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Design rules for web crippling of CFRP strengthened aluminium rectangular hollow sections

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ABSTRACT

Web crippling failure (web buckling and web yielding) is critical for thin-walled members when subjected to concentrated load. Carbon fibre reinforced polymer (CFRP) is attracting increasing research interest as a strengthening material for metallic structural members. Improved web crippling capacity of aluminium rectangular hollow sections has been achieved with CFRP being attached to the exterior and/or interior of the webs from a series of tests conducted by the authors. This paper focuses on developing design rules for predicting the nominal crippling strength of CFRP strengthened sharp-corner aluminium tubular sections: rectangular hollow section (RHS) and square hollow section (SHS), under end bearing load. The existing design rules for bare sections without CFRP strengthening are firstly reviewed and assessed, including design rules for both cold-formed steel structural members (Australian/New Zealand standard (AS 4100-1998) and North American Specification) and aluminium structures (Australian/New Zealand standard (AS 1664-1997) and American aluminium design manual). They are modified to take account of the improved capacity due to CFRP strengthening. The proposed design rules are calibrated against test results.

1. Introduction

Thin-walled members may be subjected to web crippling when concentrated forces are applied. This is often the case where point loading or bearing force exists (i.e. floor system or joist members) [1–8]. Carbon fibre reinforced polymer (CFRP) has advanced structural properties with their high strength to weight ratio and resistance to harsh environmental effects [9,10], making it a promising material [10–13] for strengthening metallic structural members [14–19].

Regarding thin-walled steel members with CFRP strengthening, there has been a lot research aiming at predicting the improved web crippling capacity under various loading conditions with existing design rules. Australian/New Zealand standard AS 4100-1998 [20] was used to predict the improved web bearing capacity of CFRP strengthened cold-formed steel rectangular hollow sections (RHS) under end bearing load, which was conducted in [21,22]. Six CFRP strengthening configurations were adopted. Type 3 strengthening (with CFRP plate bonded on the exterior surface of the web) and Type 5 strengthening (with CFRP plates bonded on both interior and exterior surfaces of the web) were studied in depth, because they provided most convenient CFRP application (Type 2) and greatest capacity increase (Type 5). An effective length factor of 0.8 was adopted for the prediction of web buckling capacity of Type 3 strengthening and an upper bound of α_p ($=0.32$) was adopted for the prediction of web yield capacity of Type 3 and Type 5 strengthening. As an extended study, the strong effects of adhesive properties on the failure mode and the bearing capacity were observed in [22]. Similar work was conducted on CFRP strengthened light steel beams (LSB) [23] and I sections [24].

However comparing with research on web crippling of steel sections, very limited studies have been reported for that of unstrengthened aluminium members [26–29]. American design manual (AA specification) [30], Australian/New Zealand standard (AS 1664-1997) [31], European code for aluminium structures (EC9 code) [32] and North American specification (NAS specification) [33] were assessed by Young and Zhou in [27] for predicting web crippling capacities of unstrengthened aluminium RHS based on a series of tests reported in [26,27]. 150 web crippling tests on aluminium RHS were performed. A total of fourteen sections were studied under two loading conditions of end-two-flange (ETF) and interior-two-flange (ITF). It concluded that most of the sections experienced web crippling failure. It was shown that the nominal design strengths predicted by the aforementioned specifications were either quite conservative or un-conservative. Two web crippling equations for aluminium RHS under ETF and ITF loading conditions were proposed based on the unified NAS specification.

