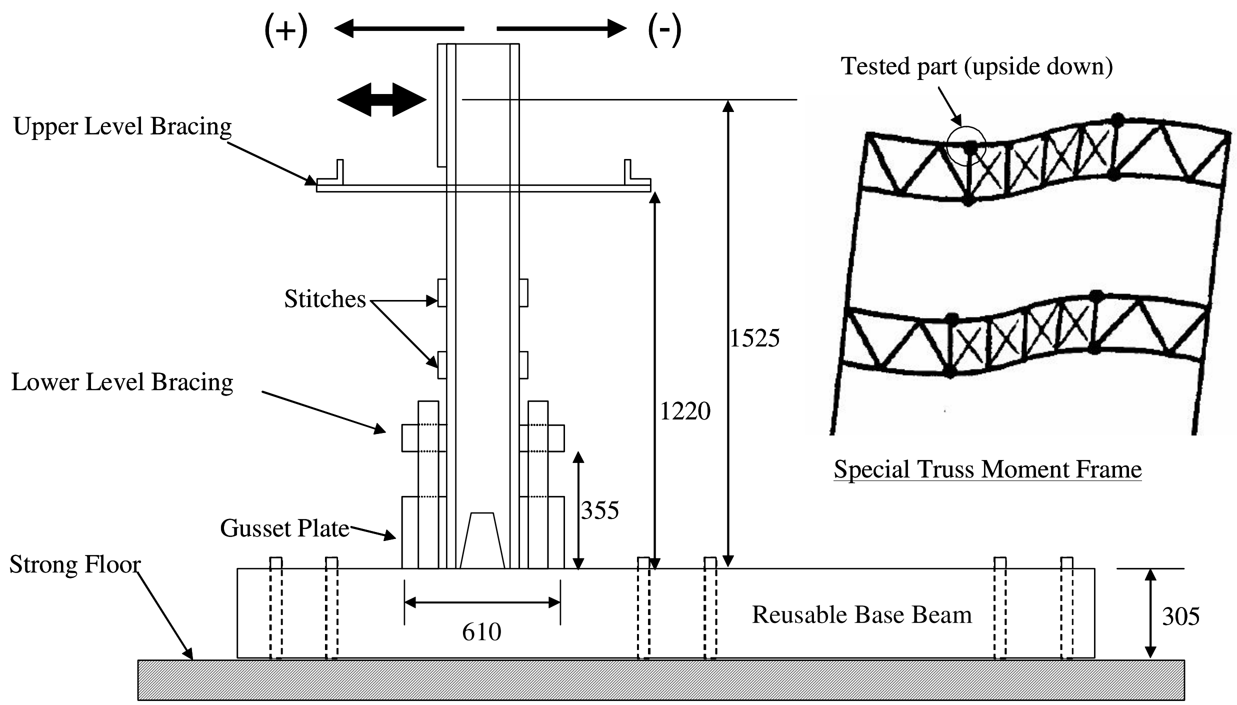


Figure 1. Test setup (dimensions are in millimeters)

The control specimens are designated C10x25 and C12x20.7 based on channel section types, while the corresponding specimens with CFRP wrapping are designated C10x25W and C12x20.7W. Table 1 summarizes the structural details of all four specimens. The double channel cantilevers in specimens C10x25 and C10x25W each had three stitches along the height, as shown in Figure 1. The clear spacing between the gusset plate and the first stitch as well as that between the first and second stitches was 150 mm whereas it was 165 mm between the second and third stitches. The first stitch plates were extended on both sides to pass in between two tubes welded to the base beam on either side of the specimen. The purpose of the extended stitch plates (the 'lower level bracing' designation in Table 1 and Figure 1) was to provide out-of-plane bracing for the plastic hinge region. The cantilever was also braced in the out-of-plane direction at another point close to the actuator. This 'upper level bracing' was achieved by connecting the specimen to a parallel support frame system through a brace that could slide in the loading direction along the parallel support frame.

For the C12x20.7 and C12x20.7W specimens, only one stitch is provided along the height. at 865 mm above the base. Unlike the C10x25 specimens, both C12x20.7 specimens were only braced at the upper level, through a system similar to that described above, i.e. there was no bracing at the level of the plastic hinge region.

