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Lateral buckling of overhanging crane trolley monorails

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Abstract

Lateral torsional buckling should be taken into account during the design of overhanging steel beams. One special type of overhanging beam is the crane trolley monorail. Lateral buckling of overhanging monorails under idealized loading and boundary conditions has been studied in the past using classical mathematical procedures. This paper aims to present a detailed investigation of overhanging monorails using finite element analysis. Effects of different loading and boundary conditions were studied in detail. It was found out that the location of loading and supports on the cross section have significant effects on the buckling capacity. Beams having different warping and torsional properties were analyzed. The effects of cross section distortion on buckling capacity were investigated for beams with single and double overhangs. The reduction in capacity due to cross section distortion has been quantified. Based on the analysis results, simple design recommendations were developed for lateral buckling of overhanging monorails, and they are presented herein.

Keywords: Lateral torsional buckling; Overhanging beams; Crane trolley monorails

1. Introduction and background

Beams are essential components of steel construction. A satisfactory design should ensure that the beam is stable and has enough strength and stiffness against the applied loads. For steel beams having an I-shaped cross section, global buckling and local buckling are typical modes of instability. Global instability is in the form of lateral torsional buckling of the beam as a whole, while local instability could be in the form of web or flange buckling. Design codes present capacity equations for lateral torsional buckling of I-shaped members [1,2]. Local buckling is usually precluded by limiting the width–thickness ratio of the compression elements (web and flange).

Lateral torsional buckling of I-beams is a complex phenomenon. If a simply supported beam is subjected to equal and opposite end moments, the compression flange of the beam can move sideways when a certain value of applied moment is reached. In this undesirable behavior, the tension flange tries to restrain the flange in compression and the resulting buckling mode is lateral-torsional, indicating a lateral displacement together with a rotation of the cross section. A closed form solution of the critical buckling moment (M_o) has been developed [3] and was adopted by many design codes [1,2] in different forms:

$$M_0 = \frac{\pi}{L}\sqrt{EI_yGJ}\sqrt{1+\frac{\pi^2 EC_w}{L^2GJ}} \tag{1}$$

where L is the unbraced length, E is the modulus of elasticity, I_y is the minor axis moment of inertia, G is the shear modulus, J is the torsional constant, and C_w is the warping constant.

In the derivation of Eq. (1) it is assumed that the cross section is prevented from lateral movement and twist at the ends of the beam. Due to the complexity of the problem, it is difficult to come up with closed form solutions for cases with different loading and boundary conditions. Only a few closed form solutions exist for the lateral torsional buckling problem and mostly numerical methods are used for the solution of such problems.

Features such as inelasticity and initial imperfections are not included in a classical bifurcation analysis. However, design codes recognize these features by converting the expressions derived on the basis of bifurcation analysis to design expressions. This then permits the use of correction

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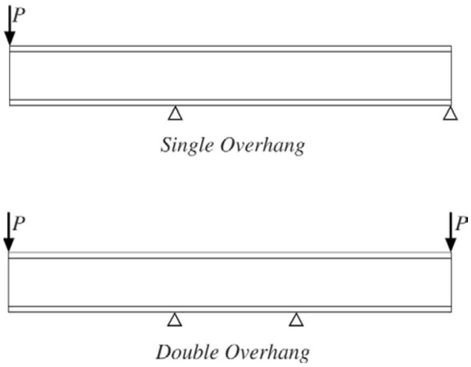

Fig. 1. A generic view of single and double overhanging beams.

factors obtained for elastic critical loads for making similar allowances to the design values.

For moment variations along the beam due to different loading conditions, Eq. (1) needs to be modified to obtain the critical moment (M_{cr}). This is usually accomplished by multiplying the critical moment obtained from Eq. (1) by a moment gradient factor, C_b:

$$M_{cr} = C_b M_0. \tag{2}$$

C_b is a modification factor for non-uniform bending moment variation along the laterally unsupported beam segment and depends on the shape of the moment diagram between lateral braces. C_b is dimensionless and varies between 1.0 and about 2.3 for simply supported and continuous beams. Moment gradient factors have been developed in the past and the most widely used ones can be found in the design codes [1,2].

