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Aluminum tubular sections subjected to web crippling

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ABSTRACT

This paper presents the details of experimental and numerical research study on web crippling property of aluminum tubular under concentrated web crippling loadings. A total of 48 aluminum square hollow sections with different boundary conditions, loading conditions, bearing lengths and section heights were tested. The experimental scheme, failure modes, load–displacement curves and strain intensity distribution curves were also presented. The investigation was focused on the effects of different boundary conditions, loading conditions, bearing lengths and web slenderness on web crippling ultimate capacity and ductility of aluminum square hollow sections. The results obtained from the experiments are shown that the effect of bearing length on the web crippling ultimate capacity under End-One-Flange (EOF) and End-Two-Flange (ETF) loading and boundary conditions is more obvious than those under Interior-One-Flange (IOF) and Interior-Two-Flange (ITF) boundary and loading conditions. The web crippling ultimate capacities under EOF and ETF loading conditions decreased as the slenderness ratio increased. As the bearing length was 150, the web crippling ultimate capacity under IOF and ITF loading conditions reached its peak when the value of the web slenderness was minimum. The web crippling ultimate capacities of aluminum tubular with bearing length = 50 mm and 100 mm under IOF, ITF, EOF and ETF boundary and loading conditions decreased progressively. The web crippling ultimate capacity of aluminum tubular with bearing length = 150 mm was approximately equal. Finite element models were developed to numerically simulate the tests performed in the experimental investigations. Based on the results of the parametric study, a number of design formulas proposed in this paper can be successfully employed as a design rule for predicting web crippling ultimate capacity of aluminum tubular sections under four loading and boundary conditions.

1. Introduction

The use of aluminum alloys in construction has been permanently increasing during the last years due to its characteristics in terms of light weight, corrosion resistance, high strength to weight ratio and ease of production. However, the modulus of elasticity of aluminum is approximately 1/3 of steel. Therefore, the web of aluminum beam is susceptible to buckling phenomena due to its lower elastic modulus. Therefore, web crippling needs to be considered in designing aluminum beams.

A considerable amount of experimental investigations has been carried out on thin walled hollow sections subjected to web crippling over many years by numerous researchers. An experimental study was conducted by Stephens and Laboube [1] to establish the web crippling strength of both box and I-beam headers for an interior-one-flange (IOF) loading condition. Based on the results of this study, design recommendations were proposed. Finite element models of the hat-section were made by Hofmeyer [2]. The quality of the finite element models for describing moving yield lines was verified. A major improvement of the ultimate failure model of web crippling was presented by Hofmeyer [3]. The ultimate failure model using the fictitious strain method performed equally well as Eurocode3, but provided more insight in the failure behavior. Experimental and numerical investigations of aluminum alloy square hollow sections with a circular hole in the webs subjected to web crippling were presented by Zhou and Young [4]. Web crippling strength reduction factor equations were proposed for the ETF and ITF loading conditions. Macdonald et al. [5] presented the results of an investigation into web crippling behavior-conducted on cold-formed thin-walled steel lipped channel beams subjected to Interior-One-Flange (IOF), Interior-Two-Flange (ITF), End-One-Flange (EOF) and End-Two-Flange (ETF) loading conditions as defined by the American Iron and Steel Institute. Web crippling strength predicted from the Eurocode3 were also compared with the experimental results and the comparisons indicated

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Nomenclature

EOF	End-one-flange boundary and loading condition
IOF	Interior-one-flange boundary and loading condition
ETF	End-two-flange boundary and loading condition
ITF	Interior-two-flange boundary and loading condition
P_{cr}	experimental web crippling ultimate capacity
P_{crC}	web crippling ultimate capacity obtained by using Chinese steel structures design code (GB50013-2003)
P_{crE}	web crippling ultimate capacity obtained by using European design of steel structures (Eurocode 3)
P_{FEA}	web crippling ultimate capacity obtained by using finite element analysis
P_{crRE}	web crippling ultimate capacity obtained by using formulas the paper put forward
P_{EOF}	web crippling ultimate capacity under EOF condition
P_{IOF}	web crippling ultimate capacity under IOF condition
P_{ETF}	web crippling ultimate capacity under ETF condition
P_{ITF}	web crippling ultimate capacity under ITF condition
f_y	tensile yield stress (0.2% tensile proof stress)
f_u	ultimate tensile stress
ν	Poisson's ratio
δ	elongation after fracture
E	elastic modulus
H	overall height of aluminum tubular section
B	overall width of aluminum tubular section
R	Internal arc radius
T	wall thickness of aluminum tubular section
L	overall length of aluminum tubular section
A	bearing length
$(h_t-2t)/t$	web slenderness
ε_i	strain intensity
ε_1	first principal strain
ε_2	second principal strain
ε_3	third principal strain

