Axial compressive behaviour of circular hollow section (CHS) strengthened by prefabricated FRP jacket system

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ABSTRACT
This paper reports a series of tests on axial compressive strength and behaviour of steel circular hollow sections (CHS) strengthened by a prefabricated FRP jacket system, Sitejacket™. The experiment program aimed to investigate the structural behaviour of FRP-jacketed CHSs including (i) axial compressive strength enhancement, (ii) axial behaviour of stub CHS and (iii) various failure modes. The main test parameter is the thickness of the CHS which is expected to directly influence the axial strength, failure mode and deformability. All test specimens were loaded to failure with a constant loading rate to enable close monitoring and recording of the failure process. Based on test results, strength and stiffness changes and different failure modes of the strengthened CHSs are reported. Full axial behaviour of various specimens including pre-and post-yielding stages of the jacketed CHSs was also presented.

KEYWORDS
Circular hollow section, column, confinement, Fibre reinforced polymer, jacket, repair, steel

INTRODUCTION
Steel structures constructed in harsh environment have shown a serious level of degradation due to steel corrosion. High demand for remedial activities for steel structures has been reported to extend the service life by all means. Traditionally, steel plating is the most commonly accommodated remedial solution for rehabilitating and strengthening steel structures while its effectiveness has been compromised due to the presence of steel corrosion endanger in both existing and newly plated steel.

Fibre reinforced polymer (FRP) composites have become popular as a versatile structural solution to reinforced concrete (RC) structures. During last two decades, a large number of academic publications and industrial case studies have been released for establishing solid theoretical and practical database to develop national and international design guidelines which enable engineers to practically use FRP composites in construction (e.g. ACI 2008, Concrete Society 2004, fib 2001). However, the applications of FRP to steel structures for rehabilitating and/or strengthening to date are very limited. Only a small number of academic publications are available and few case studies from industry have been reported (e.g. Hollaway and Teng 2008, Xia and Teng 2005, Zhao and Zhang 2007).

The effectiveness of FRP confinement system for structural rehabilitating or strengthening has frequently been reported. FRP wrapped circular RC columns in the hoop direction show excellent performance in strength and axial deformability (e.g. Mirmiran et al. 1998; Xiao and Wu 2000, Lam and Teng 2002; De Lorenzis and Tepfers 2003; Teng and Lam 2004; Bisby et al. 2005, Wu and Wang 2009, Kim and Smith 2010).

A number of experiments of FRP confined steel columns have also been reported. Similar to FRP-confined RC columns, the circular steel section (i.e. CHS) shows substantial axial strength increase and large deformation at ultimate state (e.g. Shaat and Fam. 2006, Teng and Hu 2007, Bambach et al 2009, Jaedir and Zhao 2011).

The common FRP wrapping technique utilises a wet lay-up system, i.e. wrapping resin saturated fibres around the column. Such a system can be very effective in normal applications (i.e. applying to dry structural members) but not practicable in wet or underwater applications. Industrial Composite Contractors (ICC) has been developing a pre-constructed FRP jacket system, Sitejacket™, for circular structural members. This system is specially aimed at wet or underwater applications by injecting resin between the steel substrate and a sealed pre-constructed jacket which is assembled on site (ICC 2011). A specific type of resin has been developed to ensure sufficient bond strength to wet substrates (e.g. concrete, steel, FRP laminate).

This paper presents a summary of an experimental investigation of axially loaded FRP-confined (i.e. Sitejacket™ system) CHS as a part of an industrial validation process. The fundamental behaviour of axially loaded stiff columns is experimentally investigated to identify maximum load, failure mode and axial deformation. The effectiveness of the pre-constructed FRP jacket is also investigated with particular attention on the variable wall thickness of CHS by comparison with counterpart control specimens.

EXPERIMENTAL DETAILS

Detail of test specimens

The experimental program consisted of testing six CHSs under monotonically increasing axially load by displacement control (Table 1). The specimens were classified into two categories according to their wall thickness; (i) normal section (nominal 4.8 mm wall thickness, denoted by NS in Table 1) and (ii) slender section (nominal 1.0 mm wall thickness denoted by SS in Table 1) which aim to simulate non-corroded and severely corroded section, respectively. The NS specimens were obtained from commercial supplier while the SS specimens were constructed by rolling and welding sheet metals. All CHS sections were nominally 220 mm in diameter and 670 mm in height.

