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Design of cold-formed steel channels with stiffened webs subjected to bending

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ABSTRACT

The objectives of this study are to investigate the structural behaviour and evaluate the appropriateness of the current direct strength method on the design of cold-formed steel stiffened cross-sections subjected to bending. The stiffeners were employed to the web of plain channel and lipped channel sections to improve the flexural strength of cold-formed steel sections that are prone to local buckling and distortional buckling. An experimental investigation of simply supported beams with different stiffened channel sections has been conducted. The moment capacities and observed failure modes at ultimate loads were reported. A nonlinear finite element model was developed and verified against the test results in terms of strengths, failure modes and moment–curvature curves. The calibrated model was then adopted for an extensive parametric study to investigate the moment capacities and buckling modes of cold-formed steel beams with various geometries of stiffened sections. The strengths and failure modes of specimens obtained from experimental and numerical results were compared with design strengths predicted using the direct strength method specified in the North American Specification for cold-formed steel structures. The comparison shows that the design strengths predicted by the current direct strength method (DSM) are conservative for both local buckling and distortional buckling in this study. Hence, the DSM is modified to cover the new stiffened channel sections investigated in this study. A reliability analysis was also performed to assess the current and modified DSM.

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1. Introduction

The advantages of using cold-formed steel sections are high strength-to-weight ratio, flexibility in fabricating different cross-section shapes, easy for construction and so on. Cold-formed steel sections are usually manufactured into channel sections, Z-sections, hat sections and some other open sections by cold-rolling or brake-pressing technique. The plate elements constituting the cold-formed steel sections usually have large width-to-thickness ratio. Hence, local buckling and distortional buckling are usually the governing failure modes for cold-formed steel members. In plate mechanics, the edge stiffeners, such as lips in channel sections, and intermediate stiffeners in the web can enhance the strength of sections by acting as the out-of-plane supports to the flat plate elements of sections. Thus, the stiffeners improve the efficiency of the use of material.

Extensive investigations have been conducted on cold-formed steel conventional sections and design rules can be found in the specifications of different countries, such as the European Code [1], North American Specification [2] and Australian/New Zealand Standard [3]. Two main design methods, namely the effective width method (EWM) and the direct strength method (DSM), are used to calculate members failed by local buckling and distortional buckling. However, when sections were stiffened by edge and intermediate stiffeners for optimized section shapes, the computation of effective width for each plate element could be quite tedious that involves iteration processes and the EWM becomes much more complicated compared to the DSM. Hence, the DSM was recommended for design of cold-formed steel members with complex stiffeners [4]. On the other hand, the DSM in current specifications is a semi-empirical approach [5], which was calibrated to cover only the pre-qualified sections specified in the North American Specification [2]. In recent years, efforts have been made by some researchers to investigate the structural behaviour of cold-formed steel stiffened sections. These studies include the channel columns with inclined lips [6,7], channel columns with returned lip stiffeners [8], concentrically loaded compression members with equal lipped angles [9], columns with non-symmetric lipped angle sections [10], columns of built-up closed and open sections with intermediate stiffeners [11,12], and beams with both edge and intermediate stiffeners in the compression flanges of Z-sections [13].

However, it was found that limited investigation have been conducted on cold-formed steel stiffened sections subjected to

