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Proposed design model for singly-symmetric overhanging monorail I-beams

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ABSTRACT

One special type of overhanging beams is the monorail type. The inability of restraining the bottom flange of the monorail beams leads to poor boundary conditions, especially, at the root support (interior support), which reduces the beam strength. The buckling length coefficients, used in the current standards and specifications, were firstly defined by Nethercot [10], which was conducted for the doubly-symmetric I-sections. The effect of the poor boundary conditions of the monorail beams was not considered by Nethercot [10] and accordingly was not considered by any of the current standards and specifications. In this study, a finite element model, correlated well with the experimental results, was used to investigate the behavior and the strength of singly-symmetric overhanging monorail I-beams. Nonlinear geometrical and material analyses were considered in this research. A parametric study was conducted, using the verified finite element model, to investigate the effect of different boundary conditions, at the root support and the tip, on the ultimate moment capacities of such beams. The study showed that the boundary conditions and the cantilever lengths as well as the mono-symmetric ratio had significant effect on the ultimate moment capacity and the main mode of failure of such beams. Based on the parametric study results, a handy design model was proposed. The study showed that the ultimate moment capacities of such beams, computed according to the current standards and specifications, ranged from unconservative to overconservative, when compared to those obtained from the finite element analysis and the proposed design model.

1. Introduction

The design of singly-symmetric overhanging beams did not take the same interest in any standard or specification, as doubly-symmetric simple beams took. In addition, monorail beams suffer poor conditions at their supports, because of the laterally-unsupported bottom flange (compression flange), as shown in Fig. 1. For the design of such singly-symmetric overhanging monorail I-beams, most of the current design standards and specifications relay on the buckling coefficients, presented by Nethtercot [10]. These buckling coefficients were dedicated to I-beams with doubly-symmetric sections, only. Ziemian [16] reported that "at the present time the challenge to part of mono-symmetric theory still has not been fully resolved".

The elastic critical lateral-torsional buckling moment (M_o), for simply supported doubly-symmetric I-beams, subjected to equal and opposite end moments, was proved and presented by Timoshenko and Gere [12], as follows;

$$M_o = \frac{\pi}{L_b}\sqrt{EI_yGJ + \left(\frac{\pi E}{L_b}\right)^2 I_yC_w} \quad (1)$$

where, E = modulus of elasticity; I_y = the second moment of area about minor axis of bending; C_w = warping constant; L_b = laterally-unsupported beam length; G = shear modulus; and J = torsional constant.

The elastic critical lateral-torsional buckling moment for simply supported singly-symmetric section with equal and opposite end moments was first obtained by Goodier [8], as follows;

$$M_o = \frac{\pi}{L_b}\sqrt{EI_yGJ}\left[\frac{\pi\bar{\rho}}{2} + \sqrt{\left(\frac{\pi\bar{\rho}}{2}\right)^2 + \left(1 + \frac{\pi^2 EC_W}{{L_b}^2 GJ}\right)}\right] \quad (2)$$

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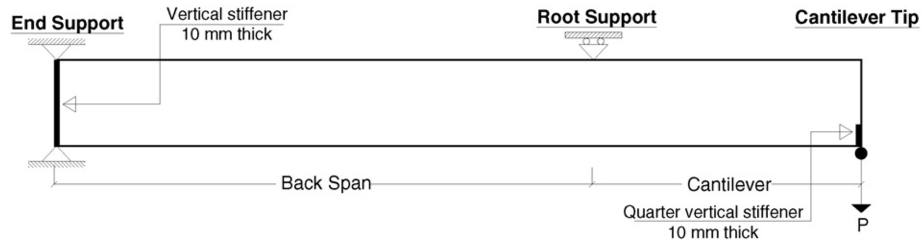

Fig. 1. Overhanging monorail beam.

where, $\overline{\rho}$ is the mono-symmetric parameter, defined as

$$\overline{\rho} = \frac{\beta_x}{L_b}\sqrt{\frac{EI_y}{GJ}} \tag{3}$$

where, β_x is the mono-symmetric property (Wagner effect). This property accounts for the change in the effective torsional stiffness from (GJ) to $(GJ + M_x\beta_x)$, due to the imbalance in the components of bending compressive and tensile stresses. This creates a torque, as the beam twists during buckling, where M_x is the applied bending moment about the major axis. The mono-symmetric property is defined, as follows;

$$\beta_X = \frac{1}{I_X}\left(\int_A x^2 y dA + \int_A y^3 dA\right)\text{-}2y_o \tag{4}$$

where, A = cross-sectional area, I_x = the second moment of area about major axis of bending; x & y = coordinates with respect to the centroid; and y_o = coordinate of shear center.

