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Compressive buckling strength of extruded aluminium alloy I-section columns with fixed-pinned end conditions

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ABSTRACT

The compressive buckling behaviour of extruded aluminium alloy I-section columns with fixed-pinned end conditions has been experimentally and numerically investigated in this study. A total of 11 column tests, involving two heat-treated aluminium alloys – 6061-T6 and 6063-T5, were carried out to acquire the compressive buckling strengths. Prior to the column tests, material properties of the two aluminium alloys were determined from tensile coupon tests, while the initial local and global geometric imperfections were separately measured by means of experimental techniques. By using the ABAQUS software package, finite element (FE) models that could account for material non-linearity and initial geometric imperfections were developed. The FE models were further validated against the test results, enabling reliable simulation of the compressive buckling behaviour of the tested columns with fixed-pinned end conditions. Based on the obtained test and numerical results, the calculation methods in the current design standards, including the European, Chinese, American and Australian/New Zealand specifications, were all assessed. It was shown that the design provisions in all the four standards provided relatively conservative strength predictions, especially for the aluminium alloys with more pronounced strain hardening capacity.

1. Introduction

Aluminium alloy profiles could be readily fabricated by means of the extrusion process, enabling efficient production of various customised cross-sections rather than being limited to the standard rolled shapes [1]. Together with the other well-known properties, such as prominent corrosion resistance and high strength-to-weight ratio, the extruded aluminium alloy profiles have been frequently employed in building structures [2]. The stability of aluminium structural members would differ from that of carbon steel members due to the lower Young's modulus and material non-linearity of aluminium alloys. Similar to stainless steels, the absence of the yielding plateau and considerable strain-hardening beyond the nominal yield point could be observed from the material stress-strain behaviour, resulting in inaccurate strength predictions from the current design methods that based on the bi-linear material behaviour and the concept of section classification [3]. Hence the sufficient material non-linearity exhibited by the aluminium alloys warranted special treatment in structural design [4]. The structural behaviour of extruded aluminium alloy I-section columns under axial compression with fixed-pinned end conditions is the focus of this study.

The buckling strength of aluminium alloy structural members has been studied through the past decades. Compression tests on aluminium alloy columns have been conducted by many researchers, involving various extruded cross-section types including H-sections [5,6], square and rectangular hollow sections [7–9], circular hollow sections [10,11], angles [12,13] and other irregular shapes [14,15]. In general, stub column tests that aimed at studying the local buckling behaviour were carried out with fixed end supports, while the centrally loaded columns with larger slendernesses were usually tested with pinned end conditions [16]. Though the full rigid restraint may not be provided over the entire loading process by introducing the fixed end supports, this type of end condition can still be utilised for testing columns with relatively small cross-sectional dimensions or load-carrying capacities [10,17], owing to its ease of implementation. The cross-sections with slender elements were commonly used to achieve greater efficiency in structural design, and the local plate buckling might occur prior to overall column buckling once the local buckling stress became lower than the overall buckling stress. Hence, accounting for the local-overall interaction effect would become one of the fundamental steps in design

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[15,18,19]. Overall, it can be found that there have been few publicly reported experimental investigations on extruded aluminium alloy I-section columns with fixed-pinned end conditions, despite the fact that the necessity of using this type of end conditions has been demonstrated in practical engineering applications.

This paper presents a comprehensive experimental study on compressive buckling behaviour of a total of 11 extruded I-sections made of two heat-treated aluminium alloys. The column specimens were axially loaded with fixed-pinned end conditions, resulting in overall flexural buckling and local-overall interactive buckling failure modes. By means of the material properties obtained from tensile coupon tests, and initial local and global geometric imperfections measured by experimental techniques, FE modelling of the buckling behaviour of the tested columns was carried out. Based upon the obtained test and numerical results, the existing design methods in the current Eurocode 9 (EC9) [20], the Chinese design code (GB) [21], the aluminium design manual (AA) [22] and the Australian/New Zealand design standard (AS/NZS) [23], were all herein assessed.

