Thin-Walled Structures 98 (2016) 565–577

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Torsion of cold-formed steel lipped channels dominated by warping response

Guanbo Bian [a,*], Kara D. Peterman [a,b], Shahabeddin Torabian [a,c], Benjamin W. Schafer [a]

[a] Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA
[b] Department of Civil & Environmental Engineering, Northeastern University, Boston, MA, USA
[c] School of Civil Engineering, College of Engineering, University of Tehran, Iran

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
16 October 2015
Accepted 26 October 2015
Available online 9 November 2015

Keywords:
Cold-formed steel
Torsion
Warping
Direct Strength Method
Torsional buckling

ABSTRACT

The objective of this paper is to provide benchmark test results, explanatory shell finite element models, and preliminary Direct Strength Method prediction for cold-formed steel lipped channels undergoing torsion dominated by warping response. Although the elastic theory for the torsional response of a thin-walled cold-formed steel lipped channel member is well-developed, the extent to which warping torsion dominates the response of cold-formed steel members is not widely appreciated. Further, for cold-formed steel members in torsion little exists in terms of experimental benchmarks and even less on situations beyond the classic elastic theory, including geometric nonlinearity and post-buckling, and/or material nonlinearity from partial to full plastification of the section. Here, a typical cold-formed steel lipped channel member loaded experimentally in torsion exhibits significant strength beyond first yield. Shell finite element models of the testing correlate well with the experiments and indicate the extent of plastification as the thin-walled member undergoes torsion dominated by warping response. Idealized end boundary conditions are developed for the shell finite element model that is conservative with respect to the response, and in agreement with classical expressions in the elastic regime. The shell finite element model with idealized end boundary conditions is used to develop a parametric study on ultimate torsional capacity for members dominated by warping torsion. The results indicate that torsional slenderness may be used to predict torsional capacity and indicate that Direct Strength Method predictions for torsion for members dominated by warping torsion are possible. Preliminary design expressions for warping torsion strength prediction are provided.

1. Introduction

Torsion is fundamental to the response of cold-formed steel members since common sections are open, with relatively weak torsional resistance, and often singly- or un-symmetric. For thin-walled cold-formed steel members torsion manifests itself in direct form or through instability. For example, cold-formed steel lipped channel beams (joists, purlins, girts, etc.) loaded away from their shear center develop torsion. Torsion also plays a key role in buckling instabilities at the member level with lateral-torsional buckling of beams, and flexural-torsional buckling of columns; and at the cross-section level with (flange/web) distortional buckling. The theory for the elastic torsional response of thin-walled open sections was developed by Vlasov [1] and utilized by Timoshenko [2] and others, and remains the primary tool for design prediction methods (see [3]–[5]).

In the classical theory [3,4] torsion (T) is resisted by shear (T_{sv}) and by shear related to restrained warping (T_w):

$$T = T_{sv} + T_w = GJ\theta' - EC_w\theta''' \tag{1}$$

where G is the shear modulus, J is the St. Venant torsional constant, E is the elastic modulus, C_w is the warping torsion constant, and θ is the angle of twist (and ’ denotes derivatives). For thin-walled cold-formed steel sections, as discussed further in the next section, the shear contribution (T_{sv}) and related shear stresses (τ_t) are relatively small and the dominant resistance develops from warping restraint (e.g., see [6]). Warping restraint creates longitudinal (σ_w) and shear stresses (τ_w) in the cross-section. The longitudinal stresses, which are the primary contributor to instability and degraded strength in thin-walled members, may be determined from:

$$\sigma_w = E\omega\theta'' = B\omega/C_w \tag{2}$$

where ω is the sectorial coordinates, and B is the bimoment. Warping stress σ_w may be found directly through differentiation of

* Corresponding author.
E-mail address: bian@jhu.edu (G. Bian).

http://dx.doi.org/10.1016/j.tws.2015.10.023
0263-8231/

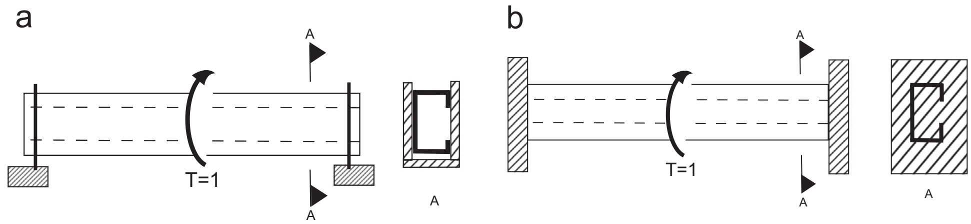

Fig. 1. Beam with mid-span torsion load: (a) torsionally supported – warping-free and (b) torsionally supported – warping-fixed.

