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Behaviour and design of cold-formed steel built-up section beams with different screw arrangements

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ABSTRACT

An experimental and numerical investigation of cold-formed steel built-up beams with different screw arrangements is presented in this paper. A total of 35 beams were tested under four-point bending with different screw arrangements in the moment span. The built-up sections were assembled using self-tapping screws from either two lipped channels connected back-to-back at the web to form an open section or two plain channels connected face-to-face at the flanges to form a closed section. Finite element (FE) models have been developed and validated against the test results for the built-up open section beams and built-up closed section beams, respectively. It is shown that the FE models can accurately predict the behaviour of cold-formed steel built-up beams with different screw arrangements. A parametric study on built-up beams with larger span and various screw spacing was further carried out using the verified FE models. The test and numerical results were compared with the design strengths predicted by the direct strength method (DSM) for cold-formed steel structures, with contingent considerations of the screws when determining the elastic buckling moments in the finite strip analysis. A reliability analysis was performed to evaluate the reliability of the current DSM equations. It is shown that the current DSM equations can predict the design strengths of built-up open section beams well in this study, with the assumption that the strength of the built-up section is the sum of two component profiles. However, the design equations for local buckling strength are generally conservative for the built-up closed section beams failed by local buckling. Meanwhile, the design equations for lateral-torsional buckling (LTB) strength cannot be directly used for the built-up closed section beams with relatively large screw spacing that failed by LTB with cross section distortion or separation of two component channels. It should be noted that LTB mode with cross section distortion was found in built-up closed section beams with large screw spacing. A modified design rule based on DSM is then proposed, which is shown to improve the accuracy of the predicted strengths. Moreover, the maximum longitudinal screw spacing for built-up closed section beams was also recommended for design practice.

1. Introduction

Cold-formed steel is commonly manufactured into singly symmetric or point symmetric open sections with the advantage of flexibility and convenience in fabrication. However, the torsional rigidity of such open sections is relatively weak. Cold-formed steel built-up sections can be formed into doubly symmetric sections to overcome this issue. Doubly symmetric built-up open sections and built-up closed sections can be made by connecting two channel sections using self-tapping screws. The steel plates of cold-formed sections are usually thinner than those of hot-rolled steel sections, hence, local and distortional buckling usually occurred together with overall buckling for the failure modes of the cold-formed steel built-up members. Therefore, the structural behaviour of cold-formed steel built-up section members may differ from that of traditional hot-rolled steel built-up members. On the other hand, the built-up sections are only connected at discrete points along the member length, making the structural behaviour of cold-formed steel built-up section members more complicated than that of cold-formed single open section and tubular section members.

The method of modified slenderness ratio for built-up section columns was prescribed in the North American Specification [1]. Most of the available studies conducted on built-up sections had also been focused on compression members. Peters [2] investigated the effect of fastener spacing on built-up box-shaped compression members consisting of a track section overlapping a channel section. Stone and Laboube [3] found the actual, instead of the modified slenderness ratio of

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Nomenclature

The following symbols are used in this paper:

