FRP-STABILISED STEEL COMPRESSION MEMBERS

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ABSTRACT
An innovative use of fibre reinforced polymer (FRP) composite materials, to control the manifestation of local buckling in a steel bracing section, is proposed. In this method, the high stiffness and linear behaviour of FRP materials are utilized to provide “bracing” against flange local buckling (FLB) and web local buckling (WLB) in a way that strategically leverages the unique mechanical properties of each material in an efficient application domain. The research is aimed at demonstrating the feasibility of using small quantities of FRP to provide cross-sectional stability to steel members through the bonding of FRP strips to plate elements in a steel cross-section for the purposes of: increasing the bracing members critical load; constraining plastic flow in cross-sectional plate elements; and facilitating the manifestation of a well-formed and stable hysteretic response of the member under cyclic loading. The member becomes, in effect, an FRP stabilised steel section.

KEYWORDS
flange local buckling, FRP, lateral torsional buckling, steel, web local buckling

INTRODUCTION
In recent years, the field of structural engineering has seen extensive advances in the application of fiber reinforced polymer (FRP) composite materials for repair and strengthening of structures and their components. The merits of FRP retrofit of reinforced concrete members have been well researched and documented. Relatively limited work however has been conducted investigating the use of FRP to retrofit steel members. Carbon FRP (CFRP) materials have been used to strengthen steel members (e.g.: Cadei et al. 2004; Miller et al. 2004), enhance fatigue or fracture performance (e.g.: Jones and Civjan 2003) and provide local stability for steel compression members (e.g.: Ekiz and El-Tawil 2006; Shaat and Fam 2006). The present work investigates the concept of an FRP stabilised steel member. It is proposed that through the strategic application of FRP to a steel compression member a degree of buckling restraint may be affected.

The linear behaviour, high strength, and stiffness of FRP composites can be applied to a steel section to increase member stability. More specifically, small amounts of FRP composites can be utilized to increase resistance to flange (FLB) and/or web (WLB) local buckling. The purpose of such an application is not necessarily to increase load-carrying capacity but to restrict plastic flow of the plate member. A recent analytical study (Accord et al. 2006) utilized nonlinear finite element analysis to examine the effects of low modulus glass FRP (GFRP) strips bonded to I-shaped sections developing plastic hinges under a moment-gradient loading. The inclusion of GFRP strips provided effective bracing of the flange outstands delaying the formation of local buckling of the compression flange, ultimately increasing structural ductility. Similarly, Shaat and Fam (2006) focused on the increase in axial strength and stiffness of long and short hollow square section (HSS) columns wrapped with CFRP of varying types, number of layers, and fiber orientations. Results indicated an increase in axial load capacity for the short columns ranging from 8% to 18% while the stiffness increase ranged from 21% to 28%. A reported 13% to 23% increase in axial strength of the long specimens showed no correlation with CFRP applied, a result the authors attribute to variation of specimen out-of-straightness and misalignment of the test set-up.

Abraham and Harries (2007) proposed a concept analogous to that of buckling restrained braces (BRB) whereby a “partially buckling restrained brace” (PRRB) is affected by applying FRP to the slender outstands of a steel compression brace element to improve its hysteretic behaviour. Although not as robust as BRBs, PBRBs are felt to be appropriate for regions of low and moderate seismic where the outstanding performance (and associated cost) of BRBs is unnecessary.
Abraham and Harries (2007) and Abraham (2006) report an experimental program including six A992 Grade 50 (345 MPa) WT 155x10.5 steel brace specimens. Of these, one was encased in a circular steel HSS 177.8x3.2 section filled with grout creating a BRB; four were retrofitted with pultruded FRP strips; and one was tested as an unretrofit control specimen. The BRB specimen was tested for the purpose of comparison with the FRP retrofit options and was not the primary focus of this investigation. Of the four FRP-retrofit braces, high strength (HS) CFRP strips were applied to two and ultra-high modulus (UHM) GFRP strips were employed for the remaining two. For both CFRP and GFRP materials two cases were considered: a) a single 50.8 mm wide by 1.4 mm thick strip applied to the WT web; and b) two 25.4 mm wide strips placed on top of each other at the same location. The FRP strips were applied to each side of the stem of the WT centered 38 mm from the tip. The two 25.4 mm strips were preassembled and allowed to cure prior to installation on the WT section. The two FRP configurations used resulted in the same area of FRP materials having the same centroid applied to the steel section. The region of the WT stems to which the FRP was applied was ground using a 40 grit zirconia-alumina sanding belt to remove mill scale, corrosion product and to achieve a uniform roughened surface area of bare (white) steel. Following sanding and prior to FRP application, the steel surface was cleaned with a degreasing/corrosion inhibiting agent and allowed to dry. In this manner, it is believed that no corrosion product formed between the time of surface preparation and FRP application. A commercially specified adhesive system intended to bond FRP and steel adherands was used. The average adhesive thickness was measured to be 0.58 mm. Figure 1 gives a summary of the six specimens tested and their designations. Table 1 provides nominal manufacturer reported material properties.

