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Experimental response of cold-formed steel lipped channel beam-columns

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ABSTRACT

In this paper, the structural strength and stability of cold-formed steel lipped channel beam-columns under bi-axial moments and axial force are experimentally investigated. The results are employed to evaluate the reliability of the current North American cold-formed steel design standard, AISI-S100-12, for predicting the strength of beam-columns, by both the effective width method (EWM) and the direct strength method (DSM). Fifty-five 600S137-54 (AISI-S200-12 nomenclature) lipped channel beam-column sections with three different lengths: 305 mm (short), 610 mm (intermediate), and 1219 mm (long) are tested under combined bi-axial bending moments and axial force to characterize the failure modes and the member capacity. A loading rig specifically designed to apply eccentric axial load, in order to provide bi-axial bending and compression to the specimens, was developed and detailed herein. The experimental observations reveal that the failure modes are highly dependent on the stress distribution applied on the cross-section by the combined actions. The results show a considerable potential for improvement in current specification approaches which utilize a simple interaction equation, as this typically results in conservative strength predictions. The potential for further improvement of the current specification for predicting the strength of cold-formed steel beam-columns is discussed.

1. Introduction

Axial capacity and bending moment capacity of cold-formed steel structural members, e.g. lipped channels and Zee sections, have been studied extensively. Current design codes such as the North American Specification of the American Iron and Steel Institute and the Australian/New Zealand Standard (AZ/NZS) for cold-formed steel structures formally provide two design methods to determine the axial strength of columns and the flexural capacity of beams; the traditional effective width method (EWM), and the more recently developed direct strength method (DSM) [1,2]. EWM takes into account the effect of plate local buckling by reducing each plate in a cross-section to its effective width, that in turn leads to the reduction of a gross cross-section to an effective cross section (via an iterative solution). Alternatively, DSM takes cross-section stability into account through a series of design strength equations driven by advanced elastic buckling analyses, such as the finite strip method, for the elastic buckling loads of the member in local, distortional and/or global modes of failure, including interactions.

Although extensive efforts have been devoted to determining the capacity of cold-formed steel members under pure axial or flexural actions, the design of structural members including a combination of actions has seen less study in both EWM and DSM, particularly experimental research works [3–8].

Instead, design under combined actions, e.g. in AISI-S100-12 for both EWM and DSM, is developed as a simple linear combination of the isolated pure axial or flexural design previously studied. However, stability, particularly local and distortional buckling, is directly tied to the stress distribution developed over the cross-section under the combined actions and simple linear interactions are known to be inaccurate. Current cold-formed steel beam-column design does not determine stability under the actual combined actions, and ignores any nonlinear interaction in the strength between axial load and bending.

In this study, the structural strength and stability of cold-formed steel lipped channel beam-columns under bi-axial moments and axial force are experimentally investigated. In the long term potential improvements in current specification approaches, that utilize a simple interaction equation for beam-column strength prediction,

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are sought; here, we aim to document the extent of shortcomings in current design when compared with experimentally determined strengths. Fifty-five 600S137-54 (AISI-S200-12 nomenclature) lipped channel beam-column sections with three different lengths: short (seventeen, 305 mm specimens), intermediate (twenty, 610 mm specimens), and long (eighteen, 1219 mm specimens) are tested under combined bi-axial bending moments and axial force to characterize the failure modes and the member strength. The combined axial force and bi-axial bending moments were applied via a custom test rig designed to apply axial load with eccentricities. The current specification approaches including both effective width and direct strength methods are evaluated by a reliability based method and the potential for further improvement of the current specification for predicting the strength of cold-formed steel beam-columns is discussed.

The presented results are a part of an ongoing comprehensive study developing a new explicit DSM prediction for cold-formed steel beam-columns. This larger effort includes geometric and material nonlinear shell finite element collapse analyses, proposing a new design formulation that takes into account the cross-section stress distribution under combined actions, additional tests on cold-formed steel Zee sections, parametric analyses on different sizes of the cross-sections, and reliability assessment of new DSM beam-column equations.