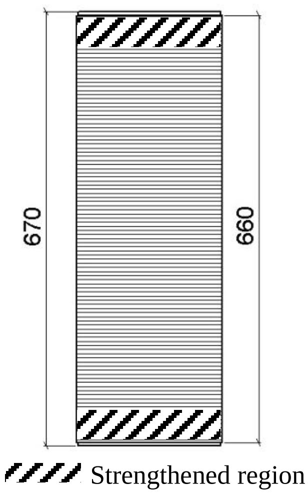

Figure 1. Test specimen

Figure 2. Test set-up

All jackets were constructed by the use of exactly the same amount of fibres through vacuum infusion process (ICC 2011). The jacket consisted of one layer of unidirectional carbon fibre at circumferential direction and mechanical properties of carbon fibre are given in Table 2.

Table 1. Test specimen

ID	CHS				Jacket		
	Diameter (mm)[#]	Wall thk. (mm)[#]	Height (mm)	fy (MPa)[##]	Fibre	No. of layer	Weight (gsm)
NS[^]-C-1	220	4.8	670	350	Carbon fibre	-	-
NS-J-1~2						1	610
SS[^^]-C-1		1.0		250		-	-
SS-J-1~2						1	610

[#]: nominal diameter or thickness, [##]: Manufacturer's data
[^]: commercially available section, [^^]: constructed form rolling and welding thin sheet metal

The FRP confinement consists of three curved pre-constructed FRP plates, i.e. one jacket and two joinery plates which appropriately fit and form an enclosed shell outside of the CHS. Both ends of the jacket which covers approximately 300 degree of circumferential length of column was connected to two joinery plates on its inner and outer face with nominal 50 mm double overwrap length. The length of jacket was designed to be 10 mm shorter than CHS in height to avoid direct loading to the jacket (i.e. 5 mm gap at the top and bottom, Figure 1). The surface of all CHS was prepared by grit blasting. After placing the jacket in position, the gap between the jacket and CHS was filled by resin then cured in ambient temperature for at least 7 days to test. In addition to the jacket, two layers of 50 mm wide carbon fibres were applied by typical wet lay-up method at top and bottom region of the jacket to avoid premature failure at loading and bearing region (refer to hatched regions in Figure 1).

Table 2. Material Proprieties

	Modulus (GPa)	Strength (MPa)	Areal weight (gsm)	Fibre thickness (mm)
Carbon fibre[#]	230	4900	610	0.337

[#]: Manufacturer's data

All testing was conducted in a universal testing machine of 3,000 kN capacity. The base test platen was fixed to a stiff reaction frame, however, the top loading platen was joined to a spherical seat was connected to the crosshead (Figure 2). All specimens were loaded to 15 kN at a load rate of 5 kN/min and then loaded to failure with a constant ram displacement of 1 mm/min. Applied load and crosshead displacement were recorded by digital data logging system throughout the tests.

EXPERIMENTAL RESULTS

Failure load and failure mode

All unstrengthened control specimens failed by typical buckling failure (i.e. elephant's foot buckling). A clear forming of a circumferential yield line was observed in both NS-C1 and SS-C1 specimens. For the normal section specimen, (i.e. NS-C1), the buckling failure occurred after experiencing a yield plateau (i.e. a large axial displacement with little strength increase) (Figures 3 and 4). The slender specimen (i.e. SS-C1) showed very little or no post yielding behaviour and sudden strength loss just after the buckling failure. Such behaviour implies that the slender structure did not have a sufficient deformability.