Table 1. Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Rupture Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT 155x10.5</td>
<td>345</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>HS Carbon FRP</td>
<td>2790</td>
<td>155</td>
<td>0.018</td>
</tr>
<tr>
<td>UHM Glass FRP</td>
<td>895</td>
<td>41.4</td>
<td>0.022</td>
</tr>
<tr>
<td>Adhesive</td>
<td>31</td>
<td>3.91</td>
<td>0.025</td>
</tr>
</tbody>
</table>

1 tangent modulus of elasticity

The WT sections were cut to a length of 1664 mm. The connection detail was designed to a) reflect an AISC-compliant (2005) brace connection; and b) result in a transfer of forces coincident with the neutral axis of the WT section. Three 22 mm diameter A325 bolts were used to connect the brace to double-angle clip connection at both ends. All of the brace specimens were heavily instrumented and tested under concentric cyclic compressive loading to failure. Each brace was initially subjected to a small tensile force of approximately 8.9 kN to allow the loading sequence to pass through zero in each cycle. For all braces, with the exception of the BRB, the first loading cycle imposed a maximum 22.2 kN compressive load and then returned to the initial 8.9 kN tensile load. The following cycles incrementally increased the maximum compressive load by 22.2 kN each cycle and each returned to the initial 8.9 kN tensile load upon cycle completion. Each brace specimen reached at least 200 kN in this manner and cyclic loading was continued until failure occurred as defined by either excessive lateral deflection or FRP strip debonding. The BRB, expected to achieve a higher load capacity, was cycled in increments of 44.5 kN.
ELASTIC BUCKLING EXPERIMENTAL RESULTS

Each specimen (except B) exhibited elastic lateral torsional buckling (LTB) typical of a slender WT section. This behaviour is characterized by large lateral translations of the stem tip, twist about the centroid and nominal strong axis translation as shown in Figure 2. For the very slender stem WT tested ($d/t = 29.8 = 1.24\sqrt{E/F_y}$), plastic ‘kinking’ of the stem was observed with increased axial (and thus lateral) displacement. This behaviour is particularly obvious in Specimen C (Figure 2, far left). The presence of FRP on subsequent specimens helped to mitigate this post-buckling crippling.

The FRP retrofit specimens did not provide a significant increase in axial capacity compared to the control specimen C. The GFRP-2 and GFRP-1 retrofit specimens exhibited 6% and 9% increases in axial capacity, respectively; modest compared to the 91% increase exhibited by Specimen B. Specimens CFRP-2 and CFRP-1 exhibited a slight decrease in axial capacity as compared with the control Specimen C.

Despite little effect on axial capacity, the retrofit specimens did exhibit greater control over the weak-axis lateral displacement as well as the weak and strong-axis bifurcation loads. Weak-axis lateral displacement values of 2.5 mm and 7.6 mm, representing mid-height lateral displacements of L/655 and L/218, respectively, are arbitrarily selected to illustrate specimen behaviour. A weak-axis lateral deflection of 2.5 and 7.6 mm occurred at higher loads for the FRP-retrofitted specimens than for the control Specimen C. The load to cause a 2.5 mm (L/655) weak-axis lateral deflection increased between 10% and 51% for the FRP-retrofitted specimens. The load to cause a 7.6 mm weak-axis lateral deflection increased between 7% and 20% for the FRP-retrofitted specimens. An increase in the weak-axis bifurcation load ranging from 4% to 12% for specimens GFRP-2, CFRP-2 and GFRP-1 (listed in decreasing order) was observed. The strong-axis bifurcation load was observed to increase from 94% to 116%. This increase suggests a mechanism where the FRP provides stability to the relatively unstable stem and ultimately delays the onset of strong-axis buckling of the brace member.

