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INHIBITING STEEL BRACE BUCKLING USING CFRP WRAPS

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ABSTRACT

The use of carbon fiber reinforced polymer (CFRP) composites for the rehabilitation of structurally inadequate buildings and bridges is rapidly increasing but the majority of applications have been developed for reinforced concrete structures. The superior mechanical and physical properties of fiber reinforced polymers make them excellent candidates for repair and retrofit of steel structures as well. To date, the main focus of research on rehabilitation of steel structures with CFRP has been mostly limited to flexural strengthening. This paper reports on an analytical and experimental study conducted to investigate the buckling behavior of steel members strengthened with CFRP laminates. To improve the effectiveness of the CFRP wraps, the steel member is first sandwiched within a core (comprised of mortar or PVC blocks) prior to attaching the external CFRP sheets. The structural requirements to prevent buckling of the steel members are derived from equilibrium considerations and verified with test results. Small scale tests of wrapped steel members show that significant improvements can be achieved in the inelastic axial deformation reached prior to buckling and load carrying capacity after buckling when CFRP wrapping is used.

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. While the use of CFRP for upgrading steel structures has lagged behind applications for concrete, there is rapidly growing interest in this technology. Most of the studies to date focused mainly on flexural rehabilitation of steel and composite steel-concrete girders. In these studies, carbon fiber sheets or plates are attached to the bottom flanges of steel or composite girders to provide additional tensile resistance thereby increasing flexural capacity, e.g. Mertz and Gillespie (1996), Sen et al. (2001); Miller et al. (2002), Mertz et al. (2002), Tavakkolizadeh and Saadatmanesh (2003), Phares et al. (2003), Al-Saidy et al (2004), Schnerch et al. (2004), Patnaik and Bauer (2004), Hollaway (2004).

The use of CFRP to strengthen steel structures in compression has not yet been adequately explored, perhaps because of the perception that CFRP components, which are thin

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walled, are as susceptible to buckling as the thin-walled steel components they would be used to strengthen. However, the few studies that have been conducted to date show the potential of this rehabilitation technique. For example, Ekiz et al. (2004), Sayed-Ahmed (2004), and Shaat and Fam (2004) have shown that improvements in the local and global buckling behavior of a steel section during plastic hinging can be achieved by CFRP wrapping.

This paper reports on a study which further investigates how CFRP can improve the compressive response of steel members under compression. The study draws upon concepts from sandwich construction and shows that when core material such as mortar or PVC blocks is sandwiched between externally bonded CFRP sheets and an inner steel member, complementary action between system components impedes buckling of the steel member leading to dramatic improvements in buckling and post buckling behavior of the entire system. The proposed strengthening technique is suitable for strengthening existing steel braces that are commonly used in building, bridges and other steel structures. When steel braces are subjected to reversed axial deformations, their hysteretic behavior is unsymmetrical due to compression buckling. The use of CFRP wrapping can potentially inhibit buckling leading to a response that is similar to that of buckling restrained braces (BRB), which deliver a symmetric hysteretic response under reversed cyclic loading.

Small scale tests on thin steel braces were carried out to investigate the proposed rehabilitation technique. The tests showed that CFRP wrapping can lead to a significant improvement in the inelastic axial deformation capacity prior to buckling and an improved load carrying capacity after buckling. The requirements to inhibit brace buckling are obtained from equilibrium conditions and verified with the test results.

Stiffening Requirements

Following the methodology described in Inoue et al. (2001), the deflected shape of a steel member encased within a stiffening system is shown in Fig. 1. The member is subjected to its axial yield capacity N_y. v_o indicates the initial deflection of the steel member and v denotes the deflection at any point of the stiffened member. Assuming that the axially yielded steel member has lost its flexural stiffness and that the ends of the member are free to rotate, the equation of equilibrium can be written as:

$$D\frac{d^2v}{dx^2}+(v+v_o)N_y=0 \tag{1}$$

where, D is the flexural rigidity of the stiffening member. Assuming that the deflected shape is a sine curve, then

$$v_o=\alpha\sin\frac{\pi x}{L} \tag{2}$$

where α is the initial deflection at the center of the steel member and L is the length of the stiffened member. By solving Eqn. 1, the deflection v of the stiffened member is given by:

$$v + v_o = \frac{\alpha}{1 - \frac{N_y L^2}{\pi^2 D}} \sin \frac{\pi x}{L} \tag{3}$$

