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Recent Developments in CFRP Strengthening of Steel Tubular Members and Connections

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ABSTRACT: Steel tubular structures are widely used in engineering applications, such as bridges, buildings, space frames, recreation structures, mining equipment and transportation vehicles. Some of the tubular structures are aging or need strengthening due to increased service load. The use of CFRP (carbon fiber reinforced polymer) to strengthen steel structures has become an attractive option. Extensive research has been conducted in the last decade in this field. This paper presents a summary of the recent developments in FRP strengthening of steel tubular members and connections. It includes various types of strengthening, such as web buckling under concentrated force, local buckling in compression and bending, energy absorption under large axial deformation, earthquake and fire damage of concrete-filled tubular members, and fatigue of welded tubular joints.

1 INTRODUCTION

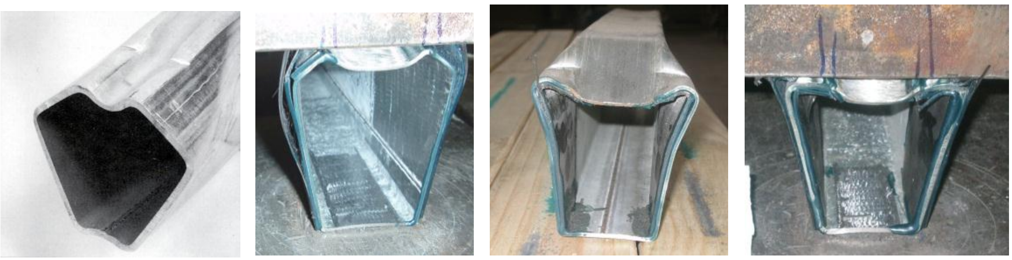
CFRP (carbon fibre reinforced polymer) has high strength to weight ratio, resistance to corrosion and to environmental degradation (Hollaway and Teng 2008). While CFRP has been widely used in strengthening aircraft and more recently concrete structures (e.g. Teng et al. 2002, Baker et al. 2002, Rizkalla et al. 2003, Oehlers and Seracino 2004), it has not been widely applied to steel structures. The knowledge gained from research on repairing aircraft cannot be directly applied to steel structures in Civil Engineering because different materials are used. Moreover the existing knowledge of the CFRP-concrete composite system may not be applicable to the CFRP-steel system because of the distinct difference between the debonding mechanism of the former and latter, alongside the unique failure modes (e.g. local buckling, fatigue) for steel members and connections. It has been shown recently in the state-of-the-art reviews (Hollaway and Cadei 2002, Zhao and Zhang 2007, Teng et al. 2012) that CFRP has great potential to strengthen steel structures in the field of Civil Engineering.

Steel tubular members and connections are widely used in civil engineering structures (e.g. Zhao et al. 2005, Wardenier et al. 2010, Zhao et al. 2010). This paper presents a summary of the recent developments in FRP strengthening of steel tubular members and connections. It includes web buckling of rectangular hollow sections under concentrated load applied through a bearing plate or welded branch member, circular and square hollow section (CHS and SHS) beams and columns, SHS columns under large deformation axial force and impact load, earthquake resistance and fire damage repair of concrete-filled tubular columns, welded steel cross-beam connections under fatigue loading. Discussions are carried out in terms of failure modes, behaviour, strength improvement and design recommendations. Up-to-date references are given in the paper.

2 WEB BUCKLING OF RHS

2.1 Failure modes

Zhao et al. (2006) carried out a series of experimental testing on cold-formed RHS strengthened by CFRP plates. The failure modes are shown in Figure 1. Web buckling was observed for RHS alone, whereas web buckling or yielding occurred for CFRP strengthened RHS. Three types of strengthening were adopted, namely Type O, Type I and Type B, as shown in Figure 2.



(a) Without CFRP (b) Type O (c) Type I (d) Type B

Figure 1. Typical failure modes of RHS subject to end bearing force (Zhao et al. 2006)

Fam & Aguilera (2012) applied GFRP (glass fibe reinforced polymer) plates to welded SHS T-joints under concentrated load. For thin-walled SHS, the localized web crippling shifted away from the GFRP plated region. For thick SHS, delamination within the GFRP plate itself occurred, while the adhesive bond layer was intact.

