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Stability of unbraced concrete beams on bearing pads including wind loading

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A R T I C L E I N F O

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A B S T R A C T

Unbraced concrete beams supported temporarily at their ends by bearing pads are considered. Such beams may have horizontal curvature due to initial sweep and/or solar heating, and may be subjected to wind. These factors, along with creep and bearing eccentricity or slope, tend to cause the beam to roll (tilt) about the supports and possibly slide laterally, which may induce failure. Collapse of such unbraced bridge girders has occurred, and the problem is analyzed here. The beam is assumed to have small horizontal curvature (small sweep), and to behave elastically under gravity and wind loads. The equilibrium roll angle depends on the beam's length, weight per unit length, modulus of elasticity, moment of inertia with respect to weak-axis bending, and height of the cross-sectional center of gravity above the roll axis, along with the lateral superelevation angle of the bearing pads, roll and yaw stiffness coefficients of the bearing pads, and wind loading. The effects of some of these quantities on the roll angle are investigated. Approximate formulas in the literature do not include the effect of wind. If a maximum allowable roll angle is specified, a factor of safety is determined and compared with the one used in the design of bridges. Finally, the critical value of the roll angle for sliding instability is obtained in terms of the coefficient of friction of the bearing pads.

1. Introduction

Bridge girders temporarily supported on bearing pads with no lateral bracing have collapsed in a number of incidents. An investigation of the collapse of girders on a Red Mountain Freeway bridge in Arizona in 2007 was described in Oesterle et al. [1]. Rollover and sliding may both have been involved. Hurff [2] cited the 2004 failure of a girder on a Pennsylvania bridge. Burgoyne [3] stated that a number of girders have collapsed under temporary support conditions, some of which have been unreported, and a couple of cases were mentioned in [4,5]. Failure of girders supported on pot bearings on a bridge under construction in Canada in 2000 was described in [6].

The collapse of bridge girders being transported on trucks and trailers is a related problem [7]. A photo of such a failure is shown in [8]. The analysis presented here can be applied to such situations, which will be discussed in the concluding remarks.

Wind can be a factor in causing rollover or sliding failure of unbraced beams [1,9,10]. Rolling (tilting) also occurs when the beam is bowed due to initial sweep, solar heating [1,2,11] or other reasons. Imperfections in the bearing pads also can be important, such as lateral slope (superelevation angle), eccentricity with respect to the girder, and skew. Creep in the beam or bearing pads could be another factor in collapse.

Analyses of the tilting of unbraced beams supported on bearing pads or trucks and trailers include those in [1,2,4,5,8–12]. Recommendations in the PCI Bridge Design Manual [13] follow the work in Mast [9]. It is recommended that bridge girders be braced as soon as they are erected, but sometimes this is not done. Therefore it is important to understand the behavior of unbraced girders, and to prevent conditions that could lead to collapse.

The analysis presented here assumes that the beam has a small initial curvature that is constant, i.e., the beam is horizontally curved with a circular shape. (An analysis of the lifting of such beams by two cables was presented in Plaut and Moen [14], with numerical examples given in [15,16].) As the beam rolls about the supports, additional deformations occur by weak-axis bending, which leads to further rolling. The results in [13] are based on deformations of a straight beam, rather than an imperfect beam. The factor of safety in [13] assumes that the roll angle is small, whereas the present analysis does not contain that restriction. Also, wind loads may be important in rollover and/or sliding, and the PCI factor of safety is extended here to include such loads.

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The beam is subjected to self-weight and wind. Under temporary unbraced conditions, an elastic analysis should usually be appropriate [2] and is conducted here. The beam is assumed to be symmetric about midspan, with a monosymmetric cross section, and is supported by bearing pads at the ends or at equal distances (overhangs) from the ends. The cross-sectional dimensions are small compared to the radius of curvature, and the weak-axis bending stiffness is assumed to be constant. The wind load is assumed to be horizontal and uniform along the beam.

The problem is formulated in Section 2. In Section 3, the PCI design guideline is described. In Section 4, a "base case" is selected and the effects of various changes of parameters on the roll angle are examined. Then sliding instability is discussed in Section 5, followed by concluding remarks in Section 6.

2. Formulation

The analysis is similar to that in [14], but much of the notation is different, as shown in Fig. 1, and follows that in [9,13,17]. The beam cross section at a bearing pad is depicted in Fig. 1b. The radius of curvature of the unstrained beam is R, the length is ℓ, the modulus of elasticity is E, the gross moment of inertia for weak-axis bending is I_g, the self-weight per unit length is w, and the total weight is $W = w\ell$. The horizontal wind load per unit length is ηw and the total wind load, ηW, is assumed to act at the center of gravity of the whole beam (see Fig. 1c). The direction of the wind load is assumed to be perpendicular to the tangent of the beam at midspan.

The subtended angle of the beam is 2ζ, the cylindrical coordinate ξ is zero at midspan, and the bearing pads are located at $\xi = \gamma$ and $\xi = -\gamma$ with overhang lengths a. The roll axis passes through the centers of the bottom of the beam at the bearing pads, and is at a distance y below the center of gravity of the cross section at the bearing pads. The offset (initial sweep) of the center of the beam from the chord through the ends is denoted δ, and the initial eccentricity of the center of gravity of the whole beam from the roll axis is e_i (positive if toward the beam midspan). The lateral superelevation angle at the bearing pads before rolling is α, and the equilibrium value of the roll angle of the beam from the vertical is θ. The rotation of the cross section at the bearing pads is $\theta \cos\gamma$, but $\cos\gamma \approx 1$ for small beam curvature.