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Nomenclature

b_f	width of flange
b_l	depth of lip
C_P	correction factor in reliability analysis
E	initial Young's modulus
f_y	yield stress
F_m	mean value of fabrication factor
h_w	overall depth of web
M_{crd}	critical elastic distortional buckling moment
M_{crl}	critical elastic local buckling moment
M_{DSM}	nominal flexural strength predicted by current direct strength method
M_{DSM*}	nominal flexural strength predicted by modified direct strength method
M_{EXP}	moment capacities obtained from experimental investigation
M_{EXP-3p}	ultimate moments of test specimens subjected to three-point bending
M_{EXP-4p}	ultimate moments of test specimens subjected to four-point bending
M_{FEA}	moment capacities obtained from finite element analysis
M_m	mean value of material factor
M_{nd}	nominal flexural strength for distortional buckling
M_{ne}	nominal flexural strength for lateral-torsional buckling
M_{nl}	nominal flexural strength for local buckling
M_p	member plastic moment
M_y	member yield moment
P_m	mean value of experimental / FEA-to-predicted moment ratio
r_i	inner radius of the round corner of sections
S_f	gross section modulus referenced to the extreme fiber at first yield
t	thickness of steel plate with coating
t^*	base metal thickness
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_P	coefficient of variation of experimental/FEA-to-predicted moment ratio
w_1, w_2, w_3	width of plate elements of stiffened channel sections
Z_f	plastic section modulus
β_0	target reliability index
β_1	reliability index using the load combination of 1.2 dead load + 1.6 live load
β_2	reliability index using the load combination of 1.25 dead load + 1.5 live load
ε	engineering strain
ε_f	strain at fracture in material coupon tests
ε_{pl}	plastic strain
η	shape factor
θ	angle of inclined web element from the vertical axis
λ_d	slenderness for distortional buckling
λ_l	slenderness for local buckling
σ	engineering stress
$\sigma_{0.2}$	0.2% proof stress (yield stress)
σ_{crd}	elastic distortional buckling stress
σ_{crl}	elastic local buckling stress
σ_{true}	true stress
σ_u	tensile ultimate strength in material coupon tests
ϕ_b	resistance factor for beams

bending. Therefore, this study focused cold-formed steel beams with stiffened channel sections subjected to local buckling and distortional buckling. A total of 16 simply supported beams were tested under both four-point bending and three-point bending about the major axis of the sections. The moment capacities and corresponding failure modes were obtained. In addition, nonlinear finite element analysis was performed for stiffened sections with various geometries. The appropriateness of DSM in current specifications was evaluated for the stiffened sections in this study based on the experimental and numerical results. Finally, modified DSM is proposed for cold-formed steel stiffened channel sections beams subjected to local and distortional buckling.

2. Test program

2.1. Test specimens

A total of 32 cold-formed steel specimens of single channels with complex intermediate and edge stiffeners were tested subjected to bending about the major x-axis. Two identical stiffened channels were tested at the same time in order to avoid out-of-plane bending. Therefore, a total of 16 beam tests was conducted. In this study, there are three section shapes, namely the "A-section", "B-section" and "C-section" as shown in Fig. 1. These channel sections were brake-pressed from high strength zinc-coated grades G500 and G550 structural steel sheets with nominal 0.2% proof stresses of 500 and 550 MPa, respectively. Two plate thicknesses of 0.48 and 1.0 mm were tested for all three sections, while an additional plate thickness of 1.2 mm was tested for C-section. The angle of inclined web element (θ) was 45°, 30° and 60° from the vertical axis for A-sections, B-sections, and C-sections, respectively. The cross-section dimensions of all specimens were measured and reported in Tables 1–3.

The test specimens were cut into a specified length of 1400 mm for all the channels. The beam specimens were selected to have a relatively short span, which was aimed to investigate the local buckling and distortional buckling of the stiffened sections.

2.2. Specimen labelling

The test specimens were labelled with characteristic information such that each beam can be easily identified, as illustrated in Fig. 2(a). For example, the label "A-0.48-B4R-a", where "A" refers to the A-section as shown in Fig. 1(a), "0.48" indicates that the plate thickness is 0.48 mm, and "B4" refers to the four-point bending test about the major axis. If a test was repeated, then a symbol of "R" was added after "B4". Finally, "a" indicates the channel "a" of a pair of channels tested at the same time.

2.3. Tensile coupon tests

The material properties of the test specimens were obtained by carrying out tensile coupon tests. The coupon specimens were prepared in accordance with the Australian standard AS 1391 [14]. The flat tensile coupons were extracted in the longitudinal direction of the beam test specimens. Two coupon specimens were tested for each of the seven different sections. The material properties including initial Young's modulus (E), 0.2% proof stress

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