Table 3. Test results

ID	Diameter (mm)[#]	Wall Thk. (mm)[#]	Failure load (kN)	Failure load (%)[^]	Axial Displacement (mm)	Axial Displacement (%)[^]
NS-C-1	219.1	4.7	1219.1	-	8.3	-
NS-J-1	219.0	4.8	1625.8	33	14.4	73
NS-J-2	219.0	4.7	1650.9	35	14.4	73
SS-C-1	219.1	0.9	110.3	-	1.9	-
SS-J-1	219.3	0.9	212.3	92	4.3	126
SS-J-2	218.8	0.9	223.8	103	4.5	137

[#]: averaged from 4 measurements (less than 4 % of coefficient variation)
[^]: increase ratio respect to control specimen

Figure 3. Failure of NS-C-1

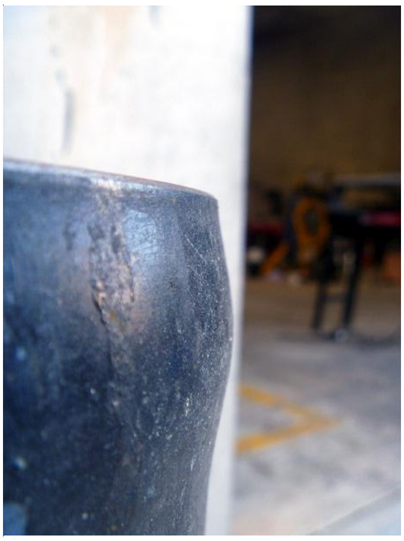

Figure 4. Failure of NS-C-1 (Detail)

All jacketed specimens showed a substantial improvement in axial strength and increase in deformability. The jacketed specimens showed an increase of maximum axial strength and displacement with respect to unjacketed control specimens of 34 % and 73 % for NS specimens and 98 % and 132 % for SS specimens, respectively (Table 3).

The jacketed specimens with the normal section (i.e. NS-J-1 and NS-J-2) showed similar behaviour to that of normal FRP confined specimens (i.e. wet lay-up system specimens) (e.g. Teng and Hu 2007 and Jaedir and Zhao 2011). Localised failure of the jacket and wall buckling occurred at the same region just after reaching the peak load following a large axial displacement. Elephant's foot buckling was observed in NS-J-1 just beneath the failed jacket joint (Figure 5) and inward wall buckling also occurred in NS-J-2 at the same height of the localised jacket joint failure (Figure 6). It should be noted that only localised failure at the jacket joint occurred in the sample NS-J-1, however, a strip of the jacket was removed in order to observe the steel failure as seen in Figure 5.

