

# A Synthesis of Research on the Rollover Stability of Prestressed Concrete Girders Supported on Elastomeric Bearings

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**Abstract:** Rollover stability is a critical concern for prestressed concrete bridge girders, particularly during handling, transportation, and erection when lateral restraint is limited. The growing use of long-span, slender sections has increased their susceptibility to rollover instability, especially under the combined influence of geometric imperfections, thermal gradients, eccentric loading, and inclination and deformation of bearing surfaces. Although these effects are well recognized in practice, current codes and design guidelines reviewed in this study (including both U.S. and European provisions) offer limited guidance, and many analytical and numerical models use simplifying assumptions that incompletely capture important nonlinear behaviors. Furthermore, experimental investigations remain scarce due to the complexity and cost of full-scale testing. This article presents a comprehensive review of rollover stability of prestressed concrete bridge girders supported on elastomeric bearings. The theoretical foundations and governing mechanisms are first summarized, including a discussion of the effects of geometric imperfections, temperature variations, wind, support conditions, and bearing rotational stiffness. Existing analytical, numerical, and experimental studies are critically examined, and key knowledge gaps are identified to guide future research and code development.

**Author keywords:** Prestressed concrete girders; rollover stability; elastomeric bearings; lateral stability; bridge construction

## Introduction

Lateral instability has resulted in the catastrophic collapse of numerous bridges during construction. Most lateral instabilities occur during transportation and construction, when girders are more vulnerable to overturning due to limited intermediate lateral support. In 2000, eight girders of the Souvenir Boulevard Bridge in Laval, Canada,<sup>1</sup> slid off their bearings and tilted, with four of the girders undergoing collapse. The investigation indicated that the sliding pot bearings did not provide sufficient resistance to rotation about the longitudinal axis of the girder, which allowed them

to twist and lose stability. In 2005, during the construction of a precast prestressed concrete bridge in Pennsylvania,<sup>2</sup> several girders collapsed due to inadequate lateral restraint combined with additional sweep induced by non-uniform thermal effects. The absence of sufficient temporary bracing increased the vulnerability of the girders to rollover during erection. A similar event occurred during the erection of the Red Mountain Freeway in Arizona,<sup>3</sup> where nine girders collapsed. The investigation concluded that the collapse was initiated by the lateral instability of a single girder, which triggered progressive failure of adjacent girders. Contributing factors included bearing eccentricity, initial geometric sweep, creep-induced sweep, thermal sweep, and bearing inclination in both the transverse and longitudinal directions. These failures have drawn increased attention to the lateral stability of prestressed concrete girders during construction stages.

Any slender girder supported with insufficient rotational restraint may experience rigid-body rotation and overturning when destabilizing moments exceed the rotational resistance provided by the supports. Therefore, rollover instability may occur in concrete or steel girders under insufficient support and loading conditions. However, rollover failure is more likely to govern the lateral stability of prestressed concrete girders during transportation and erection. This is because, in contrast to steel girders, prestressed concrete girders have relatively high torsional and minor axis flexural stiffness, producing lateral-torsional buckling

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resistance greater than the resistance to rollover stability for the uncracked sections.<sup>4</sup> Rollover instability is often mistaken for lateral torsional buckling; however they are distinct failure modes. Lateral torsional buckling occurs under flexure when the girder bends laterally and twists at the same time, typically due to superimposed loads. In contrast, rollover instability happens when the support fails to provide sufficient restraint against rotation about a roll axis parallel to the girder's longitudinal axis. The overturning is due to torsional moments that arise from lateral loads or, in the presence of geometric imperfections, material nonlinearity, or support rotation, torsional moments that arise from eccentric vertical loads, including self-weight. Engineers often rely on simplified assumptions and equations that overlook the combined effects of sweep, solar radiation, the nonlinear rotational resistance produced by the bearings, and other destabilizing factors common in real-world conditions. Experimental studies, especially full-scale investigations that reflect realistic transport or erection conditions, remain limited. With advancements in computational tools, researchers have developed more detailed analytical and numerical models to study rollover mechanisms and predict girder behavior more accurately. However, questions remain about how well these models represent field conditions and practical design cases.