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Nomenclature

b	overall width of the RHS section
b_b	total bearing width of the web defined in AS 4100
b_{bf}	bearing width of the web defined in AS 4100
b_s	bearing length of concentrated load defined in AS 4100
b_y	bearing length defined in BS5950
C_1	bearing length coefficient in web bearing capacity equation in NAS specification
C_2	web slenderness coefficient in web bearing capacity equation in NAS specification
C_3	coefficient considering the effect of $b_s/d-2t_f$ ratio
d	overall depth of the section
D_m	mean of the dead load intensity in reliability analysis
D_n	dead load intensity
E	Young's modulus of elasticity
E_{Al}	elastic modulus of aluminium
E_{CFRP}	elastic modulus of CFRP plate
F_m	mean of fabrication factors in reliability analysis
f_y	yield stress
I	area moment of inertia
k_e	effective length factor
k_f	form factor
l_e	effective length of the web
L_m	mean of the live load intensity in reliability analysis
L_n	live load intensity
M_m	mean of material properties in reliability analysis
M_p	plastic moment of a unit length
N_m	mechanism length along web
P_{Al}	load of unit web length carried by the aluminium web
P_b	web bearing capacity
P_{bb}	web bearing buckling capacity
$P_{b.Exp}$	experimental web bearing capacity
$P_{b.pre}$	predicted web bearing capacity
P_{by}	web bearing yield capacity
P_{CFRP}	load of unit web length carried by CFRP
P_{Euler}	column Euler buckling load
r	gyration radius of the web
r_0	flange corner radius of light weight steel beam (LSB) section
r_{ext}	external corner radius of cold-formed steel RHS defined in AS 4100
r_{int}	inside corner radius of the section defined in AS 1664
t	thickness of the RHS section
t_f	flange thickness of I section
t_w	web thickness of the section
t_{we}	equivalent thickness of the CFRP strengthened web
V_D	coefficient of variation of dead load intensity in reliability analysis
V_F	coefficient of variation of fabrication factors in reliability analysis
V_L	coefficient of variation of live load intensity in reliability analysis
V_M	coefficient of variation of material properties in reliability analysis
α	capacity reduction factor introduced to web bearing capacity equation in AS 1664
α_b	member section constant
α_c	member slenderness reduction factor
α_p	coefficient in the equation of web bearing yield capacity in AS 4100
β	reliability index
δW_{ext}	total virtual change of the external work
δW_{int}	total virtual change of the internal work
ϕ	resistant factor in reliability analysis
λ_n	modified member slenderness
θ	angle between the plane of the web and the plane of the bearing surface
$\sigma_{0.2}$	0.2% proof stress
Δ	displacement under bearing load

Similar web crippling tests were carried out in [8] on high strength aluminium SHS. A total of 64 web-bearing tests were conducted. Again aluminium standards of AA specification [30] and EC9 code [32] were firstly attempted and the predicted web bearing strength did not agree well with experimental results. Then the web buckling capacity in Australian/New Zealand standard: AS 4100-1998 [20] and the web yield capacity in British Standard BS5950 Part 1 [34] were modified to obtain closer predictions. The modified effective length factor k_e from AS 4100 was 1.05 and 0.95 for end loading and interior loading, respectively. The bearing length b_y in BS5950 was also modified to achieve the web yield capacity.

In the literature, there has been no report on the prediction of web crippling capacity of CFRP strengthened aluminium sections. This is most likely because that there are very limited studies conducted on web crippling of CFRP strengthened aluminium tubular sections under concentrated load. Improved capacities of CFRP strengthened sharp-corner aluminium RHS under end bearing load were reported in [29,35,36]. Islam and Young [36] conducted a series of tests on CFRP strengthened aluminium tubular sections. Forty two specimens were tested under end-two-flange (ETF) loading condition. The investigation was focused on the effects of different adhesives and FRPs for strengthening aluminium tubular sections against web crippling, so that six different adhesives and FRPs were adopted. Only one strengthening method was used in [36] with CFRP attached to the exterior of the web. An enhancement of web bearing capacity of up to 187% was achieved for the section of A100X45 × 1.6.

In another experimental programme reported by the authors in [29,35], four types of strengthening configurations were adopted in this project, by bonding CFRP plates on the exterior or/and interior of the web. A total of 24 tests were conducted. Significant increase in load carrying capacity was obtained by all strengthening methods. The test results were also compared with those of cold-formed steel RHS strengthened with the same strengthening configurations and it seems that aluminium sections generally benefit more from the CFRP strengthening schemes.

As an extension of the experimental programme of CFRP strengthened aluminium RHS in [29,35], this paper acts as the first attempt to predict the bearing capacities of such members. The existing design rules for web crippling of bare sections without CFRP strengthening are firstly reviewed and assessed. They include both cold-formed steel structural member standards: Australian/New Zealand standard (AS 4100-1998) [20] and modified North American Specification [33] in [27] and aluminium standards: American aluminium design manual (AA specification) [30] and Australian/New Zealand standard (AS 1664-1997) [31]. Then modifications are made to predict the experimental results. Modifications made in each standard are discussed and justified based on the tests results. Furthermore, the advantages and limitations of these developed design rules are also discussed. Generally, reasonable agreements between predicted and experimental web crippling strengths of