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Design of CFRP-strengthened aluminium alloy tubular sections subjected to web crippling

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ABSTRACT

Web crippling of aluminium alloy tubular structural members may occur due to the highly concentrated loadings. A nonlinear finite element analysis was performed based on a series of laboratory tests on carbon fibre–reinforced polymer (CFRP) strengthened aluminium alloy tubular structural members subjected to web crippling.resistance (capacity) factor The end-twσ_uo-flange (ETF), interior-two-flange (ITF), end-one-flange (EOF) and interior-one-flange (IOF) loading conditions specified in the North American and Australian/New Zealand specifications for cold-formed steel structures were used in this study. Nonlinear finite element models were developed and verified with test results. The material properties of aluminium alloy, adhesive and carbon fibre reinforcement polymer were taken into consideration. The traction separation law of the cohesive zone model was used to simulate the debonding between the CFRP plate and aluminium alloy tubes in the nonlinear analysis process. Geometric and material nonlinearities were also included in the finite element analysis. The finite element results explained the behaviour of the CFRP-strengthened aluminium alloy specimens subjected to web crippling. The finite element results demonstrated that the ultimate load-carrying capacity (web crippling strength), web crippling failure modes, and web-deformation curves agreed well with the tests. The verified finite element models were then used for an extensive parametric study of different tubular dimensions. This paper presents numerical data from the finite element analysis for a total of 151 simulations. It was found that the verified finite element models provided an effective and time-efficient means of predicting the web crippling strengths of CFRP-strengthened aluminium alloy members. Design equations are proposed to predict the web crippling strengths of CFRP-strengthened aluminium alloy tubular sections against web crippling loading.

1. Introduction

Aluminium alloy tubular members are being used increasingly in structural applications. Web crippling may occur at highly concentrated loadings or reactions in aluminium alloy tubular members. In fact, most web crippling design expressions have been developed based on extensive experimental investigations. Experimental investigations of web crippling of thin-walled members have been conducted since the 1940s. [1–9]. Numerical investigations of thin-walled sections, including hat sections, have been reported [10–18]. Many researchers have developed analytical and theoretical models for buckling of thin-walled members [7,9,17,19–25]. The web crippling failure of aluminium and cold-formed steel thin-walled members is a common failure mode and has been studied extensively [26–30]. The web crippling strength can be enhanced by Carbon fibre-reinforced polymer (CFRP) strengthening in the web of the sections. CFRP provides advanced structural properties with their high strength-to-weight ratios and resistance to harsh environmental effects [31]. It is an efficient method for strengthening metallic structural members using CFRP [31,32]. There have been reports of the strengthening of rectangular carbon steel tubes and light steel beams using CFRP subjected to end bearing loads [33–35]. Islam and Young [36,37] explored the use of CFRP plates to enhance the load-carrying capacity of aluminium alloy tubular structural members subjected to web crippling. A significant increase in load carrying capacity was obtained by using this strengthening technique. The CFRP strengthening technique was able to increase the web crippling strength approximately threefold for aluminium alloy sections. Compared with physical experiments, numerical simulation is relatively inexpensive and time efficient. Finite element analyses (FEA) have been carried out by different researchers to investigate CFRP-strengthened metallic structures [32,38–44]. The nonlinear finite element method (FEM) has been used widely for analysis of a wide range of structural engineering problems including simulation of CFRP repaired systems [32,38,44]. However, to date there have only been limited investigations of finite

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Nomenclature

$A_{bonding}$	CFRP bonded area
b	flange width
C	web crippling coefficient
C_h	web slenderness coefficient
C_N	bearing length coefficient
C_R	inside corner radius coefficient
CFRP	Carbon Fibre-Reinforced Polymer
COV	coefficient of variation
DL	dead load
d	overall depth of web
E_o	initial Young's modulus
ETF	End-Two-Flange
F_m	mean value of fabrication factor
FRP	Fibre-Reinforced Polymer
f_y	yield stress (0.2% tensile proof stress)
h	depth of flat portion of web measured along the plane of web
ITF	Interior-Two-Flange
L	actual length of specimen
LL	live load
M_m	mean value of material factor
N	length of bearing plate
n	exponent in Ramberg-Osgood expression
P_{Exp}	experimental ultimate web crippling loads per web
P_{FEA}	web crippling strengths predicted from finite element analysis
P_m	mean value of experimental and numerical-to-predicted load ratio
P_{NAS}	nominal web crippling strengths obtained from NAS Specification
P_{p1}	web crippling strengths calculated using proposed unified Eq. (1)
P_{p2}	web crippling strengths calculated using proposed unified Eq. (2)
P_u	Ultimate web crippling loads per web with CFRP
P_{u0}	Ultimate web crippling loads per web without CFRP
RHS	Rectangular Hollow Section
r_i	inside corner radius
SHS	Square Hollow Section
t	thickness of aluminium alloy section
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_p	coefficient of variation of experimental and numerical-to-predicted load ratio
β	reliability index
θ	angle between the plane of web and the plane of bearing surface
ε_f	elongation (tensile strain) after fracture based on gauge length of 50 mm
$\sigma_{0.2}$	static 0.2% tensile proof stress
σ_u	static tensile strength
ϕ_w	resistance (capacity) factor