This article presents a state-of-the-art review of the rollover stability of prestressed concrete bridge girders supported on elastomeric bearings. The review included publications from 1989 through 2026, beginning with the foundational study by Mast.<sup>4</sup> No explicit exclusion criteria were applied, allowing relevant studies on the rollover stability of prestressed concrete girders and elastomeric bearing behavior to be considered. The reviewed literature includes peer-reviewed journal articles, conference papers, technical reports, theses, and design codes and guidelines. The goal is to clarify the key mechanisms that contribute to rollover instability, identify the significance of influential factors, review current design specifications and guidance, and synthesize key findings and developments from existing experimental, analytical, and numerical studies. Assumptions and limitations of existing analytical approaches are also identified. The paper concludes with a comparative and synthesis table and summary of knowledge gaps and research

needs to guide future work aimed at improving design for safety and construction efficiency.

## Theory and Fundamental Concepts

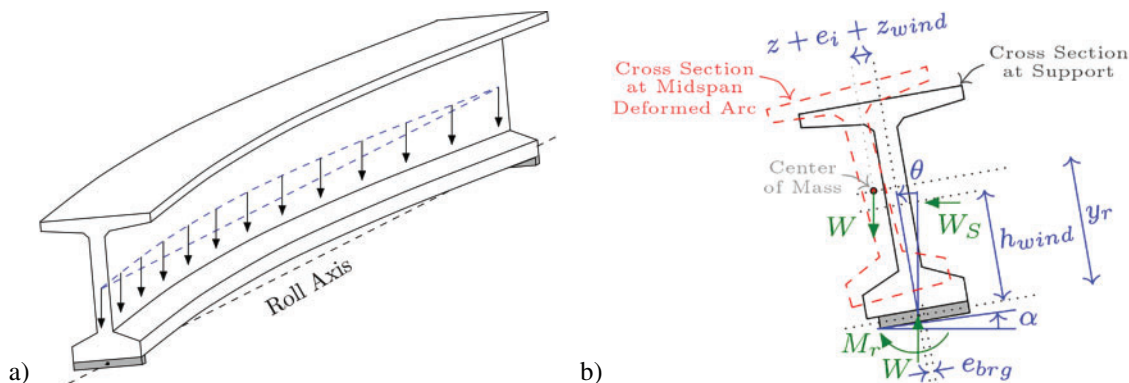
Geometric imperfections in a girder often cause a lateral shift of its center of mass, creating an eccentricity of gravity loads relative to the girder's roll axis (Fig. 1a). This eccentricity generates an overturning moment that initiates rotation of the girder about the roll axis. Fig. 1b illustrates the equilibrium of a girder with such imperfections supported on an elastomeric bearing. As the girder begins to rotate on the supports, a portion of its self-weight acts about the weak axis, producing additional minor axis bending. This deformation increases the roll angle, further amplifying the overturning moment and consequently the deflection, a form of geometric nonlinear behavior. The presence of wind loading also contributes overturning forces and corresponding moments, leading to greater eccentricity and lateral deflections. By equilibrium, the overturning moment is given by:

$$M_a = W [(z + y_r) \theta + e_i + e_{brg} + z_{wind}] + M_{OT} \quad (1)$$

where  $W$  is the girder self-weight;  $z$ ,  $z_{wind}$ ,  $e_i$ , and  $e_{brg}$  are the lateral deflection due to girder self-weight, lateral deflection due to wind loading, and initial sweep and bearing eccentricity of the girder, respectively, all taken at the center of gravity of the deflected girder;  $y_r$  is the vertical distance from the roll axis to the center of gravity;  $\theta$  is the roll angle of the girder measured from the vertical axis; and  $M_{OT}$  is the overturning moment due to the applied lateral load, taken about the roll center. The roll center is typically assumed to be located at the mid-depth of the elastomeric bearing. The elastomeric bearings resist overturning moments through their rotational stiffness,  $k_\theta$ . The resisting moment provided by the bearings is

$$M_r = k_\theta (\theta - \alpha) \quad (2)$$

where  $\alpha$  is the superelevation or tilt angle of the support. When the overturning moment exceeds the resisting moment provided by the bearings, equilibrium is no longer satisfied, leading to rollover instability. Notably, the rotational stiffness of an elastomeric bearing is nonlinear and, furthermore,



**Figure 1.** Equilibrium of girder on elastic support: a) Torsion produced by eccentric vertical loads; b) Free body diagram

as the girder rotates, the contact area between the girder and the bearing surface decreases as a result of partial uplift of the girder. This reduces the bearing rotational stiffness and, consequently, the resisting moment provided by the bearing against further girder rotation, leading to partial uplift of the girder. Therefore, changes in bearing rotational stiffness directly affect the resisting moment and, consequently, the capacity of the girder against rollover instability.