The geometrical quantities are related as follows:

$$\delta = \frac{(1-\cos\zeta)\ell}{2\zeta}, \quad a = \frac{(\zeta-\gamma)\ell}{2\zeta}, \quad \ell = 2\zeta R, \quad e_i = \frac{(\sin\zeta - \zeta\cos\gamma)\ell}{2\zeta^2}. \tag{1}$$

For beams with small curvature,

$$\zeta \approx \frac{4\delta}{\ell}, \quad \gamma \approx \frac{\ell_1 \zeta}{\ell}, \quad e_i \approx \left(\frac{\ell_1^2}{\ell^2} - \frac{1}{3}\right)\delta \tag{2}$$

where ℓ_1 is the length of the beam between the supports, i.e.,

$$\ell_1 = \ell - 2a. \tag{3}$$

Therefore, if the bearing pads are at the ends of the beam ($a = 0$, $\ell_1 = \ell$, $\gamma = \zeta$), $e_i \approx 2\delta/3$.

As shown in Fig. 1, the y and z axes are the principal axes of the beam cross section in its deformed configuration, with the z axis radially outward, and the longitudinal x axis is tangential to the curved axis of the beam through the center of gravity of the cross sections. The origin is at midspan, so that $x = R\xi = \ell\xi/(2\zeta)$. Weak-axis bending occurs in the x–z plane, and strong-axis bending occurs in the x–y plane. The weak-axis deflection is W_b (positive if radially outward) and the strong-axis deflection is V_b (positive if downward). The internal forces parallel to the x, y, and z axes, respectively, are N_x, N_y, and N_z, with corresponding twisting moment (torque) M_x and bending moments M_y and M_z. On a positive face, N_x, N_y, and N_z are positive in the +x, +y, and +z directions, respectively, and M_x, M_y, and M_z are positive about the +x, +y, and +z directions, respectively (e.g., see Fig. 2 of [14]).

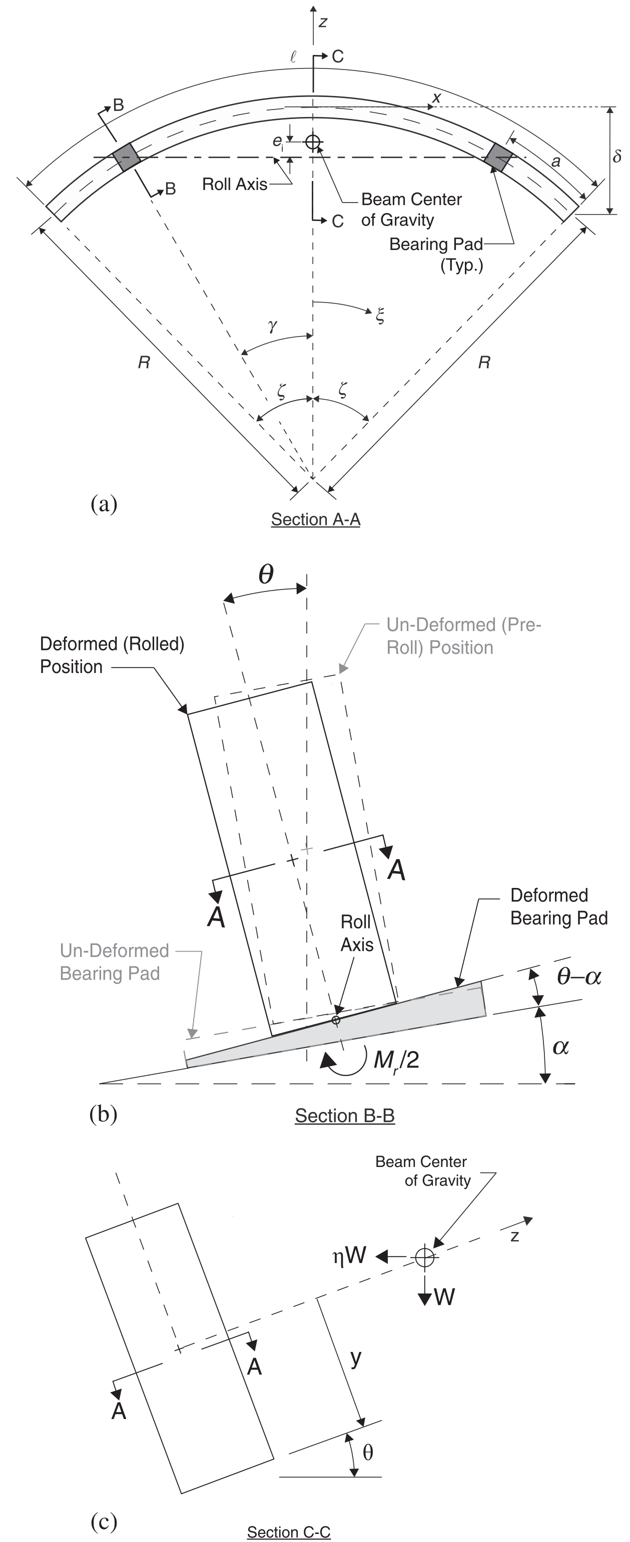

Fig. 1. Geometry of beam on bearing pads: (a) top view; (b) roll angle θ and superelevation angle α with single bearing pad resisting moment $M_r/2$ at roll axis; and (c) weight W and wind load ηW at center of gravity of deformed beam.

The bearing pads provide resistance to deflections and rotations. The rotational stiffnesses of a bearing pad in the present analysis are denoted K_r with respect to roll, K_{yaw} with respect to