2. Test specimens

2.1. Material properties

Two heat-treated aluminium alloys – 6061-T6 and 6063-T5 that have long been used for structural applications, were incorporated into this study. The material properties were determined by means of tensile coupon tests, which conformed to both the Chinese testing standard [24] and ASTM test method [25]. The obtained material properties are listed in Table 1, including Young's modulus E_0, 0.2% proof stress $\sigma_{0.2}$, ultimate stress σ_u, elongation rate ε_f and Ramberg-Osgood exponent n, which were also reported in a previous study [26]. Since the test specimens were extruded through six different die toolsets, the tensile coupons were directly cut from cross-sections generated by each die toolset. Moreover, separate tensile coupons from flange and web were prepared, enabling accurate measurement of material properties of individual cross-sectional elements. Compared to the weak hardening alloy 6061-T6, it can be found that lower nominal yield strengths $\sigma_{0.2}$ but more pronounced strain hardening capacities are highlighted for the strong hardening alloy 6063-T5.

2.2. Specimen geometry

A total of 11 specimens were prepared in this study by extrusion of the two heat-treated aluminium alloys. The cross-sectional dimensions were dominated by the shape of the six existing die toolsets. As for the test specimens extruded from the same die toolset, varied flange widths were generated by using a sawing machine. The column ends were also machined to the designed geometric lengths with the same sawing machine. The accurately measured geometric dimensions were listed in Table 2, where the geometric symbols are defined according to Fig. 1. The effective column length L_e was taken as 0.7 times the geometric length, owing to the fixed-pinned end conditions [27].

The test specimens were labelled by the material type and cross-sectional dimensions. The label T6-280-160-R-B, for example, defines a test specimen made of 6061-T6 aluminium alloy with nominal sectional depth of 280 mm and flange width of 160 mm. The symbol 'R' was used to indicate an extruded ribbed slot on one flange (shown in Fig. 2), which can be used, for example, to attach purlins and girts to a frame member by receiving screws. The last symbol 'B' revealed the fact that this column had the same cross-section geometry with the specimen 'A', yet the column length might be different. It should be noted that the increment in cross-section area due to the presence of the ribbed slot has been taken into account in Table 2 for the four related test specimens.

2.3. Initial geometric imperfections and load eccentricity

Though the extruded aluminium alloy profiles were cold finished to improve surface finish and minimise geometric imperfections, both initial local and global geometric imperfections of the tested columns were separately measured prior to testing. The experimental techniques, successfully applied for measurement of geometric imperfections in both aluminium alloy and stainless steel columns [26,28], were also adopted in this study. Similarly, three cross-sections - the mid-length cross-section and two end cross-sections (50 mm away from each end) were chosen to determine the initial local imperfection amplitudes, while the global geometric imperfections were measured from a total of five cross-sections, including the previous three cross-sections and two other quarter-point cross-sections.

Specifically, a digital linearly-varying displacement transducer (LVDT) driven by a calibrated electric guideway was used to acquire the local imperfections, while an optical theodolite and a calibrated vernier caliper were used to determine the global curvature along the specimen length. The initial local and global imperfection amplitudes were taken as the maximum values among the measured cross-sections, which are summarised in Table 3. It can be seen that the maximum value of local geometric imperfection amplitudes reaches 0.54% of the plate width, while the average values of local geometric amplitudes are 0.32% and 0.33% of the plate width for specimens of 6061-T6 and 6063-T5 alloy, respectively. The average value of the ratio of global curvature over geometric length measured from the specimens of 6061-T6 alloy is much smaller than that obtained from the specimens of 6063-T5 alloy. Only two of the test specimens (T5-270-145 and T5-270-178) display global curvatures slightly beyond the 0.8‰L limit, yet still below the 1.5‰L limit. Consequently, by referring to the recommendations presented in the Chinese standard for aluminium profiles [29], nine of the test specimens could be categorised as extruded precision profiles, while the remaining two columns were regarded as general profiles.

Table 1
Measured material properties for the two aluminium alloys.

Alloy	Die toolset	Location	E_0 (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_f (%)	n
6061-T6	1	F	70,100	279.9	296.2	4.9	28.0
		W	68,900	258.1	289.7	8.1	25.8
	2	F	72,600	257.8	291.5	15.9	25.8
		W	70,000	270.5	298.5	13.3	27.1
	3	F	70,800	248.0	285.6	12.1	24.8
		W	72,500	264.8	297.9	11.2	26.5
	4	F	68,300	231.7	260.6	13.9	23.2
		W	69,100	249.7	291.4	10.8	25.0
6063-T5	5	F	63,300	142.5	185.3	16.9	14.2
		W	67,200	154.6	201.6	15.9	15.5
	6	F	63,700	170.2	215.6	24.2	17.0
		W	64,600	168.4	218.0	16.8	16.8

F: Flange, W: web.