2.2 Behaviour and strength improvement

Typical load versus deformation curves are plotted in Figure 2 for a cold-formed RHS 100×50×2 with various types of strengthening. It can be seen from Figure 2 that CFRP strengthening increases not only the ultimate load capacity but also the ductility of RHS member. The increase of bearing capacity is about 50% for Type O, up to 200% for Type I and up to 4.6 times for Type B, respectively (Zhao et al. 2006). The load carrying capacity increased up to 50% for GFRP plate strengthened welded SHS T-joints under concentrated load (Fam & Aguilera 2012).

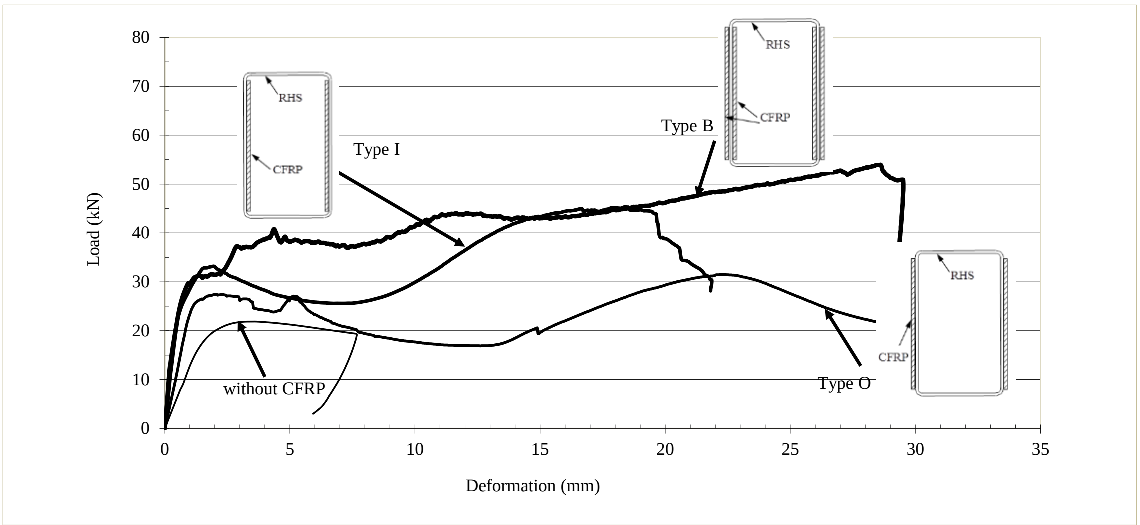


Figure 2. Load versus deformation curves (adapted from Zhao et al. 2006)

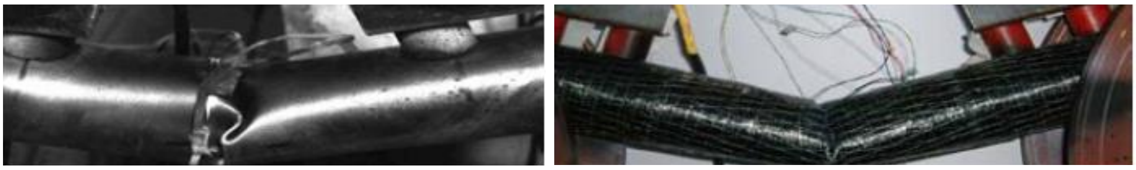
2.3 Design recommendation

The design of CFRP strengthened RHS depends on the governing failure mode of unstrengthened RHS (web bearing buckling or web bearing yielding) and types of strengthening (Zhao et al. 2006): (i) For Type O strengthening of RHS which fails by web buckling, use the same design formulae as those for RHS (Standards Australia 1998) except for a lower effective buckling length factor of 0.8. (ii) For Type I or Type B strengthening of RHS which fails by web buckling, use the same web yielding formulae as those for RHS (Standards Australia 1998) except for an upper bound value α_p of 0.32. (iii) For RHS which fails by web yielding, use the same web yielding formulae as those for RHS (Standards Australia 1998) except for an upper bound value α_p of 0.32 and steel ultimate strength replacing its yield stress.