Table 1. Test Matrix

Specimen	Built-up Member	Stitch	Bracing	CFRP Wrap
C10x25	MC10x25	3 stitches at 355 , 585 & 825 mm from base	Lower Level & Upper Level Bracing	no wrapping
C10x25W	C10x25	3 stitches at 355 , 585 & 825 mm from base	Lower Level & Upper Level Bracing	4 longitudinal layers on flanges at plastic hinge region
C12x20.7	C12x20.7	One stitch at 865 mm from base	Upper Level Bracing	no wrapping
C12x20.7W	C12x20.7	One stitch at 865 mm from base	Upper Level Bracing	6 layers (3 long. 3 trans.) from base to stitch level

Surface Preparation

Surface preparation for both specimens was conducted following the instructions of the adhesive epoxy and CFRP suppliers. The steel surface was first grinded to clean the surface and then sanded using 80 and 120 grit sandpapers to achieve a uniform surface. Just before application of the CFRP wrap, the surface was cleaned with a degreaser. After cutting the CFRP sheets to the required length, the first layer of the epoxy resin was applied to the surface, after which the first layer of CFRP was attached to the steel surface. After waiting for 20-30 minutes, another layer of epoxy was applied, and the second CFRP layer was attached. After the wrapping process was completed, the specimens were allowed to cure for one week.

Wrapping Scheme

The wrapping scheme for both specimens is shown in Figure 2. For Specimen C10x25W, the CFRP sheets were just attached to the bottom portion of the channel flanges, i.e. in the plastic hinge region. The fibers in the CFRP sheets were aligned along the length of the cantilever. Four sheets were used in the wrapping scheme. The sheets were terminated at different points to reduce stress concentration at the end point and to improve force transfer between the CFRP and steel. The first layer was 370 mm high from the base whereas the others are 330, 290, and 255 mm, respectively. Each layer started 12 mm above the bottom end of the previous layer.

Unlike C10x25W where only the flanges were wrapped, wrapping for C12x20.7W was applied all around the section including the gusset plate up to the first stitch, which was located at 865 mm from the base. A total of six layers of CFRP sheets were used. The fibers in three of the sheet were aligned in the longitudinal direction, while fibers in the remaining three sheets were aligned in the transverse direction.

Material Properties

Dual Grade A36/A572-Grade 50 steel was used for all steel members. The CFRP sheets used in the tests are unidirectional high strength carbon fiber fabrics. The properties obtained from the manufacturer for the CFRP sheets are as follows: tensile modulus is 227 GPa, ultimate tensile strength is 3800 MPa, maximum elongation at failure is 1.67%; and net carbon area is 0.165 sq. mm per mm of width. The epoxy resin was obtained from the same manufacturer. The properties of the epoxy as reported by the supplier are summarized in Table 2.

Table 2. Properties for the resin

	Yield Strength (MPa)	Strain at Yield (%)	Elastic Modulus (MPa)	Ultimate Strength (MPa)	Ultimate Strain (%)
Tensile	54	2.5	3030	55.2	3.5
Compressive	86.2	5	2620	86.2	5
Flexure	138	5	3720	138	5