considerable underestimations for the range of specimens under EOF and ETF loading conditions. A combination of experimental tests and non-linear elastic–plastic finite element analyses were used to investigate the effect of holes on web crippling under interior-two-flange (ITF) loading conditions by Uzzaman et al. [6]. Design recommendations in the form of web crippling strength reduction factors were proposed. A design rule which was based on a theoretical and numerical model of strength of cold-formed steel lipped channel beams was put forward by Macdonald and Heiyantuduwa [7]. Based on the results of the parametric study, a design rule was developed which was much more flexible to adapt for new types of sections and ranges of dimensions. Zhou and Young [8] numerically investigated cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. A unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures was proposed.

There is little experimental and numerical research being carried out on the behavior of aluminum beams under four loading and boundary conditions subjected to web crippling. Therefore, the ultimate capacity, failure modes and ductility of aluminum beams subjected to web crippling need further investigation. In this study, a series of web crippling tests of the aluminum square hollow sections was conducted. The test specimens were tested under EOF, IOF, ETF and ITF boundary and loading conditions. The effects of bearing lengths, web slenderness and boundary and loading conditions on the ultimate capacity and initial stiffness of aluminum beams subjected to web crippling were investigated. Furthermore, using the calibrated finite element model, a parametric study was conducted to comprehensively investigate the effects of some important geometric parameters on the ultimate capacity of aluminum beams subjected to web crippling. The design formulas of ultimate capacity were also proposed for aluminum beams subjected to web crippling at the end of the paper.

2. Experimental investigation

2.1. Test specimens

Experimental investigations were designed to examine the influence of various boundary and loading on web crippling ultimate capacity. A total of 48 aluminum square hollow sections with different boundary conditions, loading conditions, section heights, and bearing lengths were tested in Table 1. The specimen had the nominal thickness ranging from 1.1 to 2.6 mm, the nominal heights of webs ranging from 65 to 110 mm, and the flange widths ranging from 25 to 100 mm. The measured ratio of the height to the thickness (web slenderness) of the webs ranged from 30 to 88. The symbols of aluminum tubular sections are defined in Fig. 1.

The bearing plates were fabricated with Chinese Standard Q345 steel having the nominal thickness of 30 mm. All the bearing plates were machined to specified dimensions, and the length was 300 mm. The bearing plates were designed to act across the full flange widths of the specimen sections, so as to ensure the overall displacement loading.

In the paper, the specimens were tested in four loading conditions, namely, End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF) and Interior-Two-Flange (ITF). In order to eliminate the boundary effect, the distance from the edge of the bearing plate to the end of the member was set to be at least 1.5 times the overall depth of the web. Schematic sketch of web crippling tests in four boundary and loading conditions are considered in Fig. 2. Fig. 3 shows photographs of web crippling tests in four boundary and loading conditions.

2.2. Specimen labeling

In Table 1, all specimens were labeled to easily identify material type of the specimens, section geometry, and the loading condition, as well as length of the bearing could be identified from the label. For example, the labels AL60 × 65-EOF-N100 is defined as the following specimens:

- The first letters indicates the material type of the specimens, where 'AL' refers to aluminum.
- The following number symbols are the nominal dimension of the specimens in mm, where '60 × 65' ($b \times h$) means the nominal flange width (b) of 60 mm, and the nominal height (h) of 65 mm.
- The following three letters indicate the loading and boundary condition, where EOF refers to exterior-one-flange test.
- The last part of the label 'N100' indicates the bearing plate width in mm, where '100' means the nominal bearing length (a) of 100 mm.