Timoshinko and Gere [12] expressed a differential equation of equilibrium for unbraced built-in cantilever with doubly-symmetric I-sections, using infinite series. They assumed full fixity at the root and a point load at the tip, applied at the level of the centroid. From the boundary conditions, an equation for calculating the critical load (P_{cr}) was obtained, as follows;

$$P_{cr} = \gamma_2\sqrt{\frac{EI_yGJ}{{L_b}^2}} \tag{5}$$

where, γ_2 = coefficient provided in Tables 6–3 of Timoshenko and Gere [12].

Trahair [13] developed an approximate formula to estimate the elastic critical lateral-torsional buckling of built-in cantilevers and overhanging segments, which were free to warp at the supports. The investigation considered built-in cantilever beams subjected to end moment, point load or distributed load. He proposed solutions for unbraced built-in cantilever beams with doubly-symmetric sections and varying load height. An elastic finite element program was used to obtain equations for the elastic critical lateral-torsional buckling moment (M_o), when the load was at the level of the centroid, as follows;

– for point load at the tip,

$$M_o = (3.95 + 3.52X)\frac{\sqrt{EI_yGJ}}{L_b} \tag{6}$$

– for uniformly distributed load,

$$M_o = (5.83 + 8.71X)\ \frac{\sqrt{EI_yGJ}}{L_b} \tag{7}$$

where,

$$X = \frac{\pi}{L_b}\ \sqrt{\frac{EC_w}{GJ}}. \tag{8}$$

Özdemir and Topkaya [11] studied the lateral-torsional buckling of doubly-symmetric overhanging crane trolley monorails, with single and double overhangs. The effects of load position and support location among the cross sections were investigated. Simple expressions were developed for predicting the moment gradient coefficient (C_b) values for different boundary conditions.

Andrade et al. [2] studied the elastic critical moments for doubly and singly-symmetric I-cantilevers. The so-called 3-factor formula, included in the ENV version of Eurocode 3, is one of the most commonly used general formulae to estimate the elastic critical moments in steel beams subjected to lateral-torsional buckling. They extended the application of this formula to built-in cantilevers by providing approximate analytical expressions to determine the C_1, C_2 & C_3 factors. The study considered the cantilever end support full built-in or free to warp and subjected to uniformly distributed load or concentrated load at the tip.

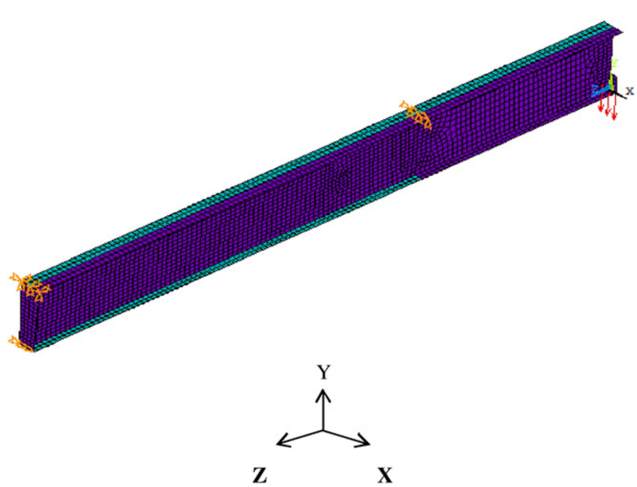

Fig. 2. Finite element model used in the study.

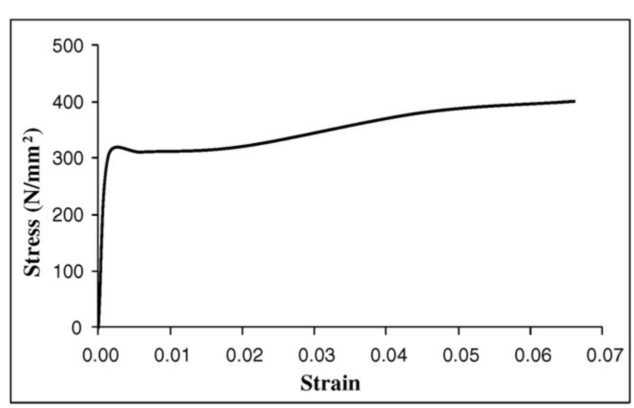

Fig. 3. Elasto-plastic multi-linear kinematic hardening stress–strain curve (Gindy [7]).