Effect on Global Brace Behaviour

The slenderness ratio of a compression member is a function of member length and radius of gyration, $r$. Abraham (2006) investigated the local stabilizing effect of FRP on global brace behaviour. The stem of the WT section tested is locally very slender and presents a specific region at which to concentrate an FRP retrofit application. Considering only the WT stem, the increase in weak-axis radius gyration ($r_y$) due the application of the FRP ranged from 12% to 14%. This suggests the prospect of increasing stability on a local level. However, a negligible increase in $r_y$ is determined when the entire WT cross section is considered; thus there is a negligible effect on the global brace behaviour. The FRP-retrofitted members tested seem to mirror this predicted behaviour. The GFRP retrofit specimens in particular seemed to increase resistance to lateral displacement of the stem, while minimally increasing the member’s axial compressive capacity suggesting only a localized effect.

Additionally, the softer GFRP retrofit provided sufficient restraining forces to mitigate residual deflections following significant buckling. Mitigating residual displacement also mitigates the formation of the plastic “kink” which forms in the member and ultimately contributes to the degradation of brace’s compressive capacity under cyclic loading. Thus reduced residual displacements lead to reduced degradation of capacity resulting in greater compressive capacity for subsequent load cycles. The improved brace performance is shown...
schematically in Figure 3 (Bruneau et al. 1998) as a) an increased “plateau” length (AB); b) no degrading compression curve (BC); and c) no degradation on subsequent compression cycles (Cr to Cr'). Thus greater hysteretic energy may be dissipated without actually increasing the brace capacity. The test results presented additionally suggest that a softer FRP material is better suited for this application contrary to conventional perceptions that the retrofit material stiffness should be similar to that of the steel substrate.

![Figure 3. Sample brace hysteresis modified to reflect reduced residual displacement.](adapted from Bruneau et al. 1998)

**PROGRAM INVESTIGATING PLASTIC BUCKLING BEHAVIOUR OF SLENDER SECTIONS**

To investigate the local stabilizing effects of FRP on buckling-susceptible slender members, an experimental program of stub column tests was carried out. Fifteen 356 mm long WT 155x10.5 sections having the same FRP details shown in Figure 1 (with the exception of the BRB Specimen B) were tested in concentric compression to failure. Three specimens of each detail were tested. With the exception of the specimen length, all details, materials and preparation are the same as that previously described (Figure 1 and Table 1). The specimen length was selected to ensure local buckling of the WT stem with no LTB of the section. Due to the relatively stocky flanges, these did not experience any instability. The stem slenderness, \( \frac{d}{t} = 29.8 = 1.24 \sqrt{\frac{E}{F_y}} \), is more than three times that of the flanges: \( \frac{b}{2t} = 8.8 = 0.37 \sqrt{\frac{E}{F_y}} \), while \( \frac{L}{r_y} = 18.6 \). Specimen length was also selected to provide a bonded length of FRP both above and below the midheight of the specimen greater than the effective bond length of the FRP, calculated as falling between 60-75 mm and 30-40 mm for the CFRP and GFRP, respectively (Nozaka et al. 2005). Specimen ends were ground for bearing and made parallel. Loading was applied uniformly to the entire cross section at a rate of approximately 20 kN/min.

**PLASTIC BUCKLING EXPERIMENTAL RESULTS**

Each specimen was dominated by stem or web local buckling (WLB). No evidence of FLB or LTB was seen in any specimen tested. A summary of average test results is given in Table 2. Representative behavior of one of the GFRP-1 specimens is shown in Figure 4. The WLB bifurcation load given in Table 2 is the applied load at which WLB at the tip of the stem initiated. This load was determined by comparing strain gage readings on either side of the stem tip and determining the apparent through-stem eccentricity of the axial load. Prior to WLB, these gages “track” each other, recording essentially the same compressive strains (Figure 4(b)). At the initiation of WLB, the stem begins to bend and the strain readings diverge, as one becomes increasingly compressive and the other reverses and eventually goes into net tension as the buckle becomes substantial (Figure 4(b)).