To evaluate girder stability, Mast<sup>4</sup> introduced two analytical methods for calculating factors of safety, one against cracking and one against rollover, for girders supported on elastic bearings. These definitions later formed the basis of the PCI Bridge Design Manual provisions<sup>5</sup> for assessing girder stability during handling and transportation. The factor of safety is defined as the ratio of resisting moment over the applied overturning moment:

$$FS = \frac{M_r}{M_a} = \frac{K_\theta (\theta - \alpha)}{W[(z + y)\theta + z_{wind} + e_i] + M_{OT}} \quad (3)$$

where  $K_\theta$  is the rotational stiffness of the support, which is assumed to behave linearly elastically, and  $\alpha$  is the support inclination. At a certain rotation, the tensile stress at the top flange exceeds the concrete modulus of rupture, and cracking initiates. The corresponding tilt angle associated with the onset of cracking,  $\theta_{cr}$ , can be calculated from the ratio  $M_{cr}/M_g$ , where  $M_{cr}$  is the lateral moment required to initiate cracking, considering the existing stress developed by the combined effects of prestressing, self-weight, and wind loads, and  $M_g$  is the moment generated by the girder self-weight.<sup>6</sup> By substituting into Eq. 4, the factor of safety against cracking,  $FS_{cr}$ , can be determined:

$$FS_{cr} = \frac{K_\theta (\theta_{cr} - \alpha)}{W((z + y_r)\theta_{cr} + e_i + z_{wind}) + W_S h_{wind}} \quad (4)$$

where  $W_S$  is the wind load on the girder and  $h_{wind}$  is the vertical distance from the roll axis to the mid-depth of the girder.

Cracking reduces the lateral stiffness of the girder, leading to larger lateral deflections under the same loading conditions. To account for this reduction in stiffness, Mast<sup>7</sup> proposed an empirical factor,  $(1 + 2.5\theta)$ , to estimate the cracked moment of inertia from the uncracked moment of inertia. This factor is applied to the lateral displacement terms  $z$  and  $z_{wind}$  to estimate the deformation of the cracked section. By incorporating this amplification into the stability formulation, the factor of safety against rollover can be expressed as

$$FS_r = \frac{K_\theta (\theta_r - \alpha)}{W[(z_0\theta_r + z_{wind})(1 + 2.5\theta_r) + y_r\theta_r + e_i] + W_S h_{wind}} \quad (5)$$

where  $\theta_r$  is the critical rollover rotation angle corresponding to the onset of uplift. Mast defined  $\theta_r$  by establishing equilibrium between the resisting and overturning moments, with the bearing reaction acting at the kern point. The Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders<sup>6</sup> extended this formulation by incorporating the effects of lateral loads into the moment

equilibrium equation. According to the PCI Recommended Practice, lift-off is assumed to occur when the resultant bearing reaction reaches the kern point of the bearing. The corresponding rotation at which lift-off initiates is given by

$$\theta_r = \frac{W(z_{max} - e_{brg} - h_r\alpha) - (WS)[h_r + (z_{max} - e_{brg})\alpha]}{K_\theta} + \alpha \quad (6)$$

where  $e_{brg}$  is the bearing eccentricity;  $z_{max}$  is the maximum kern distance of the bearing, calculated as

$$z_{max} = \frac{W_{brg}}{6} \quad (7)$$

where  $W_{brg}$  is the bearing width in the direction of rotation. The Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders,<sup>6</sup> Section 3.4.5, and the PCI Bridge Design Manual,<sup>8</sup> Section 8.10, specify minimum factors of safety of 1.0 against cracking, and 1.5 against rollover.