the twist ([3], [4], and [5]), or through B, which develops in the section as it responds to torsion, T, and is available from numerical beam finite element solutions (e.g. MASTAN [7], [8]). The shear stresses due to warping vary around the cross-section according to:

$$\tau_w = -\frac{ES_w\theta'''}{t} \quad (3)$$

where S_w is the warping static moment, and t is the thickness of the member. The shear stresses due to St. Venant torsion vary through the thickness, per:

$$\tau_t = Gt\theta' \quad (4)$$

Research on cold-formed steel beams in torsion demonstrated the detrimental role of the torsional response on bending strength and the importance of including this response in design [9]. Analysis demonstrates that the torsional warping stresses change significantly as the beam twists and are highly sensitive to the end boundary conditions [10]. Exploration of the stability of the section further indicates that cross-section buckling is also sensitive to the longitudinal warping stresses that develop in the twisted section [10]. For the common case of a cold-formed steel beam with restraint on one flange the torsional stresses that develop are even more complex, but their correct inclusion can aid design ([11], [12], and [13]). Research provides significant insight on torsional response of cold-formed steel members, but less has been done to examine torsion in isolation for cold-formed steel members – the approach that has long been used to understand axial, bending, and shear actions.

In cold-formed steel design the basic philosophy is to try to eliminate torsion to the greatest extent possible. For example, AISI-S100 [5] provides prescriptive bracing criteria to limit torsion in beams. When torsion must be considered, design directly or indirectly applies stress-based interaction expressions to limit the impact of torsion. Eurocode [14] limits the total longitudinal stress from all actions, including torsion, to be less than the yield stress, F_y (divided by a partial safety factor). AISI-S100 [5] employs a reduction factor, R, on bending strength to account for bending-torsion interaction, where R is the ratio of the maximum bending stress to the combined bending (σ_b) plus warping stress (σ_w), i.e.:

$$R = \frac{(\sigma_w)_{max}}{|\sigma_b + \sigma_w|} \leq 1.0 \quad (5)$$

The resulting reduction, which is applied to the bending capacity calculated without consideration of torsion, provides a reduction similar to a longitudinal stress-based linear interaction equation. The dominance of a stress-based approach to account for a limit state (torsion) is unusual in modern design where strength-based limit states are used for all other actions.

The approach taken in this paper is to explore basic aspects of torsion in cold-formed steel members first from a review of classical elastic response, then from a pilot set of experiments at a single length, and finally from companion shell finite element models that extend into the nonlinear geometric response and yielding. Torsional response in buckling, initial yielding, and full plastification are all explored. Ultimately, the goal is to provide strength-based expressions for the prediction of torsional limit states, when warping torsion dominates the response, that can be integrated into design through appropriate interaction equations.

2. Classical elastic torsional response in cold-formed steel members

While it is generally understood that thin-walled open members, such as those used in cold-formed steel applications, rely on warping to restrain torsion the extent to which this is true and the conditions under which this is true are less well understood. Distribution of torsion between T_w and T_{sv} is dependent on cross-section properties, boundary conditions, and the member length.

To illustrate, consider the torsional response of a 400S162-54 [345 MPa (50 ksi)] cold-formed steel member (nomenclature per AISI-S200 [15]). Two cases with midspan torsion applied, as shown in Fig. 1 are considered: torsionally supported – warping-free (i.e. the ideal fork type boundary conditions), and torsionally supported – warping-fixed. The members are modeled in MASTAN [8]

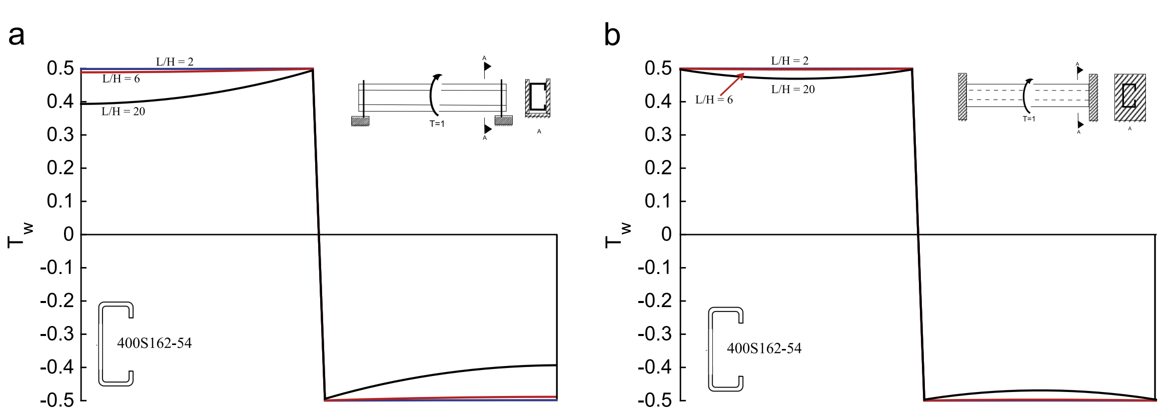

Fig. 2. Diagram of restrained torsion along member length for 400S162-54 for different member lengths (a) torsionally supported – warping-free and (b) torsionally supported – warping-fixed.