The presence of the FRP increased the axial load carrying capacity between 4% and 14%. The bifurcation loads were increased as much as 17%. In these tests, the CFRP specimens exhibited a more pronounced improvement in behaviour. Similarly, the specimens having two 25.4 mm wide FRP strips (C/GFRP-1) performed better that those with one 50.8 mm strip (C/GFRP-2). Debonding of the FRP strips was a post-peak phenomena in all tests. Generally debonding occurred at an applied load of about 75% of the peak load on the descending branch of the load curve. Debonding of both the “tension” FRP strip at its ends (shown in Table 2: GFRP-2) and of the “compression” strip near the middle (Table 2: CFRP-1) was observed. In at least one case, a compressive failure (without evidence of debonding) of a 50.4 mm wide CFRP strip was observed indicating generally sound bond quality (Figure 5). Due to the short specimen length, little anchorage length for the FRP is provided which
exacerbated the “end peel” failure mode (Table 2: GFRP-2). A longer bond length relative to the plastic buckling region should lead to further improved performance.

Table 2. Results of plastic buckling tests (average of three tests in every case).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>CFRP-1</th>
<th>CFRP-2</th>
<th>GFRP-1</th>
<th>GFRP-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak axial compression (kN)</td>
<td>345</td>
<td>392</td>
<td>370</td>
<td>377</td>
<td>358</td>
</tr>
<tr>
<td>WLB bifurcation load (kN)</td>
<td>320</td>
<td>375</td>
<td>348</td>
<td>371</td>
<td>327</td>
</tr>
</tbody>
</table>

A representative photograph taken during post-peak response at axial load of 80% of peak load (debonding shown by arrows)

![Representative Photograph](image)

Similar to the behaviour exhibited by the elastic buckling specimens, in all cases the presence of the FRP served to mitigate the “kink” associated with plastic buckling. This improved behaviour is evident in Table 2 where all FRP specimens exhibit a smooth curvature over their 356 mm length whereas Specimen C exhibits a pronounced kink having “wavelength” of approximately 260 mm. Following FRP debonding, a “kink” formed in some

![Load-Displacement Curves](image)

(a) load-displacement curves.

(b) load-strain curves.

Figure 4. Representative behavior of Specimen GFRP-1-A.

Figure 5. Specimen CFRP-2A showing compressive failure of bonded CFRP.
specimens. The initiation of this kink is barely apparent associated with the debonding shown for Specimen GFRP-2 in Table 2.

CONCLUSIONS

The concept of strategically applying FRP material to a steel brace to create a partially buckling restrained brace as presented in this paper may not hold great promise as a viable retrofit option per se. The nominal affect of the addition of small amounts of FRP has little effect on the elastic buckling behaviour of the long brace sections typically found in building structures. The FRP retrofit is able to affect local behaviour however and will enhance the brace behaviour to a degree. Improvement in load-carrying capacity is proportional to the increase in effective radius of gyration (r_y) affected by the presence of the FRP. For elastic buckling, the entire section is considered in which case the increase in r_y is nominal. For plastic buckling, only the outstanding plate element (tee stem, in the present case) is considered in which case the proportional improvement in capacity is greater.

Prior to FRP debonding, the presence of the FRP controls the plastic buckling and delays the formation of the plastic “kink”. The formation of this kink affects the cyclic compressive capacity of the section upon subsequent reloading, the tensile stiffness of the section and can lead to section fracture in relatively few loading cycles. Thus the application FRP may represent a viable option for improving the energy absorption and ultimate cyclic ductility of elements susceptible to plastic buckling in a seismic lateral force resisting system. This concept is being explored by the lead author in relation to the retrofit of steel moment frames.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the in-kind support of the Fyfe Company Inc. and Fox Industries. The second author was the recipient of the 2006 AISC/Klingelhofer Fellowship. Experimental work was conducted in the Watkins Haggart Structural Engineering Laboratory at the University of Pittsburgh.

REFERENCES