

Strengthening of steel members in compression by mortar-filled FRP tubes

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ABSTRACT

A strengthening approach to improve the buckling resistance of steel members in compression is introduced in this paper, where a mortar-filled FRP tube is sleeved outside the steel member and wrapped with FRP fabrics at the ends of the tube. Through axial compression tests on 18 specimens with bi-axial symmetrical cross-section, the load-strain development and failure modes were obtained and improved load bearing capacity and ductility were evidenced. The effects of the cross-section of core steel, slenderness and FRP fabric layers wrapped at the ends of specimens were investigated. It was found that, after strengthening, the failure modes changed from steel yielding at the mid-height of the steel member due to global buckling to local damage at the steel end. As a result, the load bearing capacity increased by 44–215% and ductility increased by up to 877%. The segmentation model was developed for strengthened specimens, by which the calculated load bearing capacity agrees well with the experimental result.

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1. Introduction

The buckling of steel components in compression is an important concern in the design of new steel structures or the repair of existing ones. Harrowing accidents such as the collapse of the Quebec Bridge in Canada as far back as 1907 [1] and the damage to transmission towers in South China due to snow as recently as 2008 [2,3], have alerted engineers to the need to pay more attention to the buckling resistance capacity of compressed steel members.

Since the 1980s, when fibre reinforced polymer (FRP) composites were first employed in civil engineering, their excellent properties of light weight and high strength have been well-known to researchers and engineers, and caused them to have been widely used in the strengthening of reinforced concrete structures [4–8]. Moreover, pasting FRP fabrics to metal surfaces has also developed as an approach to metal strengthening to improve fatigue life, durability and load-bearing capacity [9–12]. However, methods to enhance the buckling resistance of steel members in compression have not yet been fully studied.

Teng and Hu [13] conducted experimental and numerical studies on FRP-jacketed circular steel tubes under axial compression, which showed that FRP jacketing was effective to restrict local buckling (the elephant's foot collapse) near the base and increase ductility. Shaat and Fam [14,15] reported their experimental and theoretical studies of compressed steel columns pasted with glass

fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP), in which the maximum increments of load-bearing capacity for short and long columns were 18% and 23%, respectively. Sherif et al. [16] proposed a new strengthening method of steel bracing using mortar and FRP, in which mortar blocks were attached around single angle and double angle braces with FRP sheets wrapped outside, and the maximum compressive load was increased from 52% to 200% after strengthening. Feng et al. [17] and Qian et al. [18] reported experimental studies of compressed aluminium columns with square and circular sections strengthened by CFRP using the vacuum bag-aided method. The local buckling in compact columns and global buckling in slender columns were restrained and the load-bearing capacity was improved to 473% for the former and 172% for the latter. Based on the tests, the formulas to estimate the local buckling strength and the global buckling stability factor were proposed. In the studies [13–18], a common practice has been to wrap or paste FRP fabrics along the full length of metallic members. But this method is difficult to apply as too much labour work is needed, such as sanding all surfaces, and the efficiency of the FRP was limited to increase the stiffness which is important for bulking. Liu [19] presented the experimental and analytical results of a retrofitting method, in which FRP jackets were wrapped around corroded steel columns only within the corroded zone, and subsequently filled with lightweight concrete. The strengthened specimens failed through global buckling with an increase of load-bearing capacity of 58–233%, which was still much lower than the yielding capacity of the full section $A \cdot f_y$ (f_y is yield strength and A is cross-sectional area).

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Notation

A	cross-sectional area of the steel
a_i	coefficients of polynomial series
E	elastic modulus
f_y	yield strength of the steel
f_u	ultimate strength of the steel
I	moment of inertia
k	effective length factor
L	full length of the steel
L_0	length of steel at the un-strengthened zone
L_T	transition length
P	Euler buckling load obtained from Eq. (8)
P_E	Euler buckling load
P_{E1}	Euler buckling load obtained from Eq. (1)
P_{E2}	Euler buckling load obtained from Eq. (9)
P_{est}	estimated load
P_{max}	maximum load obtained from the experiment
U	sum of elastic strain energy