2. Experimental program

2.1. Normalized P–M_1–M_2 space

A dimensionless normalized coordinate system in P–M_1–M_2 space is implemented to define the state of the applied combined actions including bi-axial bending moments (M_1, M_2) and axial force (P) with respect to the corresponding yield strength as follows (see also Fig. 1):

$$x = \frac{M_1}{M_{1y}} \quad (1)$$

$$y = \frac{M_2}{M_{2y}} \quad (2)$$

$$z = \frac{P}{P_y} \quad (3)$$

where, M_1 and M_2 are two orthogonal (typically principal) axes of the cross section and the denominators (subscript y) are the corresponding yield moments (or force). Points in the normalized P–M_1–M_2 space are defined by an azimuth angle, θ_{MM}, an elevation angle, ϕ_{PM}, and a radial length β:

$$\theta_{MM} = \tan^{-1}(y/x) \quad (4)$$

$$\varphi_{PM} = \cos^{-1}(z/\beta) \quad (5)$$

$$\beta = \sqrt{x^2 + y^2 + z^2} \quad (6)$$

The normalized axial and bending moment strength of a member are the anchor points on the x, y, and z axes. Connecting all the points corresponding to the strength of a member associated with particular θ_{MM} and ϕ_{PM} angles results in the strength (or interaction) surface of a member in the three-dimensional P–M_1–M_2 space. In this study, M_1 is assumed to be the major-axis of the lipped channel section (x in the P–M_1–M_2 space) and M_2 the minor-axis (y in the P–M_1–M_2 space). Note, this is not to be confused with the coordinate systems used in the physical testing (see Fig. 4) where, e.g., eccentricity in the physical testing coordinate system (e_x) causes bending about the major-axis. Further, note the use of a generalized coordinate system in the P–M_1–M_2 space does not play a central role in the results reported here; but is central to new ideas in developing explicit beam-column strength prediction expressions. So that the results may be evaluated in the context of that larger effort, the notation is introduced here so that all results are in a common format.

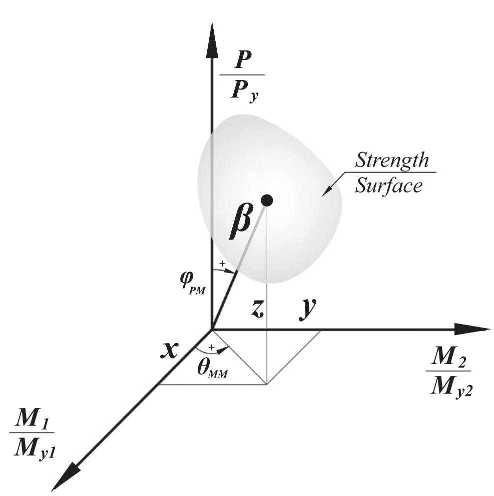

Fig. 1. Normalized P–M_1–M_2 Space.

2.2. Test matrix

Building a three-dimensional P–M_1–M_2 strength interaction surface requires many tests. Given the time and expense with testing only a limited number may be completed. Therefore, a single cross-section under a large variety of P–M_1–M_2 loading conditions and different lengths is tested here to mobilize different modes of failure. The selected cross-section is the 600S137-54 lipped channel (stud) with F_y=345 MPa (AISI-S200-12 nomenclature). The selected specimens are short (305 mm), intermediate (610 mm), and long (1219 mm) in length. The short specimens are intended to isolate global buckling and primarily mobilize local buckling. The distortional buckling half-wavelength is less than 305 mm and the specimen has warping fixed ends, thus distortional buckling is significantly boosted above its simply-supported lower bound (signature curve) value and local buckling is expected to be the primary behavioral mode for short specimens. The intermediate specimens are most likely to fail in distortional buckling, but both mixed modes, particularly local–distortional and local–global are possible. At intermediate length the global mode is still relatively high; therefore, local–global is not anticipated to be prevalent. However, at long lengths global and local–global interaction are expected to dominate. In addition, the long length specimens provide a means to explore the potential for distortional–global interaction. See [9] for further details on how the cross-section was initially selected based on these and other considerations.

Based on uniformly distributing the tests in the non-dimensionalized cylindrical coordinates (θ_{MM}, ϕ_{PM}, β) for the P–M_1–M_2 space, 17 short specimens are selected. As tabulated in Table 1, 9 specimens are considered for principal axes bending, including when the minor-axis lip is in tension (no. 1–3, θ_{MM}=270°), and when the minor-axis lip is in compression (no.4–6, θ_{MM}=90°), as well as major-axis (no. 7–9, θ_{MM}=0°) bending. Moreover, 8 other specimens (no. 10–17) are considered in four other non-principal axes with bi-axial bending and axial force (θ_{MM}= 30°, 60°, 300°, 330°). Each specimen has a designation of S600-L-X, where the 600 indicates the depth (in inches × 100, i.e., the same as the AISI-S200–12 nomenclature),