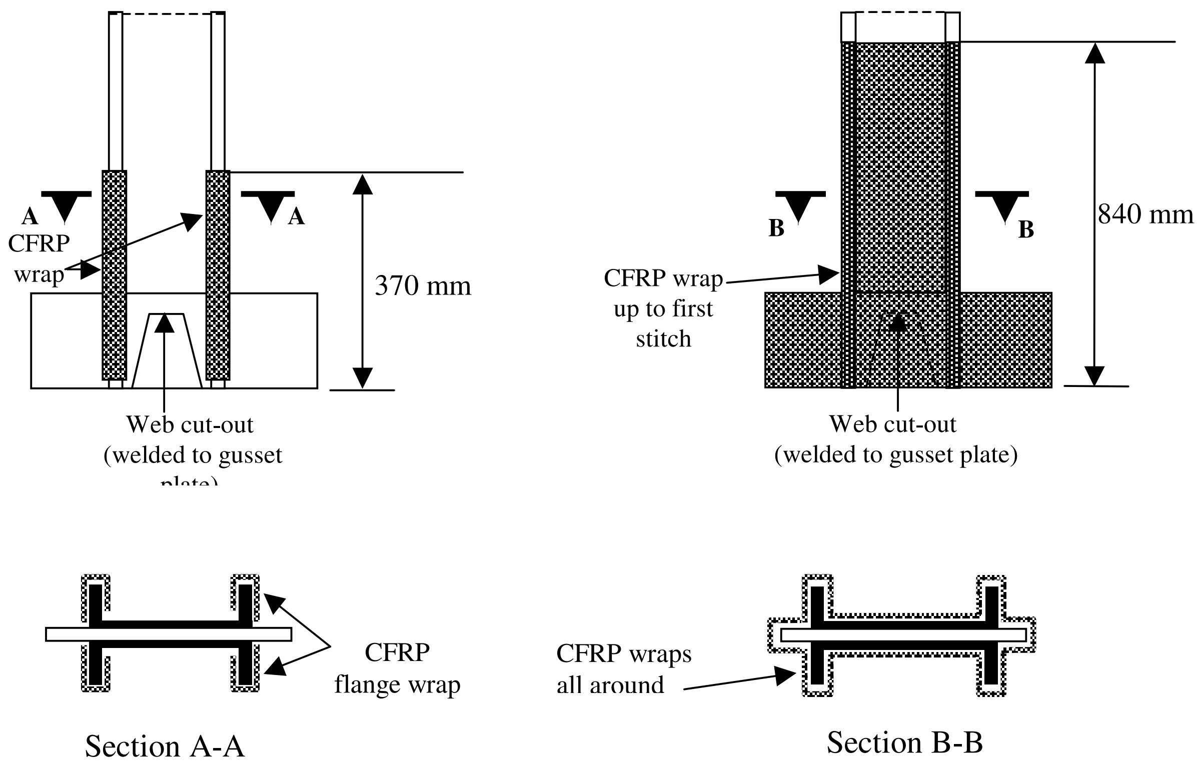


Figure 2 Cross sections of wrapped regions

Test Setup

After the specimens were constructed and wrapped with the carbon fiber sheets, they were placed in the test setup. As shown in Figure 1, the base beam was attached to the strong floor at three different places with four threaded rods at each location. The rods were pretensioned to minimize slippage of the base during the test. Load was applied at the free end of the cantilever member through a 450-kN hydraulic actuator, which was also connected to a strong wall. A load cell and LVDT were used to monitor the applied load and lateral displacement, respectively.

Loading History

The lateral displacement history was selected based on the displacement demands anticipated for a chord member in a prototype special truss moment frame (Figure 1). The displacement demands of the prototype structure translated into specimen drifts ranging from 0.8% to 7.6%. These correspond to tip displacements between 12.5 mm and 120 mm. The lateral displacement history is given in Figure 3.

Drifts for each cycle were specified and corresponding lateral loads were measured. A total of thirty three lateral displacement cycles were applied to the specimens. Distribution of the cycles are as follows, six cycles at 12.5 mm (0.8% drift), six cycles at 17 mm (1.1% drift), six cycles at 25 mm (1.6% drift), four cycles at 33 mm (2.2% drift), two cycles at 50 mm and 67 mm (3.3% and 4.4% drift), four cycles at 100 mm (6.6% drift) and three cycles at 120 mm (7.6% drift).