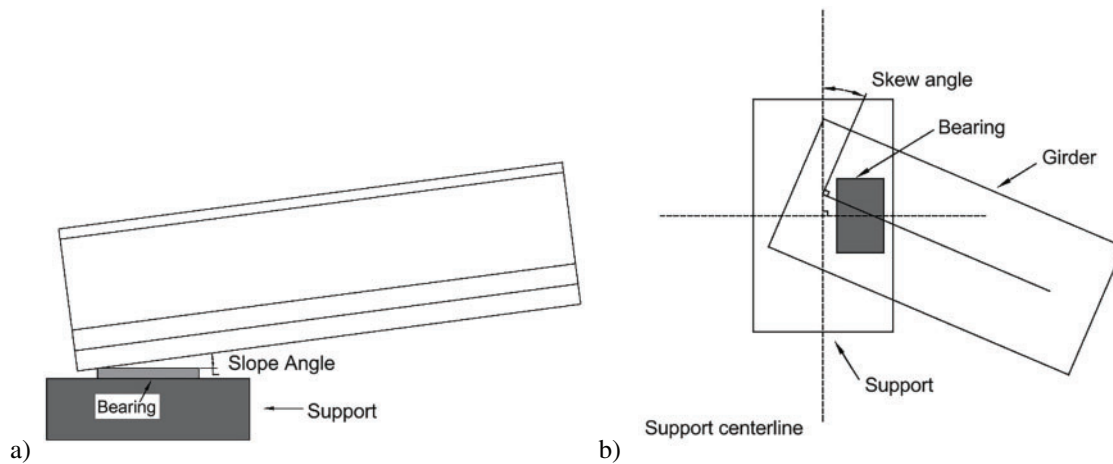
These formulations assume that the girder remains fully in contact with the bearing. However, as discussed earlier, increasing eccentricity and rotation progressively reduce the stability of the system, causing partial lift-off of the girder from the bearing surface. Consequently, full contact between the girder and the bearing in most cases will not be maintained until the instability limit. The assumption that the rotational stiffness of the bearing remains linearly elastic with no limit, which is adopted by the rollover factor of safety computed by Eq. 5, may overestimate the rollover capacity of seated girders because, at large rotations, the bearing can no longer deform uniformly, resulting in partial separation at the girder-bearing interface.<sup>9</sup>

Eamon et al.<sup>9</sup> proposed a tipping factor of safety in which the girder is assumed to overturn about an effective toe point rather than the bearing roll center. In this formulation, the resisting moment is calculated from the girder self-weight acting through an eccentricity measured relative to the effective toe point. The overturning moment includes contributions from wind loading, fascia jack forces, and applied lateral loads. However, a key limitation of this approach is that the location of the effective toe point depends on the girder properties, loading conditions, and bearing behavior. Consequently, the location of the rotation axis is not fixed and may vary throughout the loading process. The corresponding factor of safety is defined as

$$FS_{tip} = \frac{M_r}{M_{OT}} = \frac{W \cdot e}{M_w + M_b + M_p} \quad (8)$$

where  $M_w$  is the overturning moment induced by lateral wind loads and calculated about the effective toe point;  $M_b$  is the overturning moment generated by fascia jack forces; and  $M_p$  is the overturning moment resulting from an applied lateral load at midspan.

Rollover stability in prestressed concrete girders is influenced by a combination of factors. While a single factor may not cause failure on its own, the cumulative effect of multiple factors can significantly reduce the girder's stability. Geometric imperfections are one of the main contributors



**Figure 2.** Definition of: a) slope angle; b) skew angle

to this failure mode. Sweep, an unintended horizontal curvature of the girder, is the most critical factor and often results from inaccuracies in fabrication, misalignment of strands, support misalignment, or temperature gradients from solar radiation.<sup>10,11</sup> Other imperfections, such as camber, slope angle, and skew angle, also increase rollover risk. The slope angle is the vertical angle between the girder centerline at the support and a horizontal line aligned with the bearing surface (Fig. 2a). This slope may arise from camber due to eccentric prestressing forces, construction imperfections, or the overall grade of the bridge.<sup>11</sup> The skew angle refers to the alignment of the girder longitudinal axis relative to the principal axes of the bearing (Fig. 2b), resulting in nonuniform pressure distribution. Both the slope and skew angles can reduce the effective rotational stiffness of elastomeric bearings, which lowers their ability to resist overturning moments.<sup>12</sup> In addition, the effective prestressing force, along with time-dependent effects such as creep and shrinkage, induces additional deformations in the girder that evolve over time<sup>6</sup> and may amplify the geometric imperfections that are responsible for rollover instability. Temperature differences across the girder cross-section, caused by solar exposure or heat from curing, can lead to uneven thermal expansion and induce bowing or twisting of the girder. When combined with existing geometric imperfections or flexible supports, these thermal effects can further reduce rollover stability, particularly during construction operations and stages where the girder has no temporary or permanent bracing.<sup>13</sup>

## Code Provisions

To improve rollover stability, design codes provide several limitations and recommendations.

The PCI Bridge Design Manual,<sup>8</sup> Section 3.6.2.1, requires bearing surfaces to be checked for horizontal and vertical alignment, flatness, levelness, and slope, with a flatness tolerance of 1.6 mm (1/16 in). Section 10.4.1.2 specifies a limit of 0.29° (0.005 rad) for unintended bearing surface slope introduced by construction tolerances. Section 3.7.4

further recommends the installation of temporary steel or timber diaphragms immediately after erection and prior to final connection. These diaphragms are intended to prevent girder instability caused by wind, seismic effects, or thermally induced sweep.