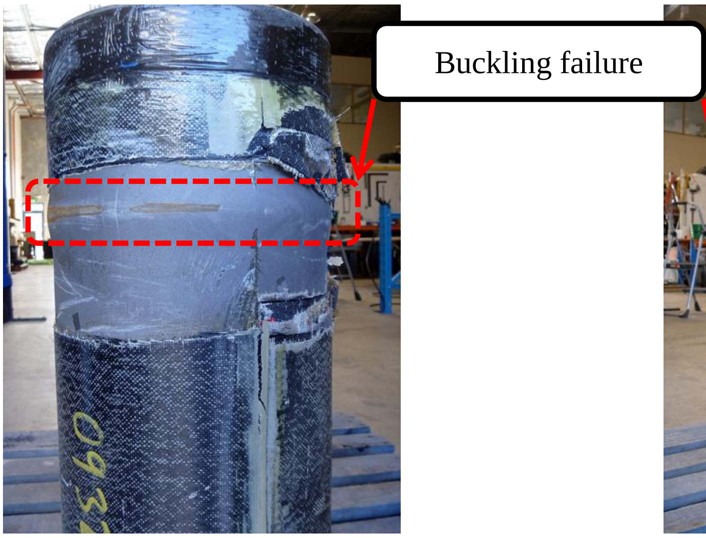

Figure 5. Failure of NS-J-1

Figure 6. Failure of NS-J-2

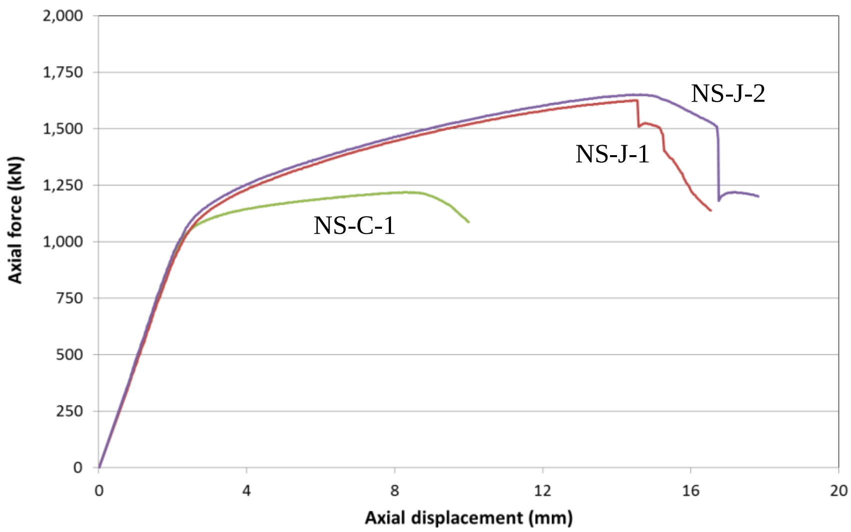

Figure 7. Axial load and displacement response – NS specimens

Figure 7 shows axial load and displacement response for NS specimen. All specimens showed similar behaviour until reaching the yield strength of the unjacketed control specimen. As load increased, the jacketed specimens displayed a significant improvement of axial stiffness (i.e. higher load/displacement slope) than that of the unjacketed specimens. Similar to the wet lay-up steel confined columns, the confinement action resulted in higher load carrying capacity and larger axial displacement.

All jacketed slender specimens (i.e. SS-J-1 and SS-J-2) showed localised crushing failure at the bearing region (Figure 8). The intentionally formed non-jacketed 5 mm bare steel collapsed vertically like a concertina and the failure kept progressing within the 50 mm strengthened jacket bearing region (Figure 9). The columns were still able to carry certain level of load during such local failure progress (approximately ranged 60 -90 % of the peak load) with high load fluctuation, however these results are not reported herein. No sign of failure in both steel and jacket system was observed in the testing region (Figure 8). It is the hypothesis that if such a localised premature failure could be avoided, the column would be demonstrated to have a much higher level of strength and/or deformability enhancement but this issue will be left to future study.

Figure 7

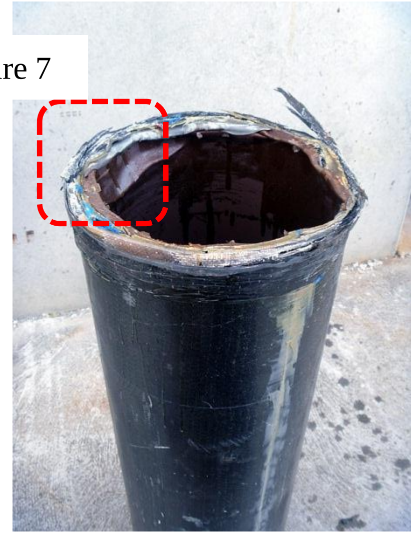

Figure 8. Failure of SS-J-1

Figure 9. Failure of SS-J-1 (Detail)

Figure 10 shows axial load and displacement response for SS specimen. The jacketed slender CHSs (i.e. SS-J-1 and SS-J-2) showed a significant increase in both axial strength (92 % and 103 %) and displacement (126 % and 137 %). Different from NS specimens, no noticeable sign of stiffness changes (i.e. slop in axial load and displacement) were observed in the post yield behaviour of the jacketed specimens.

