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Effect of moment gradient and load height with respect to centroid on the reliability of wide flange steel beams subject to elastic lateral torsional buckling

Christopher D. Eamon [a,*], Alexander W. Lamb [a], Kapil Patki [b]

[a] Wayne State University, Detroit, MI 48202, United States
[b] J3 Engineering Group, Chicago, IL 60062, United States

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The reliability of doubly-symmetric wide flange steel beams designed to the AISC Specification for Structural Steel Buildings subjected to elastic lateral torsional buckling was evaluated when considering variation in moment gradient and load height. The analysis considers continuous loads on spans subjected to various end moments with supports that are torsionally fixed and laterally supported, without additional intermediate restraints. Dead load, occupancy live load, and beam resistance random variables were considered. Beam lateral torsional buckling resistance was evaluated from numerical solution of a fundamental differential equation that accounts for the effect of moment gradient and load height. In some cases, it was found that use of the AISC design procedure results in significant inaccuracies for estimation of elastic lateral torsional buckling resistance, where underestimations occur in regions of reverse curvature bending and when loads are placed below the beam shear center, while large overestimations can occur when loads are placed above the beam shear center. These discrepancies result in significant variation in beam reliability. However, the use of accurate equivalent uniform moment factors can restore uniformity in notional reliability level.

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1. Introduction

A wide range of literature describing the elastic lateral torsional buckling (LTB) behavior of structural steel beams based on analytical, numerical and experimental data is currently available [1–14]. Moment gradient between the supports, effect of load height with respect to shear center, buckling interaction, and out-of-plane restraints at member ends are some of the common issues considered while studying the lateral torsional stability of beams. Two of these considerations, moment gradient and placement of load height with respect to shear center, are of particular concern in this study and are further discussed below.

For flexural members loaded with non-uniform moment, an equivalent uniform moment factor approach is often considered. This represents the ratio of the critical moment for a member with a particular moment gradient to the critical moment for the member with a uniform moment [15], where the critical moment refers to that which causes an instability failure. The work of various researchers has developed this concept. For example, Nethercot and Rockey [16] used numerical data in an effort to describe a general procedure to determine the elastic critical moment of beams. More recently, Suryoatmono and Ho [9] and Lamb and Eamon [13] developed a generalized parametric solution procedure that can be used to solve the governing differential equation for elastic stiffness for a wide range of moment gradients that includes the load height effect. The expression proposed by [13] was since revised by Trahair [14].

Various international design standards address the effect of moment gradient, typically with simplified empirical expressions that can account for any arbitrary moment function, as well as the use of more precise formula for specific cases. Some of these many standards include: Eurocode 3: Design of Steel Structures [17]; the Australian Standard for Steel Structures, AS 4100 [18]; Canada's Design of Steel Structures (CSA-S16) [19] as well as the American Institute of Steel Construction's Specification for Structural Steel Buildings, AISC 360 [20], the focus of this paper. Some standards also adjust for the effect of load height on the beam; Eurocode 3, CSA-16, and AS 4100 are such examples. Despite the research conducted on this issue, however, some prominent design standards such as AISC 360 have not

* Corresponding author.
E-mail addresses: eamon@eng.wayne.edu (C.D. Eamon), alexanderlamb@wayne.edu (A.W. Lamb), kapil.patki@wayne.edu (K. Patki).

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included the effect of load height in the development of equivalent moment factors (it should be mentioned that the code commentary of AISC 360 suggests that if the designer desires a more accurate solution considering load height, several alternative sources in the literature can be referenced for guidance; no specific provision is codified nor required, however). In particular, the expressions provided for the equivalent moment factor in these specifications implicitly consider loads to be acting at the shear center, neglecting the effect of load height throughout the depth of the cross-section. Moreover, the method to calculate equivalent moment factor in these specifications uses a general closed form expression which, although easy to use, for some load scenarios, produces results significantly different from the theoretical solution.