Table 1 summarizes the permissible sweep tolerances specified in various codes and guidelines. The permitted sweep for bridge girders varies significantly across these codes, with the most stringent requirement being imposed by PCI.<sup>8</sup> The PCI Tolerance Manual for Precast and Prestressed Concrete Construction<sup>14</sup> and the Manual for Quality Control for Plants and Production of Structural Concrete<sup>15</sup> limit allowable sweep and lateral displacement to 3.2 mm per 3 m (1/8 in per 10 ft) of girder length, variation in strand placement and prestressing force eccentricity to 6.4 mm (1/4 in), and camber variation from the design camber to 3.2 mm per 3 m (1/8 in per 10 ft) of girder length, with a maximum of 12.7 mm (1/2 in) for girders up to 24.4 m (80 ft) long and 25.4 mm (1 in) for girders longer than 24.4 m (80 ft). These limits remain applicable and are referenced in the newly released updated guidelines for lateral instability of prestressed concrete bridge girders.<sup>6</sup> In addition, Section 12.1 of the PCI Tolerance Manual for Precast and Prestressed Concrete Construction<sup>14</sup> limits bearing eccentricity, defined as the lateral offset between the girder bottom centerline and the elastomeric bearing pad centerline, to 25.4 mm (1 in).

The AASHTO bridge design and construction specifications provide additional guidance related to sweep and support conditions. The AASHTO LRFD Bridge Construction Specifications<sup>16</sup> require contractors to ensure the safety of precast members during all stages of construction and to provide adequate temporary bracing. Likewise, the AASHTO LRFD Bridge Design Specifications<sup>17</sup> state in Section 5.12.3.2.1 that the contractor is responsible for the safe shipping, erection, and temporary bracing of precast girders. In addition, Section 14.8.2 limits the maximum slope between the girder and the bearing surface to 0.57° (0.01 radians). If this limit is exceeded, the use of a tapered plate is required to provide a level bearing surface.

**Table 1.** Sweep permitted by design codes and guidelines

| Code or guideline           | Sweep tolerance ( $e_i$ )                      |
|-----------------------------|------------------------------------------------|
| PCI <sup>8</sup>            | 3.2 mm per 3 m (1/8 in per 10 ft)<br>$= L/960$ |
| EN 15050:2008 <sup>18</sup> | $L/500$                                        |
| Spanish Code EHE-08         | $L/750$                                        |

## Bearing Behavior and Roll Stiffness

### *Mechanical behavior of elastomeric bearings*

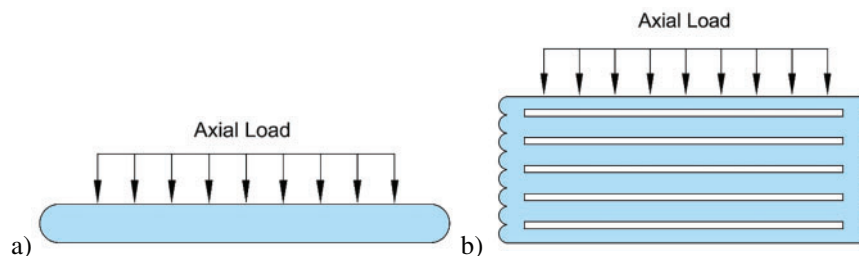
Bearings are used in bridge construction to support girders and transfer vertical loads from the girders to the substructure while permitting horizontal displacements caused by thermal expansion, construction, elastic shortening, creep, and shrinkage.<sup>19</sup> Several types of bearings are used in bridge structures, including elastomeric bearings, pot bearings, rocker bearings, cylindrical bearings, spherical bearings, and roller bearings. Each type of bearing provides different levels of translational and rotational stiffness while allowing for required seasonal thermal expansion and contraction of the superstructure.<sup>11</sup> Elastomeric bearings are produced as plain elastomeric pads, fiberglass-reinforced elastomeric pads, steel-reinforced elastomeric pads, and cotton duck-reinforced elastomeric pads. Among these, steel-reinforced elastomeric pads are widely used to support bridge girders in the United States because they are easy to use, durable, and economical.<sup>20,21</sup>

