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Plastic mechanism analysis of steel SHS strengthened with CFRP under large axial deformation

M.R. Bambach[a,*], M. Elchalakani[b]

[a]Department of Civil Engineering, Monash University, Vic. 3800, Australia
[b]School of Architectural, Civil and Mechanical Engineering, Vic. University Footscray Park Campus, Ballarat Road, Vic. 8001, Australia

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Abstract

Carbon fibre reinforced polymer (CFRP) strengthening of structures has been gaining increasing interest, traditionally in application with concrete structures, and more recently in application with steel structures. This paper presents experiments and plastic mechanism analysis of steel square hollow section (SHS) tubes strengthened using externally bonded CFRP, deforming in an axi-symmetric collapse mode under quasi-static large deformation axial compression. The fold formation process of the stub column was such that the flat sides formed the well-known roof mechanism. The collapse proceeded progressively by folding about concentrated hinge lines and yielding of the four corners. An expression for the plastic collapse axial load was obtained by equating the total energy absorbed in bending and yielding to the external work carried out during deformation of the composite tube. The predicted instantaneous post-buckling and mean collapse loads are shown to compare well with the experimental results.

Keywords: Steel SHS; CFRP strengthening; Retrofit; Large deformation axial compression; Stub columns; Plastic mechanism

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1. . Introduction

Steel square hollow sections (SHS) are used widely in many structural forms in engineering applications that may involve either static load resistance or energy absorption. SHS are produced in compact, non-compact and slender geometries (defined by the appropriate international steel specification), typically from grade 350 or 450 MPa steel. Over the past decade, carbon fibre reinforced polymer (CFRP) has gained increasing acceptance as a structural material, typically applied to concrete structures, however, more recently also to steel structures. Recent research on the strengthening of circular hollow sections (CHS) with FRP by Teng and Hu [1] and Hong et al. [2] in axial compression, Haedir et al. [3] in bending, Doi et al. [4] in bending and compression, Jiao and Zhao [5] in tension and Zhao et al. [6] and Xiao et al. [7] on concrete filled CHS has shown significant benefits in strength and stiffness of steel members with externally bonded CFRP. Research on the strengthening of SHS with CFRP is limited to a set of experiments by Shaat and Fam [8]. An extensive review of research in the general field of steel structures strengthened with CFRP is given by Zhao and Zhang [9]. The investigations on steel hollow sections [1,2,4,5,8] were all performed on compact sections. In this paper SHS having geometries within each of the slenderness categories of compact, non-compact and slender [10] are tested under large deformation axial compression, in order to investigate the effect of section slenderness on the strengthening and energy absorption capacity of the high-strength CFRP. The experiments are then studied analytically using a plastic mechanism approach.

The collapse mechanisms of SHS stub columns were studied in the past by Johnson et al. [11], Abramowicz and Jones [12] and Meng et al. [13] using virtual work methods. Wierzbicki and Abramowicz [14] used a velocity field approach to derive general formulations for the crushing of thin-walled structures. The basic folding of an isolated plate forming the classical roof mechanism was studied by Davies et al. [15] and Mahendran [16]. Ohkubo et al. [17]

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*Corresponding author. Tel.: +61 3 9905 9681; fax: +61 3 9905 4944.
E-mail addresses: mike.bambach@eng.monash.edu.au (M.R. Bambach), Mohamed.Elchalakani@vu.edu.au (M. Elchalakani).

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Nomenclature

A_c	corner area of SHS
B	overall face width of SHS
b	clear width of SHS ($b = B - 2t_s$)
b_2	internal width of SHS ($b_2 = B - 2r_{ext}$)
k_f	$= \sigma_{\rm yf}/\sigma_{\rm ys}$
k_c	$= \sigma_{\rm yf}/\sigma_{\rm yc}$
M_p	full plastic moment
M'_p	full plastic moment
P_y	yield load
W_{int} and W_{ext}	internal and external work
$\overline{P}_{theory}$	predicted mean collapse load
$\overline{P}_{classical\ theory}$	predicted mean collapse load using classical theories
$\overline{P}_{test}$	measured mean collapse load
r_{ext}, r_{int}	external and internal radii of SHS
t_s	thickness of SHS
t_f	thickness of CFRP
t_r	ratio of thickness
λ_e	section slenderness defined in AS4100 [10]
λ	$\frac{1}{2}$ wavelength
σ_{ys}	measured yield stress of face of SHS
σ_{yc}	measured yield stress of corner of SHS
σ_{yf}	measured tensile strength of CFRP