Such simplifications may have significant effect on the reliability of steel beams with regard to elastic LTB. In particular, based on deterministic analysis results, it is expected that lowering and raising vertical load placement from the shear center (i.e. at the centroid, for the symmetric sections considered here) of the beam, referred to as 'load height' in this paper (see Fig. 1), will increase and decrease beam reliability, respectively. It is also expected that large deviations in reliability may occur when both positive and negative moments appear on the span [13]. However, the potential impacts that these effects may have on beam reliability have not been quantified. In fact, few studies have investigated the failure probability of structural steel members with regard to LTB in general. Ellingwood et al. [21] and Galambos and Ravindra [22] developed initial resistance statistics for steel that can be used to evaluate LTB, while more recently, a statistical evaluation of LTB resistance properties of steel I-beams for Eurocode is presented by Silva et al. [23] and Robelo et al. [24], wherein a new partial safety factor was proposed. Szalai and Papp [25] presented a new probabilistic evaluation of standard resistance models for the stability of columns and beams, while Badari [26] validated their method by examining a simply supported steel beam subjected to LTB. Most recently, Kala [27] studied the effects of random imperfections on steel beam LTB reliability. Currently, however, there exists no systematic probabilistic assessment of steel beams subjected to elastic LTB designed according to current AISC 360 standards that accounts for general moment gradient and load height effects. To address this issue, this study aims to estimate the reliability of typical wide-flange beams subjected to elastic LTB as designed according to the AISC 360 provisions, considering the effect of continuous moment gradients and load height.

2. Load models

During its design lifetime, a structure is subjected to various loads such as dead load, occupancy and roof live loads, wind, snow, and earthquake loads, as well as others. Many interior beams in common braced frame steel construction are not subjected to significant lateral and environmental loads, and hence the load combination that frequently dominates is that of dead load and live load only, which is considered in this study.

Dead load (*DL*) statistical parameters used for code calibration are given consistently by various researchers [21,28–30] where *DL* is described as normally distributed with bias factor (ratio of mean value to nominal, or code-specified value) of $\lambda = 1.05$ and coefficient of variation (COV) of 0.10.

Occupancy live load represents the weight of people, furniture, partitions and other movable contents, and may be categorized into sustained (arbitrary-point-in-time) and transient (extreme event) components. Transient live load considers unusual occurrences of high load concentration such as a large number of people crowding together in a small room. It governs over the sustained effect with the load combination considered in this study, where 50 year maximum load statistics vary somewhat from one researcher to the next. However, when used for steel code calibration, statistics are generally taken as $\lambda = 1.0$ and COV = 0.25 [20,27,29], and it was typically assumed to follow a Gumbel distribution [21,28], although Galambos [30] assumed it to be lognormal for ease of calculation. In this study, occupancy live load is taken as a Gumbel distribution with the above statistical parameters. However, it should be noted that the results were found to be relatively insensitive to type of live load distribution used.

3. Resistance model

For reliability analysis, uncertainty in component resistance is traditionally developed from three sources: basic material properties (*M*); geometry during fabrication (*F*); and inaccuracies in the modeling method used to evaluate capacity, the professional (*P*) factor. The final bias factor for resistance, λ_R, is then taken as the product of the individual biases: $\lambda_R = \lambda_M\ \lambda_F\ \lambda_P$. Similarly, the COV of resistance, V_R, can be approximated as a function of its component COVs (V) as: $V_R = (V_M^2 + V_F^2 + V_P^2)^{1/2}$.

Ravindra and Galambos [31] report $\lambda_M = 1.05$ and $V_M = 0.10$ for rolled W shapes, while Galambos [30] later recommends $\lambda_M = 1.06$ and $V_M = 0.06$ from consideration of more recent material tests. However, these values were based on an analysis of variation

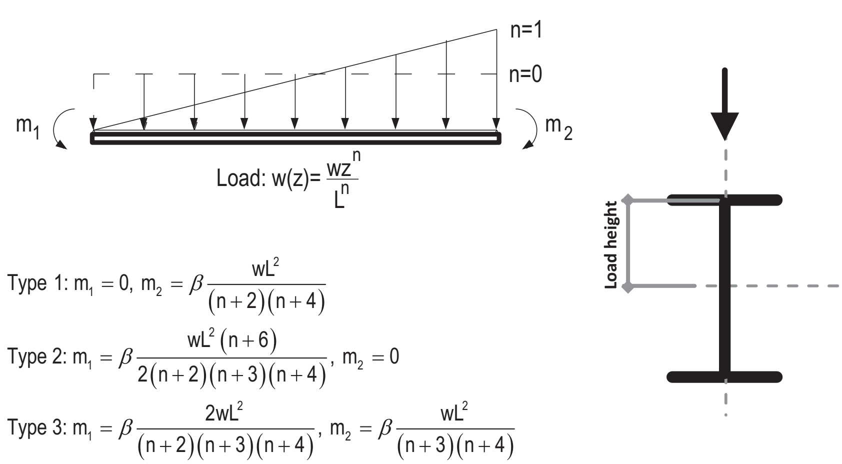

Fig. 1. Load characterization.

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