b_{f1}, b_{f2}	width of flange
b_{l1}, b_{l2}	depth of lip
C_P	correction factor in reliability analysis
e	location of screw in cross section
E	initial Young's modulus
F_m	mean value of fabrication factor
f_y	yield stress
g	vertical distance between two rows of connections nearest to top and bottom flanges
h_w	overall depth of web
L	span of beam
L_{crl}	critical local buckling half-wavelength
M_{crd}	critical elastic distortional buckling moment
M_{cre}	critical elastic lateral-torsional buckling moment
M_{crl}	critical elastic local buckling moment
$M_{crlg,s}$	critical elastic local buckling moment of the single section considering screw effect
$M_{crl,\min}$	critical elastic local buckling moment corresponding to half-wavelength of L_{crl}
M_{DSM}	nominal flexural strength predicted by direct strength method
M_{DSM*}	nominal flexural strength predicted by modified direct strength method
M_{EXP}	moment capacities obtained from experimental investigation
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_y	member yield moment
m	distance from shear center of one C-section to mid-plane of web
P_m	mean value of experimental-to-predicted moment ratio
q	design load on beam for determining longitudinal spacing of connections
r_i	inner radius of the round corner of sections
S_f	gross section modulus referenced to the extreme fiber at first yield
s_l	longitudinal screw spacing
$s_{\max}$	maximum value of longitudinal screw spacing
T_s	available strength of connection in tension
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
V_s	available strength of connections in shear
Z_f	plastic section modulus
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 1.2 dead load + 1.5 live load
ε_f	strain at fracture in material coupon tests
λ_d	slenderness for distortional buckling
λ_l	slenderness for local buckling
λ_l*	modified slenderness for local buckling
$\sigma_{0.2}$	0.2% proof stress (yield stress)
σ_u	tensile ultimate strength in material coupon tests
ϕ_b	resistance factor for beams

the built-up member can be used in the design of built-up I-shaped cross-section studs. Tang and Ma [4] studied the mechanical behaviour of bolted connections for built-up I-shaped columns consisting of two lipped channels and found that the load bearing capacity decreases sharply when the bolt spacing in longitudinal direction is larger than half of the span. Whittle and Ramseyer [5] conducted compression tests on built-up closed section members formed of intermediately welded C-channels and found that the predicted capacities based on both the unmodified and modified slenderness ratio were consistently conservative. Reyes and Guzman [6] found from laboratory tests that there is no significant statistical reduction in the failure load of built-up cold-formed steel box sections when the seam weld spacing is less than a certain value. Li et al. [7] investigated the influence of different fastener spacing on the ultimate capacity of built-up columns and recommended a suitable screw spacing for design. Zhang [8] investigated the behaviour and design of built-up open and closed compression members with different screw spacing, in which the sections had longitudinal stiffeners. Liao et al. [9] reported that the screw spacing has no impact on the ultimate axial compression bearing capacity for the multi-limbs built-up cold-formed steel stub columns investigated in their study. It was found in the research by Lu et al. [10] that local buckling cannot be restrained in cold-formed steel I-section columns when the screw spacing is larger than the local buckling half-wavelength of the component C-section. However, this may not be the case for cold-formed steel closed sections in which the screw connections were located on the flanges subjected to local deformation.

Among the existing studies, little work has been carried out on the structural behaviour of built-up beams. Landolfo et al. [11] conducted four-point bending tests to investigate the load bearing capacity of laser welded built-up cold-formed steel beams. The effective width method and strength-reduction method for cold-formed built-up I-shaped beams were proposed by Zhou and Shi [12], however, the properties of connections were not considered. The previous research conducted by the authors [13,14] was focused on the behaviour of cold-formed steel built-up sections with intermediate stiffeners under bending, in which the screw spacing was close to the web height of the cross-section and influence of the screw spacing was not considered. Recently, Li et al. [15] investigated built-up box beams with nested C and U section under pure bending, and suggested the equivalent box section method for determining the moment capacity of the built-up sections bending about the major axis. The provisions of built-up beams in the current specifications [1,16] provide very little information on fasteners for I-sections composed of two back-to-back channels, and no design equation is provided. Therefore, the effect of screw arrangements on beam strengths, and the design rule for flexural members with cold-formed steel built-up open and closed sections is explored in this study. A test program including both built-up open section and built-up closed section beams were tested under four-point bending, with different screw arrangements in the moment span. Nonlinear finite element analysis was performed for longer beams with various screw spacing. The suitability of the DSM in the current specifications was evaluated for the built-up sections in this study, with contingent consideration of the screw effects, based on the experimental and numerical results. Finally, a design rule based on the modified DSM is proposed for cold-formed steel built-up closed section beams with different screw spacing under pure bending.