Retraining local and global buckling behavior of steel plastic hinges using CFRP

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A B S T R A C T

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 that are susceptible to local and global instabilities. This paper discusses test results of full-scale steel flexural specimens subjected to reversed cyclic loading, some of which are wrapped with CFRP in the plastic hinge region. The main variables investigated are lateral bracing, to study the effect of CFRP wrapping on local buckling and lateral torsional buckling, wrapping scheme, and number of layers of fibers. The test results show that application of CFRP in the plastic hinge region of flexural members has substantial benefits. In particular, the CFRP wraps can increase the size of the yielded plastic hinge region, slow down the occurrence of local buckling, and delay lateral torsional buckling. These benefits reduce strain demands in the critical plastic hinge region and substantially improve energy dissipation capacity within the plastic hinge region.

1. Introduction

Externally bonded CFRP components have proved to be a convenient, practical and economical method for rehabilitation of concrete structures. As such, there has been explosive growth in the number of industrial applications, particularly in the fields of seismic rehabilitation and bridge repair. The most common application pertains to reinforced concrete (RC) members, where the FRPs are embedded into or externally attached to RC components to enhance structural behavior.

In contrast to the extensive research focus placed on CFRP/concrete applications, there have been far fewer efforts that investigated the use of CFRP for strengthening steel and composite steel–concrete structures. Holloway and Cadei [1] presented the first state-of-the-art review in the literature on the use of the FRP material to strengthen steel structures. They addressed several issues including prestressing FRP plates prior to bonding them to steel beams, bonding issues in terms of surface preparation and durability, and general durability of FRP composites. The second state-of-the-art review on this topic was published by Shaat et al. [2] and discussed strengthening steel girders with FRP, fatigue life improvement, surface preparation, durability of steel members retrofitted with FRP and field applications. The most recent state of the art on steel/FRP applications is summarized by Zhao and Zhang [3] and covers primarily bond between steel and FRP, strengthening of steel hollow sections, and fatigue crack propagation in steel-FRP systems.

The available literature on steel/FRP applications, as discussed in the above state-of-the-art reviews and in newer publications, can be grouped into several categories. The largest by far is flexural strengthening of steel members with FRP. The first study to investigate potential applications of CFRP to steel members was conducted at the University of South Florida, where CFRP plates were employed to strengthen steel–concrete composite girders that are commonly used in bridge applications [4]. A similar study conducted at the University of Delaware [5] was reported 2 years later. Several subsequent studies can be found in [6–8] among other more recent studies.

Tensile strengthening of steel members with FRP is another application. Jiao and Zhao [9] tested a total of 21 butt-welded very high strength (VHS) steel tubes strengthened with CFRP in axial tension. An experimental and numerical study was carried out by Colombi and Poggi [10] to verify the effectiveness of CFRP pultruded plates to reinforce tensile steel members and to identify force transfer and failure mechanisms. Another study can be found in [11].

Yet a third application for FRP has been to strengthen the connection region of steel members. A pilot study was carried out at California State University by Mosallam et al. [12] to investigate the use of polymer composites and high strength adhesives for structural repair of damaged steel frame connections.
A growing application for FRP is to repair and enhance fatigue damage. An experimental and analytical study was conducted by Jones and Civjan [13] to investigate the effectiveness of applying carbon fiber-reinforced polymer (CFRP) overlays to steel tension coupons to prolong fatigue life. Tavakkolizadeh and Saadatmanesh [14] presented the results of a study on the retrofitting of notched steel beams with CFRP patches for medium-cycle fatigue loading. Nozaka et al. [15] report a study on the use of CFRP strips for the repair of fatigue-damaged (i.e., cracked) tension flanges of steel I-girders. Liu et al. [16] report a study of the direct tension fatigue behavior of bonded CFRP sheets used to create "strap joints" between two steel plates.

One of the fastest growing areas of research pertains to enhancing the stability of thin-walled steel components with FRP. Ekiz et al. [17] demonstrated the use of CFRP wraps to enhance the plastic hinge behavior of double-channel members used for special segment members of a special truss moment frame (STMF). The work presented herein is an expansion of that earlier study. Patnaik and Bauer [18] investigated an application whereby vertically oriented, unidirectional CFRP components attached to both sides of a slender steel web promoted yielding prior to the onset of inelastic web buckling, whereas the unstrengthened beam specimens failed due to elastic web buckling prior to flexural yielding. Sayed-Ahmed [19] proposed the use of CFRP strips applied horizontally to the compression zone of slender-webbed steel sections in an effort to improve the web buckling behavior of the section. In a study investigating the use of CFRP to strengthen hollow structural square (HSS) columns, Shaat and Fam [20] report on concentric axial load tests of squat hollow steel sections wrapped with both longitudinal and transversely oriented CFRP sheets. More recent efforts in this direction include Zhao et al. [21], Tao et al. [22], Accord et al. [23], Okeil et al. [24], Harries et al. [25].