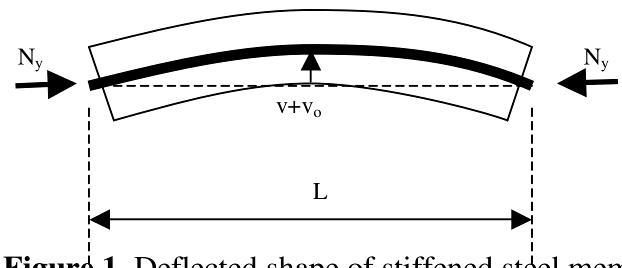

Figure 1. Deflected shape of stiffened steel member

From Eqn. 3 the maximum bending moment at the center of the stiffened member, M is given by:

$$M = \frac{N_y \alpha}{1 - \frac{N_y L^2}{\pi^2 D}} \tag{4}$$

The stiffening requirement, i.e. when the axial load on the steel member can reach the yield load without buckling is expressed as follows:

$$M_{cap} > M \tag{5}$$

where M_{cap} is the moment capacity of the stiffening member. Substituting the expression for M yields:

$$\frac{N_y \alpha}{1 - \frac{N_y L^2}{\pi^2 D}} < M_{cap} \tag{6}$$

If inequality 6 is rewritten in terms of two nondimensional parameters n & m, then:

$$\left(1 - \frac{1}{n}\right) m > \frac{\alpha}{L} \tag{7}$$

$$n = \frac{\pi^2 D}{N_y L^2} \qquad \& \qquad m = \frac{M_{cap}}{N_y L} \tag{8}$$

As seen in Fig. 2, for α/L=1/500, Eqn. 7 divides the n – m plane into two regions: YPB (yield prior to buckling) and BPY (buckling prior to yield) regions. Any combination of n and m values on the YPB region will cause axial plastic deformations of the steel member prior to buckling. Any stiffened steel member which has a combination that falls below the requirement curve (i.e. in the BPY space) will buckle before reaching its axial yield capacity. Sandwich beam theory is used to calculate the flexural rigidity and strength of the composite cross section for use in Eqn. 7. Fundamentals of sandwich beam theory are summarized in textbooks including Zenkart (1995) and are not repeated here.