V	potential energy
w_{ij}	coefficients in the i th line and j th column of determinant
x	axial coordinate of the specimen
y	lateral coordinate of the specimen
α	imperfection factor of the steel
β	reduction factor of bending stiffness
γ	ratio of P_{max} of strengthened specimen and that of reference specimen
Δ_u	ultimate deformation
Δ_{yi}	yield deformation
λ	nominal slenderness ratio
$\bar{\lambda}_r$	non-dimensional slenderness of reference specimen
$\bar{\lambda}_s$	non-dimensional slenderness of strengthened specimen
μ_i	ductility index
Φ	intermediate variable
χ	reduction factor for relevant buckling mode.

Feng et al. [20] presented a series of innovative strengthening technique to enhance the buckling resistance of compressed steel members with different materials. Among those, two are suitable for the approach developed in this paper using mortar-filled FRP tube: if the steel member cannot be released from the joint, construction procedure (b) in Ref. [20] can be adopted; if the connection between the steel and the structure is pin connection, construction procedure (c) can be adopted. In this procedure, the steel can be conveniently strengthened in situ and the maximum increment of load-bearing capacity of strengthened angle steel members was about 186% and the section yielding capacity exceeded $A \cdot f_y$.

The preliminary study introduced in [20] was to demonstrate the feasibility of this approach and only angle steel members with certain slenderness were examined. In this paper, the more thorough research on one of three presented configurations in Ref. [20] is conducted by experiment and theoretical modelling. The proposed strengthening approach is applied on 18 steel members with different bi-axial symmetrical cross-sections (Cross/I/Round/Square). The effects of two important parameters

(the specimen slenderness and the number of FRP fabric layers wrapped at the end) on the strengthening results are further investigated. In order to understand the strengthening mechanism, load-axial and lateral displacement curves, load-strain developments from key positions, and the failure modes of the specimens were recorded. In comparison to the un-strengthened reference specimens, a considerably improved load-bearing capacity and ductility were demonstrated.

2. Experimental program

2.1. Material properties

The original steel specimens were made of Q345 steel with four different sections, as shown in Fig. 1. The material properties of the steel are given in Table 1. The FRP tube used to strengthen the steel components was composed of E-glass fibre and vinyl resin and was made by pultrusion with an inner diameter of 88 mm and wall thickness of 6.5 mm. The FRP fabric wrapped

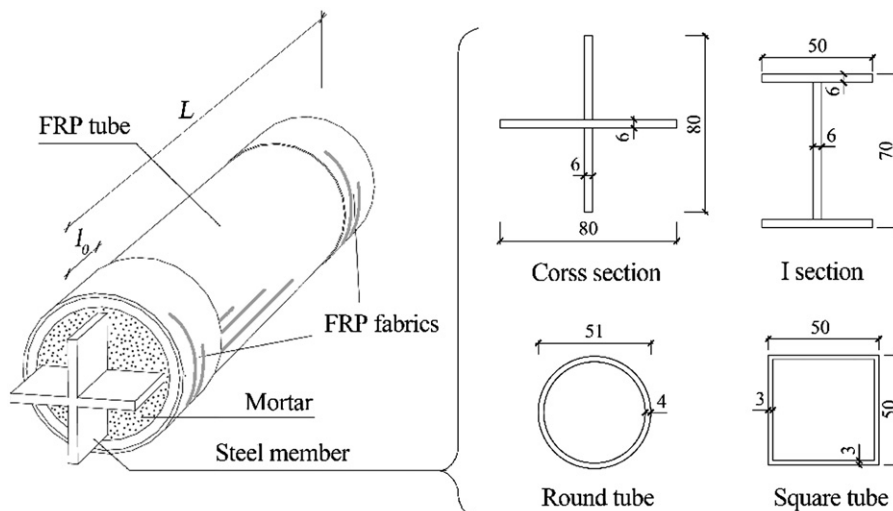


Fig. 1. Strengthening specimen configuration and section size. (unit: mm, $l_0=70$ mm except I70-5, specimen length L was summarized in Table 2).

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