Apart from simply supported and continuous beams, buckling of cantilevers has been studied in the past [3]. Due to the differences in boundary conditions, cantilevers are treated differently to simply supported beams. In addition, overhanging beams that possess the characteristics of both cantilever and simply supported beams lend themselves to another special class of problems. In the case of an overhanging beam shown in Fig. 1, there are either one or two cantilevering segments connected to a main span.

One special type of overhanging beam is the crane trolley monorail shown in Fig. 2. Overhanging monorails are quite frequently encountered in industrial structures. The monorail allows the movement of a crane trolley through the entire span of the member. As in the general case of the overhanging beams, monorails can have single or double overhangs. The design of crane trolley beams against global buckling is complex due to the nature of loading and boundary conditions.

Although buckling of overhanging beams in general has received attention in the research literature [4–7], the special case of crane trolley monorails has only been investigated by Tanner [8]. In Tanner's study [8] a generic single overhanging monorail shown in Fig. 2 was considered. As for the loading, the case where a point load acts at the end of the overhanging segment was considered. Due to this loading, the entire length of the bottom flange is in compression. Therefore, the system can be analyzed as a simple beam with overhang. For a location to be considered as an LTB brace point, the cross section needs to be braced against twist or lateral displacement of the compression flange. For the case shown in Fig. 2 the cross section is prevented from twisting at the interior support, therefore this location can be considered as a brace point. On the other hand, at the exterior support location, the displacement of the compression flange and twist are not restrained. In addition, it is not possible to restrain the end of the overhanging segment in order to have the lifting point clear of obstructions. The overhanging monorail is regarded as braced at the interior support only.

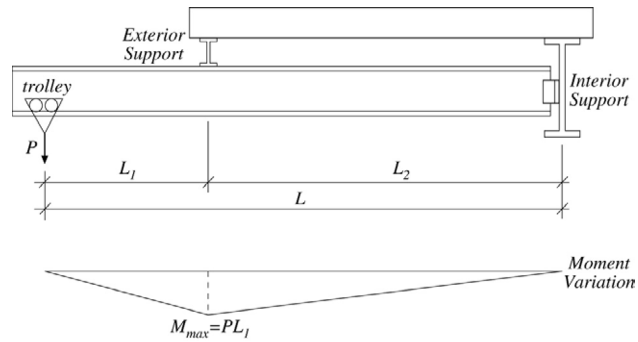

Fig. 2. A typical single overhanging monorail.

The system shown in Fig. 2 was analyzed by Tanner [8] using the classical mathematical procedures adopted for buckling of I-shaped beams. The beam was divided into two segments which comprise the main part and the overhanging part. For each part, the differential equation that represents the equilibrium of the segment in the deformed configuration was written in terms of the torsional rotation. Later, the differential equations were solved using the Bessel functions and boundary conditions were applied to reduce the problem to a system of linear algebraic equations. The critical value of the applied load was found by setting the determinant of the coefficient matrix of the system equal to zero.

Two major assumptions were made during the solution of the problem. First, it was assumed that the transverse loads are applied through the shear center of the cross section. Second, the warping stiffness was assumed to be negligible in comparison with the torsional stiffness. Tanner [8] focused on the solution for narrow flanged American standard shapes (S-shapes) which are commonly used for trolley beams. When the warping stiffness is neglected in Eq. (2) the critical buckling moment can be written as:

$$M_{cr} = \frac{C_b \pi}{L} \sqrt{E I_y G J}. \tag{3}$$

By using the mathematical procedure explained above, Tanner [8] obtained a set of C_b values as a function of the non-dimensional parameter k, which is defined as the ratio of the overhanging segment to the total beam length ($k = L_1/L$). The proposed C_b values based on the analyses are given in Table 1. For simply supported and continuous beams laterally supported at the ends, it is conservative to assume a C_b value equal to unity for cases with moment gradients. The solutions given by Tanner [8] showed that C_b values lower than unity should be expected for overhanging beams when the total length of the beam (L) is used in Eq. (3).