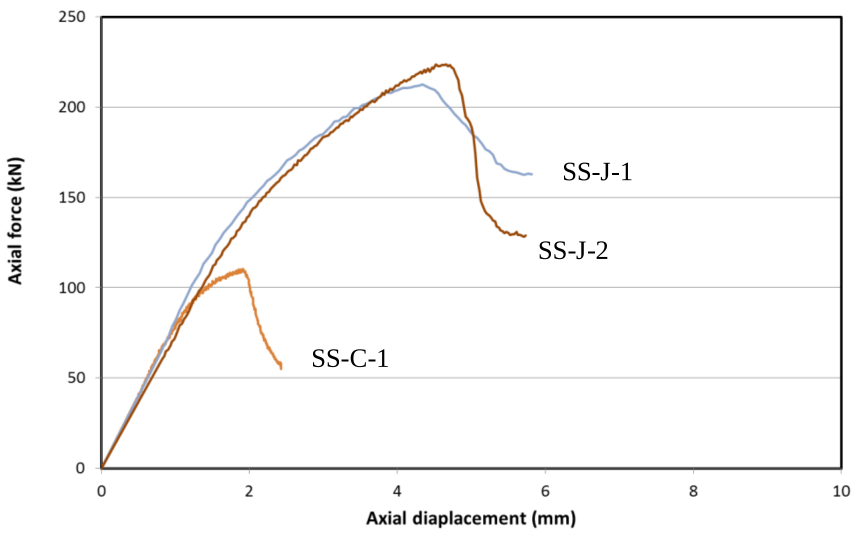

Figure 10. Axial load and displacement response – SS specimens

Stress and axial displacement response

Figure 11 shows stress and axial shortening response. The axial load was normalised by the yield stress to compare different grade CHS (i.e. 350 MPa for NS and 250 MPa for SS). The axial shortening was estimated from measured axial displacement divided by the height of the CHS (i.e. 670 mm). The normalised stress level and axial shortening showed that the slender control specimen (i.e. SS-C-1) failed at only 70 % of its yield stress and 0.3 % of axial shortening at the peak while the value were 110 % and 1.2 % respectively in the NS control specimens. These results demonstrate the SS specimen failed prematurely with respect to the following two structural criteria; (i) not fully utilising sectional capacity and (ii) lack of section stability.

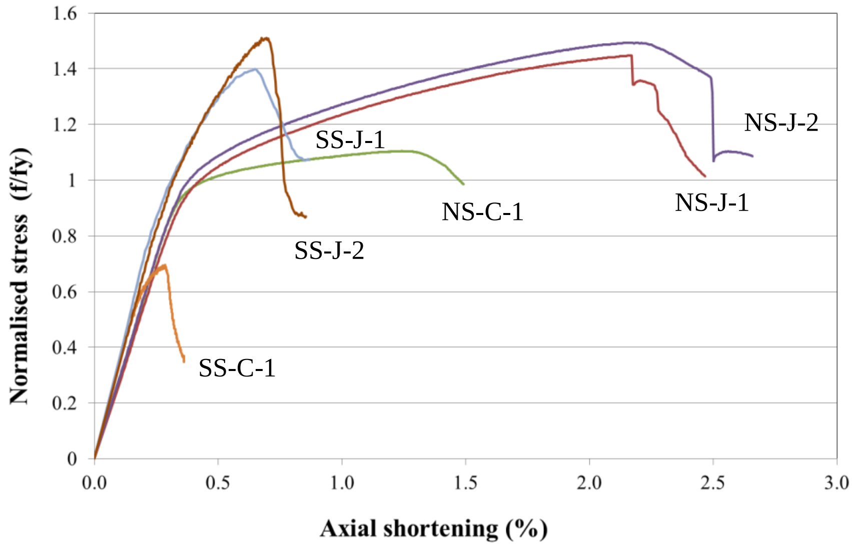

Figure 11. Stress and axial shortening response (All)

The axial shortening of jacketed specimens at the peak showed 2.16 % for both two NS specimens and 0.65 % and 0.67% SS specimens, respectively. It is clear that NS specimens demonstrated higher deformability than that of SS specimens as is expected. In terms of effectiveness of the jacket system with respect to their unjacketed control specimens, both NS and SS specimens exhibited significant enhancement. It should be noted that the failure stress and axial deformability increase of jacketed SS specimens is 100 % and 130 % with respect to the prematurely failed unjacketed control specimen. Such behaviours could be interpreted as demonstrating that (i) premature buckling failure (i.e. failure occurring well below than yield stress) of slender CHS could be rehabilitated by the jacket system, (ii) deformability of slender CHS could be significantly improved with the jacket system and (iii) the jacket system would enable slender CHS to fully utilise sectional capacity and even provide additional strength.

CONCLUSIONS

The results of an experimental program aimed at investigating axial behaviour of jacketed CHS with various wall thicknesses have been reported. The failure load, failure mode and axial displacement of all jacketed specimen were reported and compared with counterpart unjacketed control specimens. The structural behaviours of slender CHS with and without CFRP jacket has been investigated and compared to non-slender section (i.e. commercially available section). The jacket system has been demonstrated to provide substantial stability improvement of slender CHSs by increasing not only axial strength but also axial deformability.

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