Steel-reinforced elastomeric bearing pads consist of several layers of neoprene rubber bonded to embedded steel shims. Neoprene provides high resistance to heat, flames, and weathering and has reliable adhesion to metal.<sup>22</sup> Elastomers, including neoprene, are nearly incompressible, with a Poisson's ratio greater than 0.49. Consequently, when subjected to compression, they expand laterally to maintain their volume. In steel-reinforced elastomeric bearings, the steel shims are sufficiently stiff to restrain the lateral movement of the elastomer at the steel–elastomer interfaces.<sup>23–26</sup> The steel shim plates reduce the lateral bulging of the elastomer layers by restraining their expansion (Fig. 3). As a result, when the pad is compressed, the individual elastomer layers bulge toward the edges of the pad. This restraint

provided by the steel shims significantly increases the compressive stiffness of the bearing compared to an unreinforced plain elastomeric pad having the same elastomer thickness and volume. At high levels of compression, the stiffness becomes nonlinear because bulging moves a portion of the elastomer outside the main load path. Consequently, the effective thickness of the load-carrying elastomer layers decreases, which increases the compressive stiffness of the pad.<sup>26</sup> For a constant total elastomer thickness, increasing the number of steel shim plates increases the axial stiffness because the thickness of the individual elastomer layers decreases. However, the increase in shear stiffness resulting from thinner individual elastomer layers reduces the ability of the bearing to accommodate thermal expansion and contraction of the girder with minimal restraint.<sup>27</sup>

Steel-reinforced elastomeric bearings are fabricated in fully bonded, fully unbonded, and single-side bonded configurations. In fully bonded bearings, steel end plates are vulcanized to the top and bottom surfaces of the elastomeric bearing and are subsequently welded or bolted to the superstructure and substructure. In fully unbonded bearings, the end plates are omitted, and the bearing is placed directly between the supporting elements, where forces are transferred through direct bearing and friction at the contact surfaces. In a single-side bonded configuration, only the top surface of the bearing is connected to the superstructure, while the bottom surface remains unbonded and rests directly on the substructure.<sup>28,29</sup>

These bearings exhibit different responses under axial loads and bending moments. The girder self-weight and applied axial loads generate compressive strains within the bearing. When rotation is introduced, tensile strains develop in the bearing layers and counteract the compressive strains. As a result, one side of the bearing tends to move upward, leading to uplift. According to NCHRP 596, the bearing and girder surfaces remain in full contact during uplift despite the upward movement of one edge.<sup>30</sup> In unbonded bearings, however, sufficiently large rotation may cause partial separation between the bearing and the supporting surface, resulting in lift-off. The partial loss of contact between the bearing and the supporting surface during lift-off reduces the effective contact area,<sup>28,30–34</sup> which alters the distribution of stresses within the bearing and can significantly affect its rotational stiffness.



**Figure 3.** Behavior of elastomeric bearings in compression: a) unreinforced pad; b) effect of steel reinforcement in restraining bulging of pad

As discussed previously, compressive loading causes the elastomer to bulge outward. When rotation is applied, compression decreases on one side of the bearing and increases on the other. Due to the near-incompressibility of the elastomer, material is displaced laterally from the highly compressed side toward the less compressed side, partially filling the space created by the upward movement of the tension-side edge. Consequently, the bearing may remain fully compressed even as one edge moves upward. Lift-off initiates only when the applied rotation becomes large enough to reduce the contact stress at the bearing edge to zero, resulting in a loss of contact between the bearing and the supporting surface. Prior to the 2010 edition of the AASHTO LRFD Specifications,<sup>16</sup> lift-off was not permitted in the design of elastomeric bearings. Following the findings of Stanton et al.,<sup>30</sup> which showed that partial lift-off does not adversely affect bearing performance when properly considered in design, the current specifications permit partial lift-off. The current AASHTO LRFD Specifications<sup>17</sup> provide two approaches for evaluating bearing stability, methods A and B. Method A limits the overall bearing thickness to one-third of the minimum plan dimension of a rectangular bearing or one-fourth of the diameter of a circular bearing. Method B uses more detailed explicit stability equations. In general, bearings that satisfy the Method A requirements will also satisfy the more rigorous Method B stability checks.<sup>8</sup>

### **Analytical and experimental studies on bearing behavior**

An accurate representation of bearing rotational behavior is essential for evaluating girder rollover stability. In particular, changes in bearing contact conditions during the onset of uplift can reduce the effective rotational stiffness and, consequently, the resisting moment provided by the bearing against further girder rotation. During girder placement, the self-weight of the girder is transferred to the bearings. Before the installation of lateral bracing and the deck, the girders are relatively unstable, and flexible bearing pads allow the girders to rotate about their longitudinal axis, as discussed earlier. The importance of bearing rotational stiffness and lift-off was first highlighted by Mast,<sup>7</sup> who noted the lack of experimental studies on bearing behavior, its impact on beam stability, and the effect of loss of contact during rotational lift-off.<sup>35</sup> Also, Mast<sup>7</sup> investigated the roll stiffness of plain and laminated elastomeric bearing pads by comparing the resisting moments developed by plain and laminated bearings for a 41 m PCI BT-72 girder. The study showed that laminated bearings provided adequate resistance to girder overturning, whereas the girder was unstable when supported on plain pads.