element analysis of CFRP-strengthened aluminium alloy tubular sections subjected to web crippling.

The web crippling design rules can be found in AA Specification [45], AS/NZS Standard [46], and European Code [47] for aluminium structures. However, these design rules do not cover aluminium alloy sections strengthened by CFRP. Two and three loading conditions for web crippling are classified in the AA Specification [45] and European Code [47] for aluminium structures, respectively. There are four loading conditions specified in the North American Specification [48] for cold-formed steel structural members, namely, end-two-flange (ETF), interior-two-flange (ITF), end-one-flange (EOF) and interior-one-flange (IOF) loading conditions. Zhao et al. [33] and Wu et al. [49] proposed a design model based on AS 4100 [50] for the predictions of web buckling capacities of strengthened steel and aluminium rectangular hollow sections (RHS) subjected to end loading condition, respectively. Fernando [40] modified the design model proposed by Zhao et al. [33] by incorporated two reduction factors. However, this design model is not applicable for ETF, ITF, EOF and IOF loading conditions. Therefore, a more sophisticated and consistent unified design is needed to predict the web crippling strengths of aluminium alloy tubular sections strengthened by CFRP based on a large database.

The first purpose of this study was to develop accurate nonlinear finite element models of CFRP-strengthened aluminium alloy tubular structural members subjected to ETF, ITF, EOF and IOF loading conditions. The finite element method was used for the numerical analysis. The finite element models (FEM) included material and geometric nonlinearities. The developed FE models were verified against the tests results. The finite element analysis (FEA) results agreed well with those from the experiments in terms of ultimate web crippling loads, load-displacement curves and failure modes. Second, the verified finite element models were used for a further extensive parametric study for a wide range of hollow-section dimensions, with the web slenderness (h/t) ranging from 4 to 123. The third aim of the study was to propose modified unified web crippling equations by including the strengthening effect and new coefficients for CFRP-strengthened aluminium alloy square and rectangular hollow sections. The numerical results were also compared with the design strengths predicted by the proposed equations for aluminium alloy structural members. Last, a reliability analysis was performed to assess the reliability of these design rules.

2. Summary of test program

A test program conducted by Islam and Young [37] provided experimental ultimate loads and failure modes for CFRP strengthened aluminium alloy tubular sections subjected to web crippling. A series of tests was conducted on strengthened aluminium tubular members using CFRP to enhance the web crippling capacity. The test specimens were fabricated by extrusion from 6061-T6 heat-treated aluminium alloy. The tests were performed on eight different sizes of aluminium square and rectangular hollow sections which covered a range of slenderness ratios (flat portion of web depth-to-thickness) from 6.2 to 62.2.

The material properties of the aluminium alloy sections obtained from the tensile coupon tests are summarized in Table 1, which includes the static 0.2% tensile proof stress ($\sigma_{0.2}$), static tensile strength (σ_u), initial Young's modulus (E_o), exponent of Ramberg-Osgood expression (n) and elongation after fracture (ε_f) based on a gauge length of 50 mm. The six different types of fibre–reinforced polymer (FRP) comprise of

Table 1
Measured material properties of aluminium alloy sections obtained from tensile coupon tests [37].

Test Specimen	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	E_o (GPa)	n	ε_f (%)
A40 × 40 × 5	243	268	69.6	8.6	10.7
A50 × 50 × 3	277	292	64.9	11.1	9.6
A64 × 64 × 3	219	264	68.6	10.9	9.5
A76 × 76 × 3	243	265	68.2	6.9	9.2
A100 × 45 × 3	284	301	67.4	5.1	9.2
A100 × 100 × 2.3	222	254	68.8	10.6	8.6
A152 × 152 × 3.2	227	261	68.9	11.2	10.1
A100 × 45 × 1.6	272	289	66.9	5.3	8.4