provided an expression for the mean crushing load of hat sections commonly used in the automotive industry where they showed that the radius of the rolling hinge has significant effect. Mamalis et al. [18] studied non-metallic plastic square tubes under axial load. The effect of CFRP on the collapse of composite circular tubes was studied by Mamalis et al. [19,20], Gupta and Abbas [21], Hanefi and Wierzbicki [22] and more recently by Wang and Lu [23]. However, in most of these crush studies, formulations for the mean crush load were derived with little focus on the development of the collapse curves, such as those by Key and Hancock [24], Zhao et al. [25] and more recently by Elchalakani et al. [26,27] for bending of CHS.

Key and Hancock [24] developed a formulation for the instantaneous axial load versus axial deflection for an empty SHS. However, they did not consider the finite length of the central plastic hinge which is important for the case of SHS strengthened using CFRP, as the hinge cannot articulate around a single point. Also, they did not provide an expression for the mean collapse load. It is shown in this paper that their rigid plastic mechanism may be modified to include the effects of the finite length of the face hinges and the CFRP strengthening. An expression for the mean collapse load is provided and is shown to compare well with the experimental results.

2. Experimental set-up

The section dimensions of the SHS ranged from slender to compact sections according to the section designations used by the Australian Standard AS4100 [10], as shown in Table 1. The slenderness values λ_e [10] ranged from 35 to 73 (Table 1), and all columns were of length equal to three times the width of the SHS (Table 1). The material designations of the SHS were 350 MPa for all sections except the 100 × 100 × 2 SHS, which were 450 MPa sections. The measured 0.2% proof stress values from tensile coupon tests are shown in Table 1. All SHS specimens had a nominal wall thickness of 2 mm.

Table 1
Specimen dimensions

SHS column (mm)	Length of column (mm)	Slenderness (λ_e) [10]	Section designation [10]	Measured yield stress f_y (MPa)
100 × 100 × 2	300	73.4	Slender	539
75 × 75 × 2	225	48.3	Slender	417
65 × 65 × 2	195	41.4	Non-compact	405
50 × 50 × 2	150	34.8	Compact	484

High-strength CFRP was used and applied to the exterior of the SHS with Araldite 420 epoxy. The high-strength CFRP (termed MBrace CF-130) is nominally 3790 MPa ultimate tensile strength and 230 GPa elastic modulus fibre. The fibre is nominally 0.17 mm thick. Two different fibre layouts were investigated: one layer being laid transversely (i.e. around the SHS perpendicular to the direction of axial load) with one layer longitudinally (i.e. in the direction of axial load), hereafter termed 1T1L; and two layers transversely with two layers longitudinally termed 2T2L. The transverse layer was laid first, bonded directly to the steel, and the longitudinal layer second; then for the 2T2L specimens another transverse layer followed with the final longitudinal layer, as shown in Fig. 1. Araldite 420 epoxy was used between each layer. The sheets were overlapped by 20 mm (Fig. 1) such that premature failure at the overlaps might be avoided. Prior to laying the CFRP the surface of the SHS was prepared by hand grinding to roughen the surface, then cleaned with acetone. All specimens were cured for at least 10 days at room temperature as per the manufacturer's instructions. After curing, the ends of the composite SHS were ground square and the CFRP was minimally hand ground at the ends such that only the steel was in contact with the loading platens of the testing machine. The composite columns were tested in pure axial compression quasi-statically (1 mm/min), and were crushed to approximately half the length. A small number of specimens exhibited non-symmetric failure modes and the tests were stopped before being crushed to half the length as tilting became