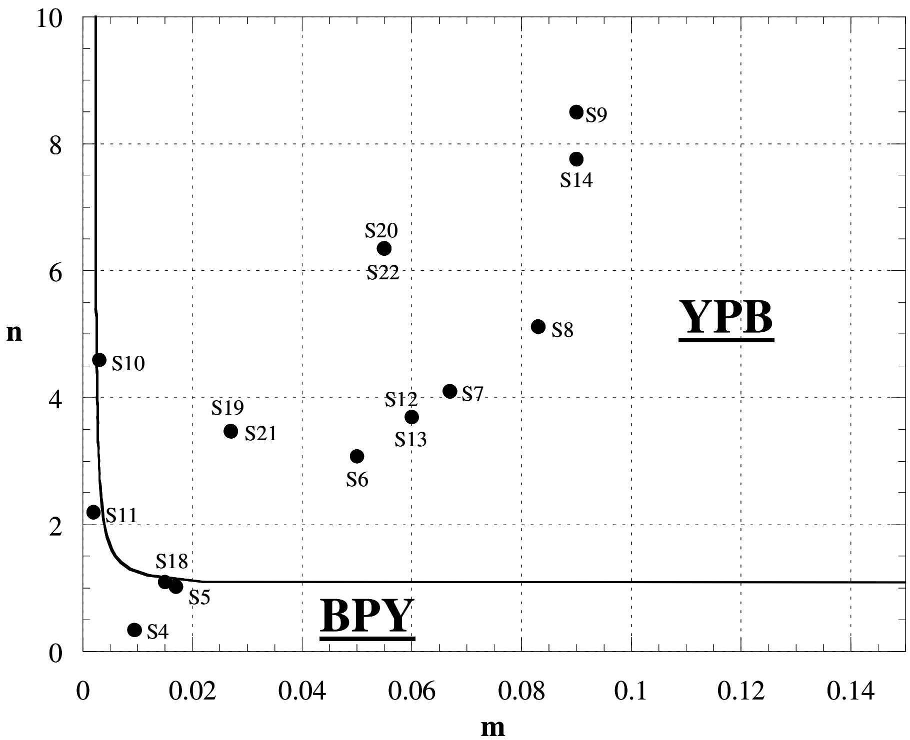

Figure 2. Stiffening requirement space.

Experimental Program

A total of 22 specimens were tested under monotonic compressive loading to investigate the improvement in buckling response of the steel members as a result of CFRP wrapping. Two different specimen layouts were used in the study. The first group of specimens consisted of a thin steel plate (2" x 0.25" cross section x 12" length) and core material sandwiched between the plate and externally wrapped CFRP (Fig. 3). The second group comprised of the same steel plate used for the first group, except that the plate was tapered at its middle, having a thickness of 1" in a 6" tapered region. To achieve a fixed end boundary condition, ends of the steel plates were either welded to a transverse plate (BC1 in Fig. 4) or they were clamped in between two angles (BC2 in Fig. 4). Both BC1 and BC2 configurations had the same unsupported length. Table 1 summarizes details of the specimens and shows that the main parameters varied were the number of layers of CFRP wrap, core material type, thickness of the core material, bond between FRP and core material and bond between core material and steel.

CFRP wrapping for all specimens was conducted following the instructions of the adhesive epoxy and CFRP suppliers. The core material was first attached to the steel member. Then, after cutting the CFRP sheets to the required length, the first layer of the epoxy resin was applied to the core material, after which the first layer of CFRP was attached onto the surface. After waiting for 20-30 minutes, another layer of epoxy was applied, and the second CFRP layer was attached. Each specimen had a varying number of longitudinal (along the length) layers of fibers and one layer of transverse (perpendicular to the length) layer. All the longitudinal layers were attached to the steel plate before attaching the single transverse layer. Plastic sheets were used to eliminate bond between two components by isolating one contact surface from another. Once the wrapping process was complete, the specimens were then allowed to cure for a week.

Dual Grade A36/A572-Grade 50 steel was used for the steel members. The CFRP sheets used in the tests were unidirectional high strength carbon fiber fabrics. The properties obtained from the manufacturer for the CFRP sheets are as follows: tensile modulus is 33000 ksi, ultimate tensile strength is 550 ksi, maximum elongation at failure is 1.67%; and net carbon area is 0.0065 sq. in per in of width. The epoxy resin was obtained from the same manufacturer.

