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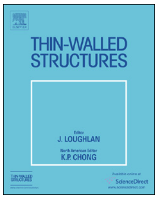

Plastic collapse analysis of CFRP strengthened and rehabilitated degraded steel welded RHS beams subjected to combined bending and bearing

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ABSTRACT

Innovative techniques using the lightweight, high strength and corrosion resistance of carbon fibres reinforced polymers (CFRP) composites have been proposed in a recent paper by the author. The present paper presents plastic mechanism analyses of CFRP strengthened and rehabilitated rectangular hollow sections (RHS) under quasi-static large deformation 3-point bending. The strengthening series was for un-degraded RHS beams from the manufacturer reinforced using externally wrapped CFRP sheets. The rehabilitation series was for artificially degraded RHS beams repaired using externally wrapped sheets or bonded plates. The main parameters examined in this paper were the section type, section and member slenderness and the type and number of the CFRP sheets. Three different phases of plastic deformation were observed during the test, namely, denting, denting and bending, and structural collapse. Two methods were used to model the large plastic deformation measured during plastic collapse of the composite RHS beams, namely, equilibrium and energy methods of analysis. It was found that the predicted collapse curves using the equilibrium approach were in good agreement with the measured curves for the bare and composite specimens examined in the strengthening and rehabilitation series, particularly for the latter series. This may be caused by a number of factors such as the specimens in the rehabilitations series were comparatively longer and had larger bearing width. The energy theory was found to have deficiencies represented in the simplified linear polygon shape adopted for the mechanism geometry, and adopting the plastic 1/2-wave length used for I-sections, as well as the use of a simplified formulae to describe the relationship between the local denting displacement and global bending rotation angle for the three phases of deformation observed during the test.

1. Introduction

The deterioration of the metallic infrastructure is due to several reasons but probably the main factor above all is corrosion. Corrosion has a huge economic and environmental impact on virtually all facets of the world's infrastructure, from highways, bridges, and buildings to oil and gas, chemical processing, and water and wastewater systems. In addition to causing severe damage and threats to public safety, corrosion disrupts operations and requires extensive repair and replacement of failed assets. The annual cost of corrosion worldwide is estimated to exceed $1.8 trillion, which translates to 3–4% of the Gross Domestic Product (GDP) of industrialised countries [1]. The present author [2] has recently performed extensive testing programme composed of 52 specimens on the strengthening and rehabilitation of corroded model box girders using Carbon Fibre Reinforced Polymers (CFRP). It was found that the average increase in the load carrying capacity obtained for the strengthening and rehabilitation series were 65% and 20%, respectively [2].

CFRP strengthening of structures has been gaining increasing interest, traditionally in application with concrete structures, and more recently in application with steel structures due to the well-known high mechanical properties of this material in particular its high strength to density ratio. Despite its intrinsic cost, the possibility to shape the CFRP lamina and to avoid the cumbersome work associated with the standard rehabilitation techniques, speed of construction, reduced disturbance to the structure, minimising economic losses due to the suspension of services and finally the very low dead weight added makes the overall cost for strengthening to be reduced. The raw materials of FRP can be supplied in the forms of dry fibre/fabric sheets and impregnating resins for the in-situ formation of FRP via the so-called wet lay-up