Stanton et al.<sup>30</sup> developed analytical equations for predicting lift-off initiation in unbonded infinite strip elastomeric bearings, assuming an incompressible elastomer and inextensible reinforcement. The study showed that lift-off occurs when the applied rotation reaches three times the

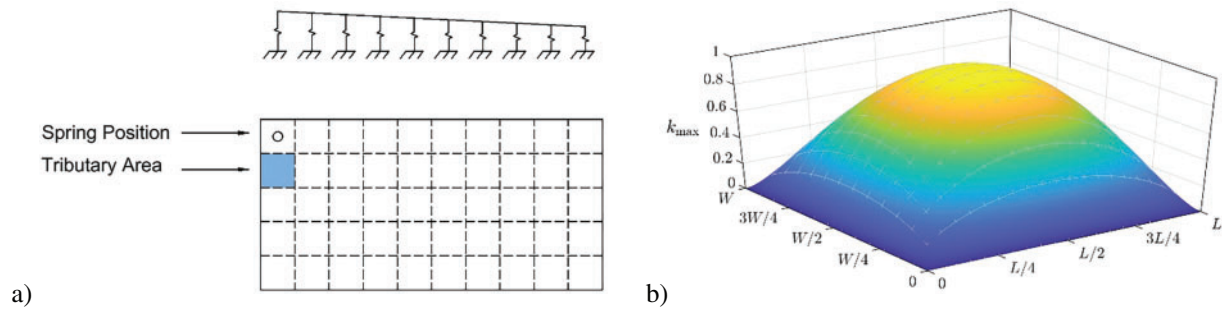
characteristic rotation, or

$$\theta_0 = 3\theta_c = -\frac{3\varepsilon_a}{S} \quad (9)$$

where  $\varepsilon_a$  is the axial strain (negative in compression);  $S$  is the bearing shape factor; and  $\theta_c$  is the characteristic rotation, corresponding to the onset of upward movement on the tension side of the bearing. Although the tension-side edge reaches its original elevation at  $\theta_c$ , the bearing remains in compression, and full contact is maintained. To account for the reduction in contact area after lift-off, the authors introduced the parameter  $\eta$ , defined as the ratio of the effective contact width to the original bearing width. As the applied rotation increases beyond the lift-off rotation, the value of  $\eta$  progressively decreases, reflecting continued reduction of effective contact area. The findings formed the basis for design recommendations and stability procedures that were subsequently incorporated into the AASHTO LRFD Specifications<sup>16</sup> for elastomeric bearings.

Green et al.<sup>36</sup> numerically studied the effects of skew angle on girder uplift at the supports. They found that increasing the skew angle reduced uplift at the girder ends and limited the loss of contact between the girder and the elastomeric bearings. However, increasing the skew angle also increased girder deflection and tensile stresses, indicating that higher bearing stiffness was required to control deflections and cracking stress. Likewise, Consolazio and Hamilton<sup>11</sup> carried out a parametric study to investigate the influence of skew angle, bearing slope, and bearing pad creep on the roll stiffness of bearings and the stability of girders. A series of tests were performed on different elastomeric bearing pads subjected to varying compressive stresses. Low to intermediate stresses represented typical dead load conditions where full and uniform contact developed across the entire bearing pad area, whereas higher stresses represented localized stress concentrations at the pad corners when skew and support slope reduced the initial contact area between the girder and the bearing. It was found that skew-slope interaction significantly reduced roll stiffness, whereas short-term bearing creep had a relatively minor effect. In a later full-scale experimental and numerical study conducted by the same authors,<sup>12</sup> the influence of skew angle and slope angle on the bearing roll stiffness was evaluated. The results confirmed that combining skew angle with bearing slope caused a noticeable reduction in bearing pad roll stiffness.