The performance and energy absorption capacity of a steel plastic hinge are directly dependent on delaying the onset of global buckling and local instability in the plastic hinge zone. This paper presents the results of a study conducted to investigate whether local and global instability, and therefore the reversed cyclic response of steel plastic hinges, can be improved by using CFRP wrapping. This is a topic that has not been previously studied by others and therefore this paper presents new information about a novel application of FRP. This study is motivated by the desire to investigate whether CFRP technology could be used to relax the stringent local slenderness and lateral torsional buckling limits that are imposed on members of special truss moment frames and special moment resisting frames. The strengthening technology is particularly well suited because it does not require field welding, 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; and (5) significant reduction in low-cycle and high-cycle fatigue life.

In the experimental study outlined in this paper, the plastic hinge regions in three large-scale steel flexural members are wrapped with CFRP and the specimens are tested under reversed cyclic loading. The main variables investigated are local versus lateral torsional buckling and the orientation, wrapping scheme and number of layers 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.

2. Experimental program

2.1. General description of test specimens

Three double channel built-up members with CFRP wraps in the plastic hinge region are tested to failure under reversed cyclic loading. The specimens are identical to two 'baseline' specimens tested by Kim et al. [26] in a previous investigation at the University of Michigan. These latter specimens are unwrapped and serve as control specimens. The baseline specimens are designated C10 × 25 and C12 × 20.7 based on channel section types. Built-up double channel members are often used in seismic resistant steel structures, such as in braced frames or truss moment frames (Fig. 1), where they can be subjected to large ductility demands. The main variables to be investigated in this study are: (1) lateral bracing, to observe the effect of CFRP wrapping on local buckling and lateral torsional buckling, (2) wrapping scheme of carbon fibers, and (3) number of layers of fibers.

Each of the five specimens discussed in this report consists of a reusable base beam made of two tube sections welded together, a gusset plate (254 mm (10") × 610 mm (24") × 32 mm (1.25"')), and a double channel built-up cantilever member (Fig. 1). Each test specimen is representative of a truss chord in the special segment of a truss moment frame as shown in Fig. 1. The cantilever member is connected to the base beam through a gusset plate fillet welded to the base beam tubes. As shown in Fig. 2, the bottom parts of the channel webs are cut out to permit more extensive fillet welding in the connection region. Kim et al. [26] observed that such a connection detail reduces demands in the connection...
region and improves cyclic performance. The dimensions for the test specimens are shown in Fig. 1.

The wrapped specimens are designated C10 × 25W, C10 × 25W − 1 and C12 × 20.7W. Table 1 summarizes the structural details of all three specimens. The rationale behind the detailing employed in the tested specimens can be found in [27,26]. The double channel cantilevers in specimens C10 × 25, C10 × 25W and C10 × 25W − 1 each have three stitches along the height, as shown in Fig. 1. The clear spacing between the gusset plate and the first stitch as well as that between the first and second stitches is 150 mm whereas it is 165 mm between the second and third stitches. The first stitch plates are 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 Fig. 1) is to provide out-of-plane bracing for the plastic hinge region. The cantilever is also braced in the out-of-plane direction at another point close to the actuator. This ‘upper level bracing’ is achieved by connecting the specimen to a parallel support frame system through a brace that can slide in the loading direction along the parallel support frame.

For the C12 × 20.7 and C12 × 20.7W specimens, only one stitch is provided along the height at 865 mm above the base. Unlike the C10 × 25 specimens, both C12 × 20.7 stitches are only braced at the upper level, through a system similar to that described above, i.e. there is no bracing at the level of the plastic hinge region. The intention behind the reduced bracing is to promote lateral torsional buckling and to therefore provide an opportunity to study the effect of CFRP wrapping on this type of behavior.

### 2.2. Construction and surface preparation of test specimens

Individual members of the specimens (two channels, gusset plate, stitches, base beams) are all welded together according to the geometry described in Table 1. Threaded rods are then tag welded to the specimen at prescribed locations for installation of instrumentation (clinometers and linear potentiometers) which will be discussed later on.

Surface preparation for all specimens is conducted following the instructions of the adhesive epoxy and CFRP suppliers. The steel surface is first ground to clean the surface and then sanded using 80 and 120 grit sandpapers to achieve a uniform surface. The surface is cleaned with a degreaser, just before application of the CFRP wrap. After cutting the CFRP sheets to the required length, the first layer of the epoxy resin is applied to the surface, after which the first layer of CFRP is attached to the steel surface. After waiting for 20–30 min, another layer of epoxy is applied, and the second CFRP layer is attached. After the wrapping process is completed, the specimens are allowed to cure for 1 week.