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Nomenclature

A_1	Parameter
b_0	Clear width of compression/tension flange
B_0	Overall width of compression/tension flange
b_{CFRP}	CFRP plate Width
d_0	Overall depth of section
D_0	Overall depth of section
d	Updated depth of section
E_{CFRP}	Tensile elastic modulus of CFRP
E_a	Tensile elastic modulus of adhesive
E_s	Tensile elastic modulus of steel
e	Eccentricity
G_a	Shear modulus of the adhesive
h	Clear web depth
h_1	Machine bearing width
h_2	Mechanism dimension
K_f	σ_{yf}/σ_{ys}
L	1/2 Wave length of mechanism
L_0	Span of beam
L_1	Mechanism length
LTB	Lateral torsion buckling
M_p	Plastic moment
M_{pc}	Predicted plastic moment of the composite I-section
M_{1-7}	Predicted moment components from mechanism analysis
m_{pwf}	Full plastic moment per unit width of the effective web
m_{pbf}	Full plastic moment per unit width of the effective bottom flange
m_{ptf}	Full plastic moment per unit width of the effective top flange
F_u	Ultimate load from tests
P_{1-7}	Predicted load components from mechanism analysis
P^{CFRP}	Ultimate load bond strength
r	Rolling radius
R_a	Adhesive strain energy
r_y	Radius of gyration of beam
t_f	Thickness of the flange
t_a	Thickness of the adhesive
t_w	Thickness of the web
t_t	Thickness of top flange
t_b	Thickness of bottom flange
t_w	Thickness of web
t_{tf}	Effective thickness of top flange
t_{bf}	Effective thickness of bottom flange
t_{wf}	Effective thickness of web
$t_{eq,top}$	Equivalent thickness of top flange
$t_{eq,bottom}$	Equivalent thickness of bottom flange
$t_{eq,web}$	Equivalent thickness of web
t_{CFRP}	Thickness of the CFRP plate
t_r	t_f/t_s
t_{eq}	Equivalent thickness of composite plate
W_{int}	Internal work
W_{ext}	External work
x	Location of neutral axis
y_s	Bottom flange displacement
α	Mechanism angle (Fig. 12)
α_c	Member slenderness reduction factor
β	Empirical parameter
η	Empirical parameter to determine 1/2 wave length
$\phi_{1,2}$	Mechanism angles
γ	Mechanism angle
Δ	Local displacement of top flange
Δ_t	Total deflection
δd	Extension of CFRP plate
$\delta\theta$	Incremental change in angle θ
$\delta\alpha$	Incremental change in angle α
δW_i	Incremental change in internal work
θ	Total bending rotation angle of the beam
σ_{ys}	Yield strength of steel
τ	Shear stress

process, which allows the use of CFRP on irregular and curved surfaces where application of steel plates may be impossible or highly challenging [2–5].

Many of the research in CFRP strengthening of steel open sections focused on I-sections with some research dealt with other profiles such as T-sections by Harries et al. [3], angle sections by Eltawil and Ekiz [4], and lipped channels by Silvestre et al. [5]. Experimental results have shown the effectiveness of strengthening steel beams and steel–concrete composite girders by bonding a CFRP plate to its soffit [6–14]. A number of failure modes are possible in such CFRP strengthening steel beams: (a) plate end debonding [6]; (b) in-plane bending failure [9]; (c) lateral buckling [11]; and (d) intermediate debonding due to yielding and the opening-up of a crack [11]. Additional but less likely failure modes include: (e) local buckling of the compression flange; and (f) local buckling of the web. Out of the debonding failure modes plate end debonding is likely to occur due to high stress concentrations at the plate ends. Plate end debonding is a premature failure mode which often occurs before significant contribution from the CFRP is made. The research has shown this type of failure mode can be prevented by using longer CFRP plates thus placing the plate ends in lower bending regions [6]. Unlike to plate end debonding, intermediate debonding initiates in a region where CFRP is highly stressed and move towards the plate ends. Often the initiation of intermediate debonding is governed by the presence of cracks or steel yielding [11]. Experimental research [15] has shown that the intermediate debonding is governed by the high interfacial shear stresses thus depends strongly on the interfacial shear fracture energy of the bond joint.

Early contributions of collapse mechanism analysis using virtual work methods in the field of structural crashworthiness were performed on steel tubes as they represent good energy absorbing devices by Johnson et al. [16], Abramowicz and Jones [17], and Meng et al. [18]. Wierzbicki and Abramowicz [19] used a velocity field energy 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 using equilibrium approach by Davies et al. [20] and Mahendran [21]. Ohkubo et al. [22] 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. [23] studied non-metallic plastic square tubes under axial load using energy approach. The effect of CFRP on the collapse of composite circular tubes was studied using energy approach by Mamalis et al. [24,25], Gupta and Abbas [26], Hanefi and Wierzbicki [27] and more recently by Wang and Lu [28]. However in most of these crash studies, formulations for the mean crash load were derived with little focus on the development of the collapse curves, such as those by Key and Hancock [29], Zhao et al. [30], Elchalakani et al. [31,32] for bending of circular compact and slender tubes and more recently Bambach and Elchalakani [33] for CFRP strengthening of square tubes. Zhao