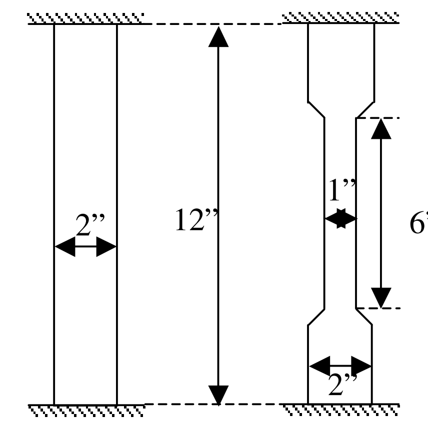

Figure 3. Steel Specimens

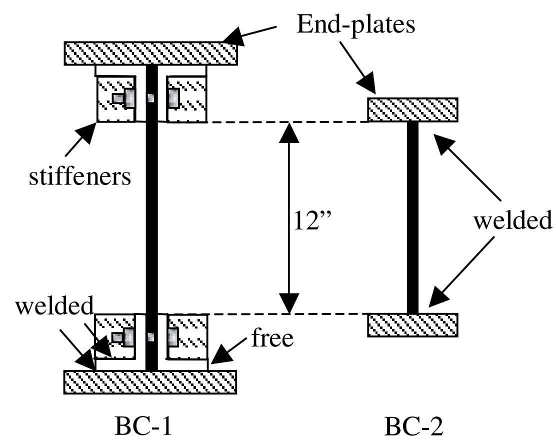

Figure 4. Boundary conditions

After the specimens were constructed and wrapped with the carbon fiber sheets, they were placed in a 500 kips compression machine. A load cell and LVDT were used to monitor the applied load and axial displacement, respectively. Specimens were loaded monotonically at a displacement rate of 0.05 in/min up to a displacement of 1”, i.e. a very large compressive displacement compared to the length of the specimen (12”). Fig.5 shows one of the control specimens and a specimen with mortar core after the test.

Results & Discussions

Key test results are listed in Table 1. The table shows the maximum load achieved normalized by the yield capacity, the strain achieved prior to buckling and the percentage of the peak load still maintained at 2% deformation (i.e. 2% of 12”). The load versus displacement response for selected specimens is shown in Fig. 6. The control specimens buckled in the first buckling mode at around half of the yield load and at 2% deformation they were maintaining about 15% of their capacity. In Group-1, specimen S4, which is predicted to buckle prior to yielding according to Eqn. 7, failed by buckling followed by fracture of the longitudinal CFRP fiber on the tension side before it reached its yield capacity (Fig. 7a). Specimen S5, which is on the boundary in Figure 2, reached 2% axial strain prior to failing in the same manner as S4.

Specimens S6 to S9 reached very high axial compressive strains (3.3% to 4.6%) prior to fracture of the transverse fibers near the top of the specimens (Fig. 7b).

Table 1 Test Matrix

Specimen	Core	t_{core} (in)	# Long. Layers	Max Load $/N_y$	Load ratio at 2% deformation	Axial Strain at Buckling	Eqn. 7	FRP/Core Bond	Core/Steel Bond
Group 1 - welded									
S1	Control	-	-	0.42	0.13	0.07	-	-	-
S2	Control	-	-	0.48	0.15	0.08	-	-	-
S3	Control	-	-	0.5	0.15	0.09	-	-	-
S4	Mortar	0.25	1	0.67	0.20	0.16	BPY	✔	✔
S5	Mortar	0.5	1	1.13	1.13	2	BPY	✔	✔
S6	Mortar	0.5	3	1.34	1.19	3.5	YPB	✔	✔
S7	Mortar	0.5	4	1.35	1.23	3.33	YPB	✔	✔
S8	Mortar	0.5	5	1.42	1.23	4.1	YPB	✔	✔
S9	Mortar	0.75	4	1.34	1.19	4.6	YPB	✔	✔
Group 1 - clamped									
S10	PVC	0.75	3	0.97	0.61	0.23	YPB	✕	✕
S11	Mortar	0.5	3	0.95	0.33	0.23	YPB	✕	✕
S12	Mortar	0.5	5	1.42	1.28	2.6	YPB	✔	✕
S13	Mortar	0.5	5	1.23	1.11	1.7	YPB	✔	✔
S14	PVC	0.75	5	1.4	1.25	2.5	YPB	✔	✔
Group 2 – clamped									
S15	Mortar	0.5	5	1.11	1.11	3.33	YPB	✔	✔
S16	Mortar	0.5	5	1.25	1.2	4	YPB	✔	✕
S17	PVC	0.75	5	1.06	1	2	YPB	✔	✔
S18	Mortar	0.25	1	1	1	3.5	BPY	✔	✕
S19	Mortar	0.5	1	1.11	1	3.9	YPB	✔	✕
S20	Mortar	0.5	2	1.53	1	10	YPB	✔	✕
S21	PVC	0.5	1	1	1	2	YPB	✔	✕
S22	PVC	0.5	2	1.11	1	3.33	YPB	✔	✕

When plotted in *m-n* space, specimens S10 and S11 lie close to the delineating line that separates the YPB and BYP regions. Both specimens buckled just before reaching yield. These specimens were different than all other specimens in that the fibers were not bonded to the core material. As a result, the observed mode of failure was buckling and fracture of the fibers in the compression side (Fig. 7c). Specimens S12, S13 and S14 all yielded prior to buckling. They all eventually failed by fracture of the transverse fiber layer near the top of the specimen. The only difference between S12 and S13 was the way core material was attached to the steel member. In S12, the core material was bonded directly to the steel member, while in S13, the bond was eliminated. Since S13 performed better than S12, it was concluded that eliminating bond between the steel and core is beneficial. This was observed in other specimens as well.