3 CHS/SHS BEAMS

3.1 Failure modes

Haedir et al. (2009) carried out a series of tests on CFRP sheet strengthened CHS beams. The section slenderness of the CHS varied in such a way to cover 3 types of section classes defined in AS4100 (Standards Australia 1998), i.e. compact, non-compact and slender sections. Both longitudinal and transverse CFRP sheets were applied. The local buckling of CHS was delayed or eliminated due to CFRP strengthening as shown in Figure 3.



(a) CHS without CFRP (b) CHS with CFRP

Figure 3. Failure modes of CHS beams (Haedir et al. 2009)

Seica & Packer (2007) also conducted bending tests on CHS beams strengthened by CFRP sheet. Curing of the specimens was performed both in air and in seawater, the latter simulating the condition for underwater application to offshore structures. Two layers of CFRP was applied longitudinally followed by a third layer in transverse direction. No serious debonding problems were found in any of the specimens. Photiou et al. (2006) performed tests on artificially degraded rectangular hollow section beams (i.e. reduce the thickness of the bottom flange) repaired by CFRP and GFRP. Two types of upgrading systems were adopted. One utilised flat plate GFRP and CFRP prepregs bonded only to the tension flange. The other one utilised U-shaped GFRP prepregs, which were bonded to the tension flange and were extended up on the web. The beams with high modulus (135 GPa) CFRP demonstrated ductile response with no fibre or adhesive failure up to a maximum deflection of span/40. Carbon fibre breakage occurred only in the beams with ultra-high modulus (270 GPa) CFRP.

3.2 Behaviour and strength improvement

The strengthening efficiency depends on various factors, including the number of CFRP layers, strengthening configurations, fibre orientation, and volume fractions of the fibre and adhesives layers. The longitudinal fibres tend to increase the moment capacity, whereas the transverse fibres tend to increase the ductility as schematically shown in Figure 4. The increase in ultimate moment capacity was found by Haedir et al. (2009) to be up to 90%.

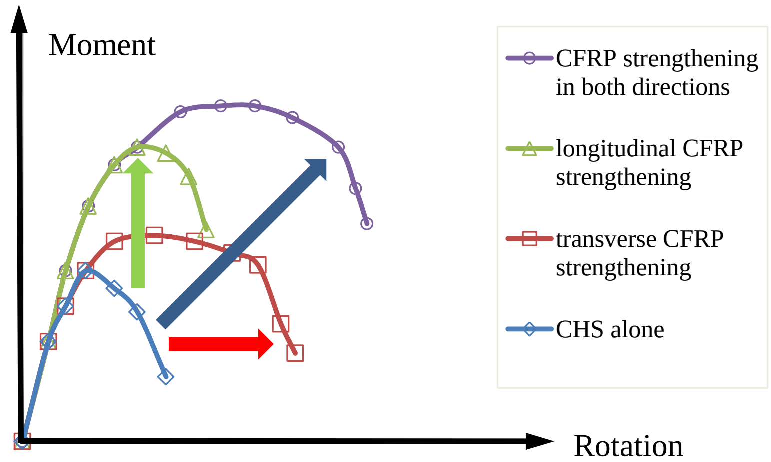


Figure 4. Schematic view of moment versus curvature curves

Seica & Packer (2007) found that for the CHS wrapped and cured in air, ultimate strength increased 16 to 27% while the flexural stiffness increased 7 to 18%. Slightly less increase was obsevred when wrapping and curing were performed under seawater. It was concluded by Photiou et al. (2006) that, provided the ultimate strains in the high modulus carbon fibres are not exceeded and the bonding mechanisms are sufficient, the steel beams can be deformed well into its plastic region. All the upgraded beams reached the plastic collapse load of the original undamaged RHS beams.

3.3 Design recommendation

Haedir et al. (2010, 2011) presented analytical models for determining the ultimate moment capacity and for predicting the moment-curvature response of CFRP-reinforced steel CHS beams. The nonlinear model accounted for material properties of the steel and CFRP, volume fractions of the fibre and adhesive, amount of CFRP, and a wider range of section slenderness. Design rules for predicting the ultimate moment capacity of composite CHS were also proposed.