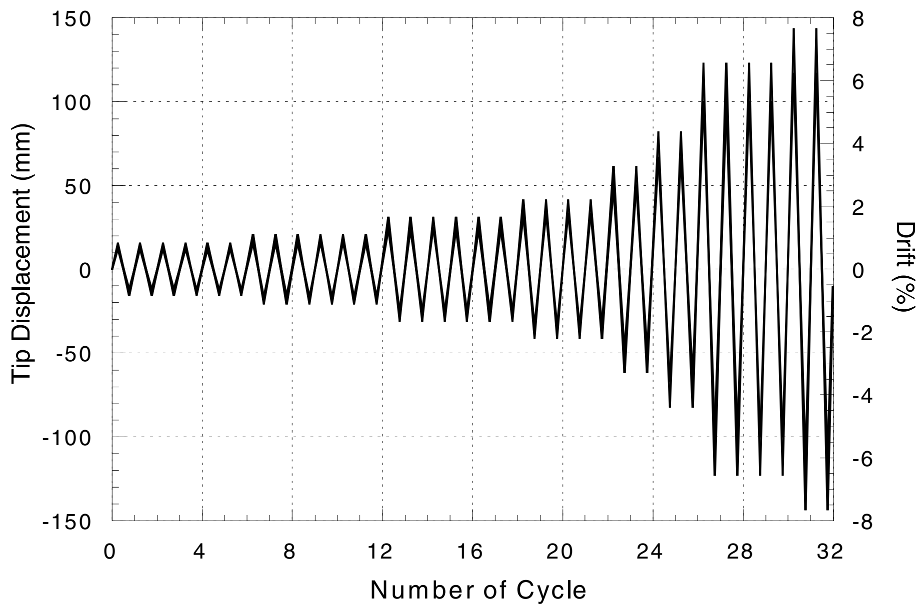


Figure 3. Lateral displacement history

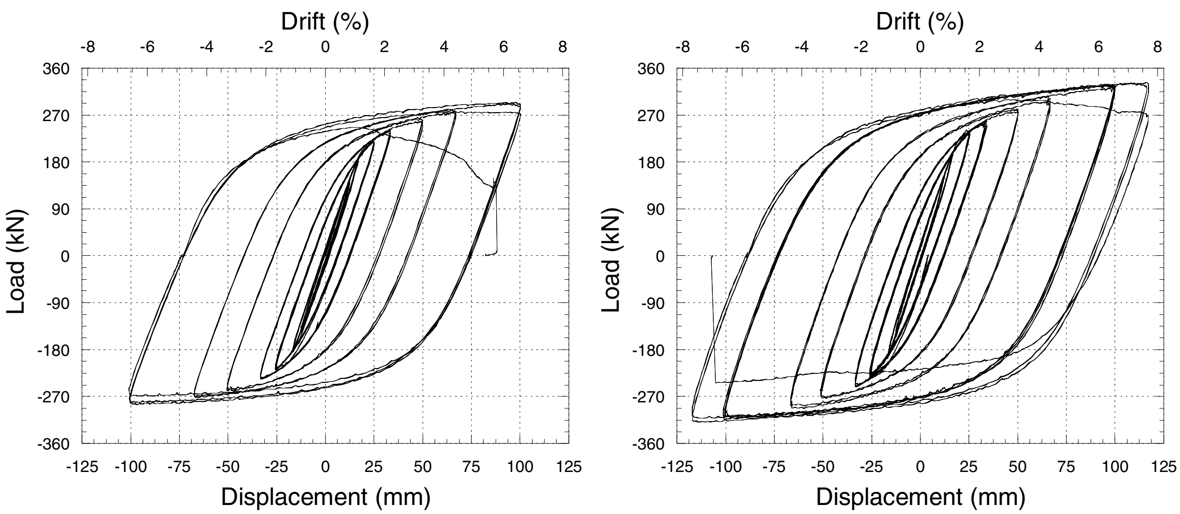
Instrumentation

Clinometers and potentiometers were used to measure rotations at the plastic hinge region and throughout the height of the cantilever member. A potentiometer placed horizontally at the end of the base beam tubes was also used to correct the displacement data obtained from the LVDT test setup slippage. Strain gauges were placed on the flange and web of the C sections on steel and CFRP surfaces at the plastic hinge region to monitor debonding of the carbon fiber sheets from the steel surface.