The tapered specimens in Group-2 performed well. All the specimens in this group achieved substantial yield strains in compression and eventually failed in the same way, i.e. crushing of the core material at the middle followed by fiber buckling in the same region. None of the specimens suffered transverse fiber failure as was observed in several of the Group-1 specimens. One interesting observation was that the steel plate buckled in its second buckling mode, thus having an S-shape in the middle (Fig 7d). Specimens S15, S16 and S17, which have more longitudinal layers than required by Eqn. 7, showed stable performance until the core material started to crush. Since the mortar core was stiffer and stronger than the PVC core, mortar specimens (S15, S16) reached higher strains than the PVC specimen (S17). The only difference between S15 and S16 was the way the core material was attached to the steel plate. There was no bond between the core and the steel plate in S16, while S15 had full bond. As with S12/S13, the unbonded specimen (S16) performed better. Specimens S18 to S22 showed similar trends in behavior, with the mortar specimens performing somewhat better than the PVC specimens.

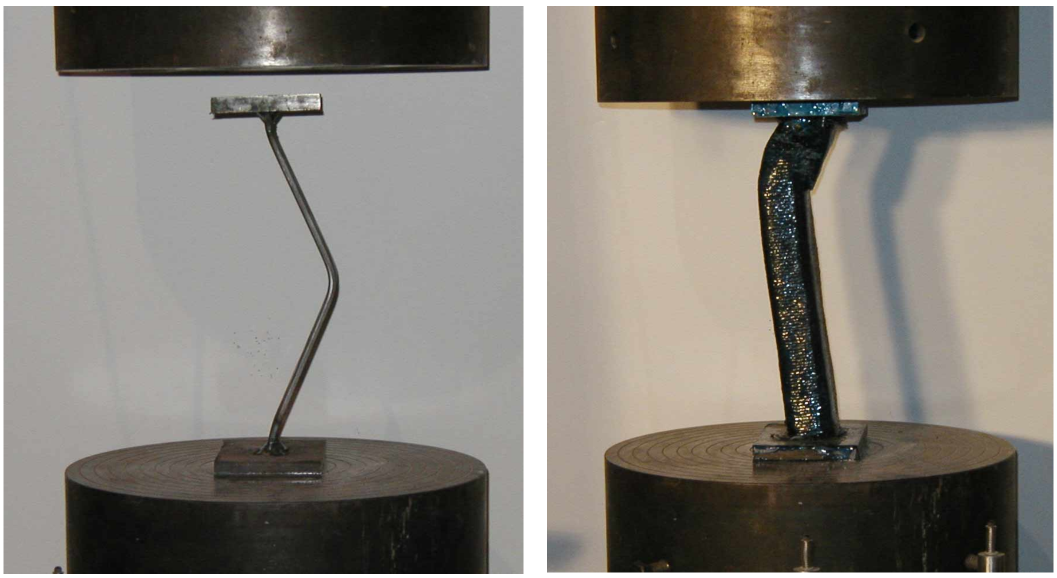

Figure 5. Test setup and final deformed shape of specimens

Summary and Conclusions

An analytical and experimental study was conducted to investigate the effect of CFRP wrapping on the buckling behavior of steel members. An expression for the stiffening requirement to prevent buckling is developed from equilibrium equations for thin steel plates. The methodology developed in this work can be extended to other types of compressive steel members. The developed model was validated with an experimental program that included specimens with different configurations, number of layers in longitudinal direction, core material type and thickness. The presence of bond between the core material and steel and bond between the core material and CFRP were other parameters investigated in the study.