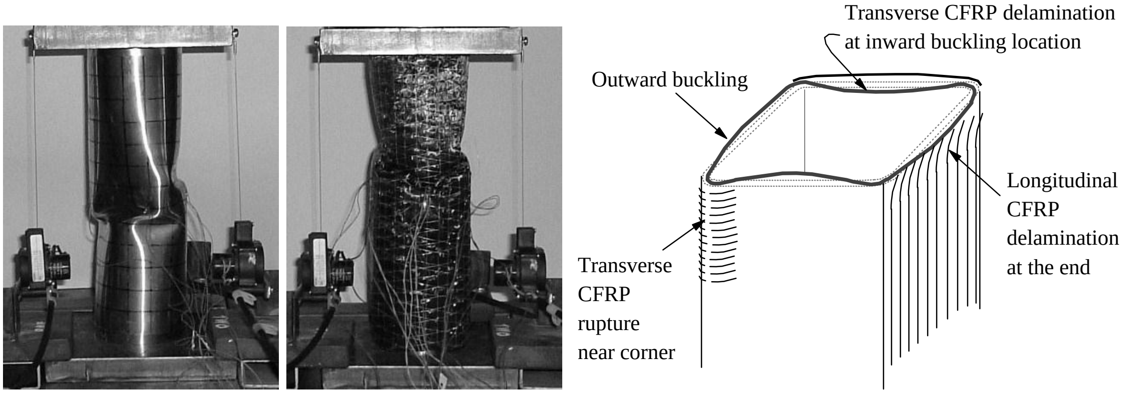
4 CHS/SHS COLUMNS

4.1 Failure modes

Haedir & Zhao (2011) performed tests on CFRP sheet strengthened CHS short columns. Shaat & Fam (2006, 2009) studied CFRP strengthened SHS columns. Typical failure modes are illustrated in Figure 5. Teng & Hu (2007) also investigated GFRP strengthened CHS short columns. For long SHS columns, three failure modes were identified by Shaat & Fam (2009): (i) CFRP fails before overall buckling; (ii) CFRP fails simultaneously with overall buckling and (iii) CFRP fails after overall buckling.

4.2 Behaviour and strength improvement

For short columns, local buckling is delayed or eliminated because of CFRP or GFRP. The increase in compression capacity of CHS short columns was found to be up to 75% if CFRP was used (Haedir & Zhao 2011) and about 10% if GFRP was used (Teng & Hu 2007). The increase in compression capacity of SHS columns was about 20% (Shaat & Fam 2006, 2009).



(a) CHS without CFRP (b) CHS with CFRP (c) SHS with CFRP

Figure 5. Failure modes of CHS/SHS columns (Haedir & Zhao 2011, Zhao & Zhang 2007)

4.3 Design recommendation

Haedir & Zhao (2011) proposed design formulae for CFRP strengthened CHS in compression, which are related to the existing standards AS4100 (Standards Australia 1988) and EC3-Part 1.1 (CEN 2005). Shaat & Fam (2007) developed a non-linear fiber model to predict the load versus (axial and lateral) displacement curves of CFRP-strengthened SHS columns. The model takes into account material and geometric nonlinearities, residual stresses and failure of CFRP in compression. Shaat & Fam (2009) developed a design-oriented model for CFRP-strengthened SHS columns, which consists of a modification of the design rules for SHS columns included in the ANSI/AISC specification (AISC 2005).

5 SHS COLUMNS SUBJECT TO LARGE DEFORMATION/IMPACT

5.1 Failure modes

Bambach & Elchalakani (2007) carried out a series of tests on SHS (width-to-thickness ratio from 25 to 50) stub columns under large axial deformation. When CFRP is applied, the SHS stub column failure mode was found to be very similar to that of unstrengthened SHS, i.e. involving multiple folding mechanisms as shown in Figure 6 (a). No delamination occurred prior to the attainment of the ultimate load, which indicates that the CFRP was well bonded to the SHS. During the large deformation crushing process, the CFRP typically delaminated from the steel at the column ends, and undergoing rupture at the corners and at the exterior of the folds.

Impact tests on CFRP strengthened SHS stub columns were conducted by Bambach et al. (2009). The failure modes are similar to those under large deformation static load except that the delamination failure is more likely to occur (see Figure 6 (b)).