EXPERIMENTAL RESULTS & DISCUSSION

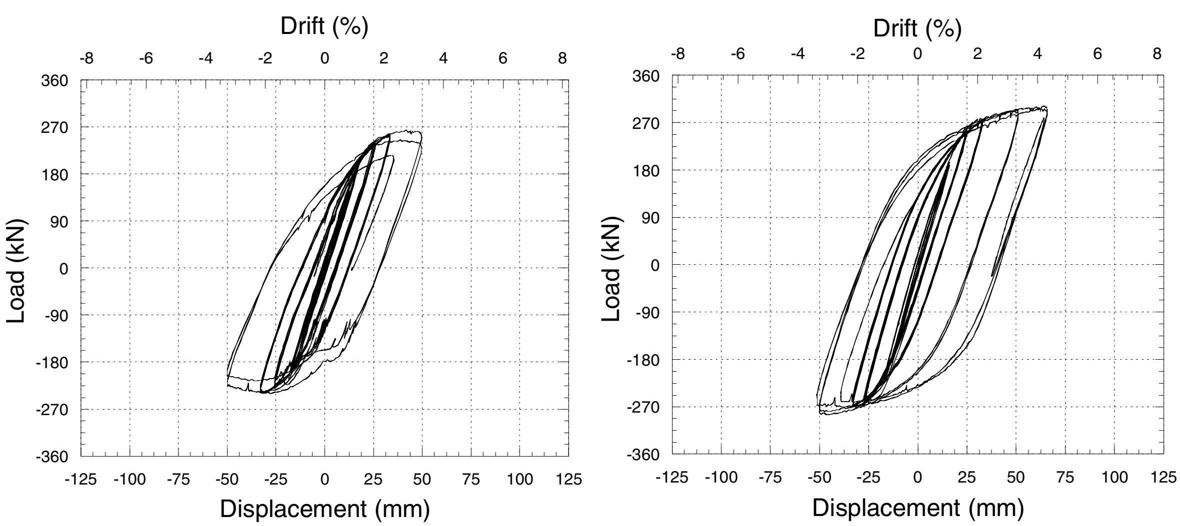
The load versus displacement response for the test specimens is shown in Figures 4 and 5. From these plots it is clear that all 4 specimens (wrapped and unwrapped) exhibited stable hysteretic response with relatively large energy dissipation capacity as deemed by the full hysteretic loops. However, as will be discussed in detail later on, the wrapped specimens performed substantially better than the unwrapped specimens.

Specimen C10x25 showed no deterioration of strength up to the third cycle of 6.6% drift. The maximum lateral load dropped slightly at the third cycle at the same drift and failure occurred during the fourth cycle. Yielding in the channels and gusset plate was noticed at the early stages of the test (approximately 1% drift) and spread over approximately 1.5 times the channel depth above the gusset plate during later cycles. Slight local buckling of the channel legs was first noticed during the 4.4% drift cycles and became significant during the 6.6% drift cycles (Figure 6a). Failure occurred by sudden propagation of a crack initiated by low cycle fatigue in the heat affected zone of the fillet weld between the channels and the gusset plate (Figure 7a). The test was terminated due to this fracture.