### 2.3. Wrapping schemes of test specimens

For specimen C10 × 25W, the CFRP sheets are just attached to the bottom portion of the channel flanges, i.e. in the plastic hinge region, as shown in Fig. 2. The fibers in the CFRP sheets are aligned along the length of the extending flanges in the direction of the member axis and four sheets are used in the wrapping scheme. These sheets are 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 is 370 mm high from the base whereas the others are 330 mm, 290 mm, and 255 mm, respectively. Each layer starts 12 mm above the bottom end of the previous layer.

Unlike C10 × 25W where only the flanges are wrapped, wrapping for C10 × 25W − 1 is applied all around the section up to 610 mm above the base (Fig. 3). A total of six layers of CFRP sheets are used. The first four CFRP layers have fibers that are aligned along the length of the channels, while fibers in the remaining two layers are aligned in the transverse direction. Due to the geometry of the test specimen, transverse layers can only be placed between the gusset plate and the first stitch, and between the first stitch and the second stitch. The absence of transverse fibers at the bottom section of the channels has an adverse effect on the observed behavior, as will be discussed later on.

Wrapping for C12 × 20.7W is applied all around the section including the gusset plate up to the first stitch, which is located 840 mm above the base (Fig. 4). A total of six layers of CFRP sheets are used. The first three layers of fibers are aligned in the longitudinal direction of the channel sections, while the remaining three layers of fibers are aligned in the transverse direction.

![Fig. 2. Wrapping scheme for C10 × 25W.](image-url)
2.4. Material properties

Dual Grade A36/A572–Grade 50 steel ($F_y = 345$ MPa) is used for all the steel members. The CFRP sheets used in the tests are unidirectional high strength carbon fiber fabrics (CF-130 M Brace). The nominal properties obtained from the manufacturer for the CFRP sheets are as follows: tensile modulus is 227 GPa (33 000 ksi), ultimate tensile strength is 3800 MPa (550 ksi), maximum elongation at failure is 1.67%; and net carbon area is $0.165 \text{ mm}^2/\text{mm}$ (0.0065 in.$^2$/in.) of width. The properties of the epoxy as reported by the supplier are summarized in Table 2.

2.5. Test setup and loading history

After the specimens are constructed and wrapped with the carbon fiber sheets, they are placed in the test setup. As shown in Fig. 1, the base beam is attached to the strong floor at three different places with four threaded rods at each location. The rods are pretensioned to minimize slippage of the base during the test. Load is applied at the free end of the cantilever member through a 450 kN (100-kip) hydraulic actuator, which is also connected to a strong wall. A load cell and LVDT are used to monitor the applied load and lateral displacement, respectively.

The lateral displacement history is selected based on the displacement demands anticipated for a chord member in a prototype special truss moment frame (Fig. 1). As discussed in [26], the displacement demands of the prototype structure translate into specimen drifts ranging from 0.8% to 7.6%. These correspond to tip displacements between 13 and 116 mm. The imposed lateral displacement history is given in Fig. 5. Drifts for each cycle are specified and corresponding lateral loads are measured during the test. A total of 32 lateral displacement cycles are applied to the specimens. The distribution of the cycles is as follows: six cycles at 13 mm (0.8% drift), six cycles at 18 mm (1.1% drift), six cycles at 25 mm (1.6% drift), four cycles at 33 mm (2.2% drift), two cycles at 51 mm and 66 mm (3.3% and 4.4% drift), four cycles at 101 mm (6.6% drift) and three cycles at 116 mm (7.6% drift).

2.6. Instrumentation

Clinometers and potentiometers are used to measure rotations at the plastic hinge region and throughout the height of the cantilever member. Two clinometers are placed along the length of the specimen. The first one is located in the plastic hinge region (405 mm from the base beam) and the second one is located above the plastic hinge region (1150 mm above the base beam) (Fig. 6(a)). A third clinometer is installed on the base beam to monitor any possible base rotation during the test. Potentiometers are also used to measure rotations at the base together with the clinometers. They are attached on the outside flanges on both sides.
Properties of the epoxy resin.

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(a) Placement of clinometers. (b) Placement of potentiometers in plastic hinge region.

Fig. 6. Instrumentation.

of the channel members to measure the change in the distance of a point in the plastic hinge region and base beam (Fig. 6(b)). Another potentiometer is also placed horizontally at the end of the base beam tubes and is used to correct the displacement data obtained from the LVDT in the case of a base beam slippage during the test. Strain gauges are placed on the flanges and web of the channel sections on both steel and CFRP surfaces at the plastic hinge region to monitor debonding of the carbon fiber sheets from the steel surface.