(a) Static large deformation (b) Impact loading

Figure 6. Failure modes of SHS columns (Bambach & Elchalakani 2007, Bambach et al. 2009)

5.2 Behaviour and strength improvement

Bambach & Elchalakani (2007) revealed that the compression strength increases up to 102%, whereas the energy absorption increases up to 113%. Bambach et al. (2009) found that the application of CFRP to existing steel SHS can increase the dynamic mean crushing load of the member by about 80% and energy absorption by about 50%.

5.3 Design recommendation

Bambach & Elchalakani (2007) applied the plastic mechanism analysis method (Zhao 2003) to CFRP-strengthened SHS columns undergoing large deformation. The derivations are similar to those reported in the literature for SHS members in compression by Key & Hancock (1986) and Zhao et al. (2002). The influence of CFRP has been considered through modifications of the material properties. A theoretical method previously developed (Bambach & Elchalakani 2007) for calculating the mean crushing load of steel–CFRP SHS quasi-statically has been modified by Bambach et al. (2009) to account for strain-rate effects, and compared well with the experimental results.

6 CONCRETE-FILLED TUBULAR MEMBERS

Research was conducted (Zhao Y. et al. 2005, Tao et al. 2007a, Sun et al. 2008) on concrete-filled steel hollow section short columns strengthened by CFRP. The dominating failure mode was found to be CFRP rupture at outward mechanism locations. Xiao et al. (2005) studied circular CFST columns confined by CFRP to avoid plastic hinges forming at critical locations in buildings (i.e. soft storey behaviour) under earthquake loading. A gap (made with 1-mm-thick soft foam tapes affixed on the surface of the steel tube) was introduced between the CFRP and the tubular column to delay the engagement of the CFRP, to achieve both increased strength and ductility. A series of tests were conducted (Tao et al. 2007b, 2008, Tao & Han 2007) to investigate the feasibility of using CFRP in repairing CFST columns after exposure to fire.

Teng et al. (2007) developed a hybrid FRP–concrete–steel double-skin tubular column. The test results confirmed that the concrete in the new column is very effectively confined by the two tubes and the local buckling of the inner steel tube is either delayed or suppressed by the surrounding concrete, leading to a very ductile response. When such hybrid sections are used as beams, the inner steel tube could be shifted towards the tensile side. Such beams were found to have a very ductile behaviour (Yu et al. 2006). More research is needed to develop design rules for such composite columns.

7 WELDED STEEL TUBULAR JOINTS

Welded cross-beams are used in undercarriages of motor vehicles and trailers. They are subjected to fatigue loading. Xiao & Zhao (2012) investigated the strengthening of such welded cross-beam connections using CFRP sheet, as shown in Figure 7. Both circumferential and transverse restraining CFRP patches were applied in the corner region that prevents early debonding successfully and led to significant increase in fatigue life. A further improvement in fatigue life was achieved by placing a steel angle between the vertical and horizontal members. Numerical simulations and fracture mechanics analysis are needed to predict the increased fatigue life of such welded tubular joints.

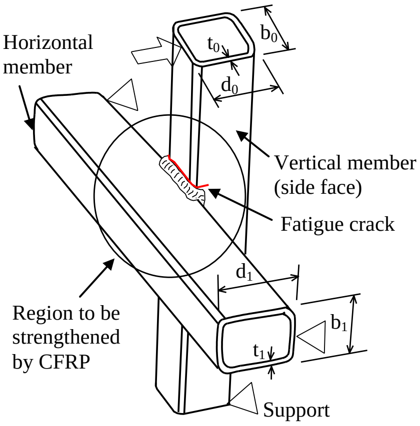


Figure 7. Schematic view of CFRP strengthening of welded cross-beams (Xiao and Zhao 2012)

8 CONCLUSIONS

This paper presented a summary of the recent developments in FRP strengthening of steel tubular members and connections. It covered strengthening of web buckling, local and overall buckling of steel beams and columns, increased energy absorption under large axial deformation and impact loading, improved earthquake resistance and fire damage repair of concrete-filled tubular members, and fatigue strengthening of welded tubular joints.

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