(a) C10x25 (b) C10x25W

Figure 4. Load versus displacement curves for C10x25 specimens



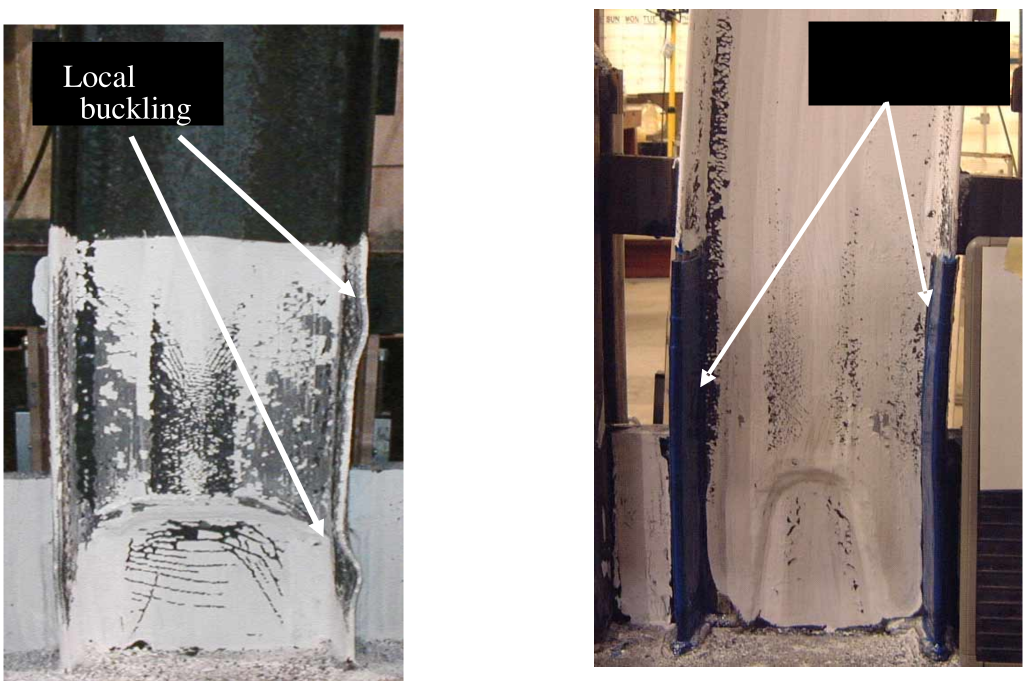
(a) C12x20.7 (b) C12x20.7W

Figure 5. Load versus displacement curves for C12x20.7 specimens

Specimen C10x25W remained elastic up to the 1.6% drift. Debonding between the CFRP and steel was not observed up to completion of the 1.6% drift cycles. Epoxy started spalling shortly thereafter, especially at the edges of the CFRP sheets. The sheets continued to progressively debond throughout the remainder of the test. The edges of the first layer of CFRP debonded completely during the third cycle to 2.2% drift.

The beneficial effect of the CFRP wrap was clearly evident in several aspects of behaviour. Yielding of the steel spread to a large region in the double channels and extended above the wrapped flange region. The yielded area was greater than the area of the corresponding control specimen. Local buckling of the section flanges was delayed until 6.6% drift compared to the 4.4% drift level for the baseline specimen (Figure 6). At this drift level, CFRP layers started to separate from the steel surface and one of the CFRP wraps spalled off completely during the third cycle to 7.6% drift. The flange without the carbon fiber wrapping fractured shortly thereafter during the subsequent reversal in loading (Figure 7b). Unlike the C10x25 specimen, the wrapped specimen did not show any deterioration in strength until the very last cycle where fracture occurred. As shown in Figure 8, the use of the CFRP wrap resulted in a 75% increase in energy dissipation capacity compared to the unwrapped specimen.

Specimen C12x20.7 showed significant strength deterioration followed by fracture of one channel after the first 2.6% drift cycle (Figures 5a and 9). Yielding in the channels was first noticed at early stages of the test and spread over approximately 1.5 times the channel depth above the gusset plate during the larger drift cycles. Lateral-torsional buckling of the individual channels was first detected during the 2.2% drift cycles, becoming significant during the 3.3% drift cycles, displacement at which cracking in the region connecting the gusset plate and the channels was noticed, leading to termination of the test.



(a) C10x25 (b)C10x25W

Figure 6. Deformed shapes at 6.6% drift

Spread of yielding could not be observed in specimen C12x20.7W since the specimen was completely wrapped up to the stitch level. However, from the load deflection curve it was observed that the system remained almost elastic up to the 2.2% drift level. After the first cycle to that drift level, the stiffness of the system started to decrease gradually. Lateral torsional buckling of the channels was first noticed during the 3.3% drift level and it became significant when the specimen reached the next drift level of 4.4%. In the positive loading direction, the target drift was reached but in the negative direction the maximum drift that could be reached was 3.3% because of substantial lateral torsional buckling, i.e. twisting of the specimen limited the drift level that could be achieved. At that drift level, the fuller hysteresis loops observed for C12x20.7W resulted in substantially better overall energy absorption compared to the control specimen (75% more as shown in Figure 8).