The results showed that significant improvements in buckling and post-buckling response of steel plates can be achieved when the plates are sandwiched between mortar or PVC blocks then wrapped with CFRP laminates. All the specimens falling within the YPB space predicted by Eqn. 7 either maintained or exceeded their axial yield capacities at 2% strain levels. Having the specimens tapered in the middle alleviated the problem of eventual transverse fiber fracturing close to the ends of the specimens. It was also observed that performance of the strengthening scheme depended upon the strength and stiffness of the core material with mortar performing better than PVC as a core material.

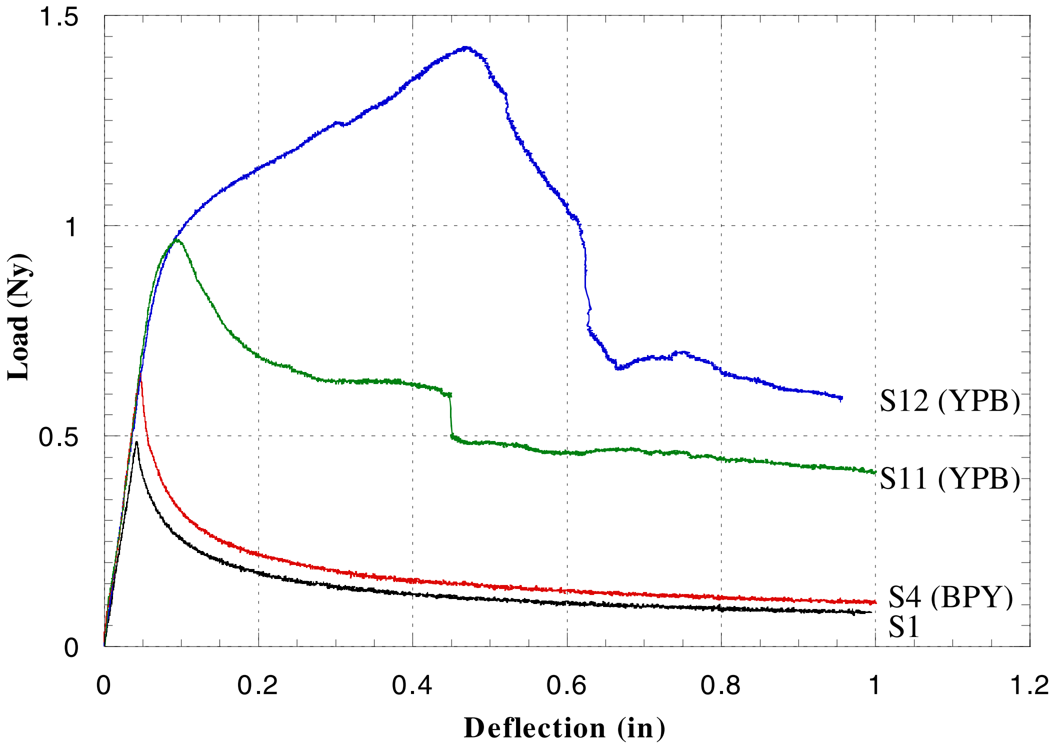

Figure 6. Load deflection curve for different cases.

(a) Fracture of longitudinal fibers

(b) Transverse layer fracture

(c) Buckling of longitudinal fibers

(d) 2^{nd} mode buckling in embedded steel member

Figure 7. Different failure modes

Specimens with bond between the steel plate and core material sustained smaller axial strains prior to buckling than specimens without bond. Bond between the steel member and surrounding core material transfers axial forces to the core and fibers, promoting earlier system failure. By eliminating the bond between core and steel, better performance of the system was observed. It was also observed that absence of bond between the core material and fibers permitted the CFRP wrap to buckle early, adversely affecting the strength of the entire system.

Although the specimens tested so far are quite small, they point to the exciting possibilities afforded by the proposed rehabilitation technology. The authors are currently conducting additional research to 1) develop suitable analysis and design models, 2) construct larger scale specimens to investigate the size effect, and 3) investigate other applications of CFRP to strengthen steel members.

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