3. Experimental results

The load versus displacement response for the test specimens is shown in Figs. 7–11. From these plots, it is clear that all five specimens (wrapped and unwrapped) exhibited stable hysteretic response with relatively large energy dissipation capacity as deemed by full hysteretic loops. However, as will be discussed in detail later on, the wrapped specimens perform substantially better than the unwrapped specimens.

3.1. C10 × 25

From the results of the study conducted by Kim et al. [26], specimen C10 × 25 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, Fig. 7) and spread over approximately 1.5 times the channel depth above the gusset plate during later cycles. Slight local buckling of the channel flanges was first noticed during the 4.4% drift cycles and became significant during the 6.6% drift cycles (Fig. 12(a)). 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. The test was terminated due to this fracture.

3.2. C10 × 25W

This specimen was tested by Chao and Goel [27] in collaboration with the first author. The specimen remained elastic up to the 1.6% drift level. 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 behavior. 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. At this drift level, CFRP layers started to separate from the steel surface and one of the CFRP wraps popped 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.

### 3.3. C10 × 25W − 1

Observing the spalling off of CFRP wraps in specimen C10 × 25W, it was decided to place two layers of transverse layers of fibers on top of the longitudinal layers which were placed on the flanges for specimen C10 × 25W. These transverse layers were intended to keep the longitudinal layers in place. Specimen C10 × 25W − 1 showed similar behavior as C10 × 25W but reached higher loads at each drift level up to 6.6% drift. Longitudinal fibers started to buckle early (2.2% drift) on the flanges just below the gusset plate line and at 3.3% drift, fracture of the longitudinal fibers was observed at the same region. The crack width continued to progressively increase throughout the remainder of the test reaching up to 12 mm at 6.6% drift. Although the fracture of longitudinal fibers occurred in the plastic hinge area, there was no sign of buckling of flanges until the 6.6% drift level. While going to third cycle to 6.6% drift, initiation of buckling was observed and at the fourth cycle, slight buckling of the flanges became visible. During the first cycle to 7.6% drift, buckling became severe and one of the flanges fractured at the weld connecting the flanges to the gusset plate.

### 3.4. C12 × 20.7

Specimen C12 × 20.7 showed significant strength deterioration followed by fracture of one channel after the first 2.6% drift cycle. Yielding in the channels was first noticed at the 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. It became significant during the 3.3% drift cycles (Fig. 15(a)), the point at which cracking in the region connecting the gusset plate and the channels occurred, leading to termination of the test.
Spread of yielding could not be observed in specimen C12 × 20.7W since the specimen was completely wrapped up to the stitch level. However, from the load deflection curve (Fig. 11) it was inferred that the system remained almost elastic up to the 1.6% drift level. After the first cycle at 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 (Fig. 15(b)) 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.

4. Analysis of experimental results

Figs. 16 and 17 show the energy dissipated by the different specimens. The energy calculations are made based on the method specified in [26]. As shown in Fig. 16, the use of the CFRP wrap in specimen C10 × 25W resulted in a 75% increase in energy dissipation capacity compared to the unwrapped specimen, C10 × 25. While the load capacity of C10 × 25W − 1 was higher than C10 × 25W at the same drift levels (Figs. 8 and 9), C10 × 25W completed two cycles at 7.6% more than C10 × 25W − 1 and so it total energy dissipated was more. Nevertheless, C10 × 25W − 1
still dissipated 45% more energy than the baseline specimen. The relatively poor performance of C10 x 25W - 1 compared to C - 10 x 25W appears to have stemmed from over constraining the longitudinal CFRP wraps, by wrapping them with transverse layers. This led to premature local buckling of the CFRP skin, which damaged the wraps quite early on the loading history thereby reducing the effectiveness of the strengthening scheme.

The benefit of the CFRP wraps was manifested differently in C12 x 20.7W. Compared to the baseline specimen, this specimen benefited from the CFRP by delaying the onset of the lateral torsional buckling. The use of CFRP resulted in fuller hysteresis loops and substantially better overall energy absorption compared to the control specimen (75% more as shown in Fig. 17).

In all, the test results show 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. In particular, the CFRP wraps were observed to increase the size of the yielded plastic hinge region and slowed down the occurrence of local buckling. They also delayed lateral torsional buckling. These benefits potentially reduced strain demands in the critical plastic hinge region, increasing the rotational capacity and improving low-cycle fatigue behavior. This led to substantially increased energy dissipation capacity within the plastic hinge region.

5. Summary and conclusions

The beneficial effect of CFRP wrapping on the inelastic reversed cyclic behavior of steel flexural members was described. The plastic hinge regions in two types of large-scale steel specimens were wrapped with various combinations of 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 show 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 could be used to improve the behavior of new steel structures or effectively upgrade existing structures in regions of high seismic risk.

References