(a) C10x25 (b) C10x25W

Figure 7. Fracture of channel flanges

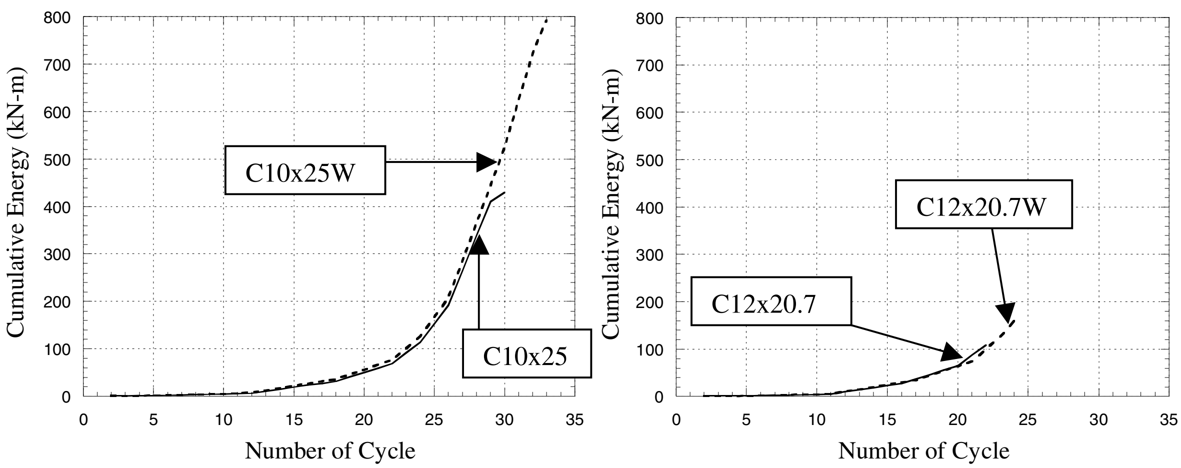


Figure 8. Cumulative energy versus drift curves

Beyond the symmetric 3.3% drift level that could be achieved, the test was continued with half cycles in which the intended drift in the positive direction was reached, coming back to zero displacement, i.e. the specimen was not pushed in the negative direction beyond the original zero position. The results of these additional loading cycles are not shown in Figure 5 or reflected in Figure 8 to permit rational comparison of behaviour to the control specimen. At the 6.6% drift level, local buckling of the flanges became visible through the wrap, as shown in Figure 9b. The specimen was taken to the stroke limit of the actuator for the positive half leading cycles (5.5 inches, 9% drift) but no failure was observed from repeated application of the half cycles. The CFRP wrap improved the behaviour of the C12x20.7 specimen, resulting in higher strength and capacity. Fracture of the flange during the early stages of the tests was not observed as in the C12x20.7 specimen due to the beneficial effects of the CFRP wraps.

(a) C12x20.7 (b) C12x20.7W

Figure 9. Failure of C12x20.7 and local buckling of C12x20.7W flange

SUMMARY AND CONCLUSIONS

An experimental study on the effect of CFRP wrapping on the inelastic reversed cyclic behavior of steel flexural members was described. The plastic hinge regions in two large-scale steel specimens were wrapped with CFRP sheets and the specimens were tested under reversed cyclic loading. The response of the specimens was compared to the behavior of unwrapped control specimens.

The test results showed that application of CFRP in the plastic hinge region of flexural members significantly improved the overall structural behavior of the wrapped specimens compared to the unwrapped control specimens. Based on the limited test data presented here, the beneficial effects of CFRP wraps can be summarized as follows. CFRP wrapping can: 1) increase the size of the yielded plastic hinge region; 2) inhibit the occurrence of local buckling; and 3) delay lateral torsional buckling, all of which can potentially reduce strain demands in the critical plastic hinge region, increase rotational capacity, improve low-cycle fatigue behavior, and substantially increase energy dissipation capacity of the plastic hinge region.

The experimental results presented here suggest that CFRP wrapping can be used to improve the behavior of new steel structures or effectively upgrade existing structures in regions of high seismic risk. The proposed technology does not require field welding and has many benefits over existing strengthening methods including simplicity, ease of installation and handling, and resistance to corrosion (as long as precautions are taken to prevent galvanic action between carbon and steel).

The authors are currently conducting additional research to 1) construct suitable analysis models, 2) develop design guidelines for rehabilitating steel members using CFRP wraps, and 3) investigate other applications of steel/CFRP members.

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