Harper and Consolazio<sup>26</sup> presented a numerical approach to estimate the axial stiffness of bearing pads. The method was validated through axial compression tests conducted on two standard types of elastomeric bearings used in Florida. In addition, the authors proposed a simplified grillage method to calculate the roll stiffness of steel-reinforced elastomeric bearings. In this approach, the bearing pad was divided into rectangular regions, and a compression-only spring was assigned to each region to approximate the non-linear moment-rotation behavior of bearings developed as a result of lift-off and loss of contact, as shown in Fig. 4a. The authors noted that the compressive stiffness distribution becomes nonuniform under compression due to rubber bulging, such that the stiffness varied with the distance from



**Figure 4.** Simplified modeling of elastomeric bearings: a) grillage model introduced by Harper and Consolazio;<sup>26</sup> b) distribution of compressive axial stiffness in steel-reinforced elastomeric bearing predicted by bubble function

the center of the bearing. A parabolic bubble function was introduced to estimate the distribution of axial stiffness within the bearing pad. The bubble function was defined as

$$k(x, z) = k_{\max} \left[ 1 - \left( \frac{2x}{L} - 1 \right)^2 \right] \left[ 1 - \left( \frac{2z}{W} - 1 \right)^2 \right] \quad (10)$$

where  $L$  and  $W$  are the smaller and larger plan dimensions of the bearing, respectively,  $x$  and  $z$  are normalized coordinates, and  $k_{\max}$  is the maximum axial stiffness at the center of the pad. The distribution of axial stiffness resulting from Eq. 11 is shown in Fig. 4b. Cardoso and Lima<sup>37</sup> numerically studied the influence of geometric imperfection and skew angle on bearing stiffness and girder rollover stability using this bubble function. This study confirmed earlier research findings indicating that the rotational stiffness of the bearing decreases with increasing sweep and skew angle.

Oliveira et al.<sup>38</sup> numerically investigated the effect of bearing pad dimensions on the rollover stability of precast girders supported on bearings. The results indicated that bearing stiffness was a key parameter affecting beam stability. Concurrently, Krahel et al.<sup>35</sup> proposed a simplified analytical model to describe the nonlinear contact interaction between precast girders and steel-reinforced elastomeric bearings, including contact loss mechanisms that develop during lift-off. In this model, the interaction between the girder and the bearing was represented by a rigid beam supported on elastic springs. The girder was assumed to rotate primarily about its longitudinal axis; therefore, the bubble function was modified to vary only about this axis, and the bearing moment–rotation behavior was treated as a plane problem.<sup>39</sup> Under these assumptions, the amplitude of the bubble function was also modified to provide axial stiffness equivalent to the original formulation (Fig. 5a). Moreover, the authors proposed a new simplified approach to approximate nonlinear softening due to lift-off. It was assumed that some springs lose contact with the rigid plate during lift-off, thereby altering the peak compressive stress and the stress distribution along the pad. To approximate this behavior, the axial stress distribution along the pad length was modified by excluding the portion under the width of the bearing where lift-off has been calculated, as illustrated in Fig. 5b. Using the energy method, the following

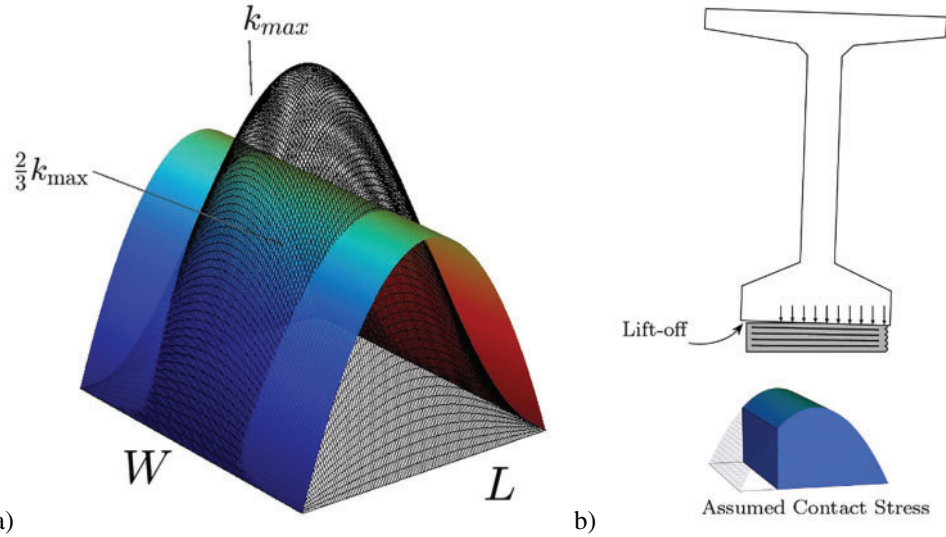
closed-form nonlinear equation was developed to determine the moment–rotation relationship of the bearing:

$$M = \frac{E_{\text{pad}} W \theta (L^2 + 6Lx_0 + 3x_0^2) (L - x_0)^4 + 30PHL^2 x_0^2}{20HL^2 (L + 2x_0)} \quad (11)$$

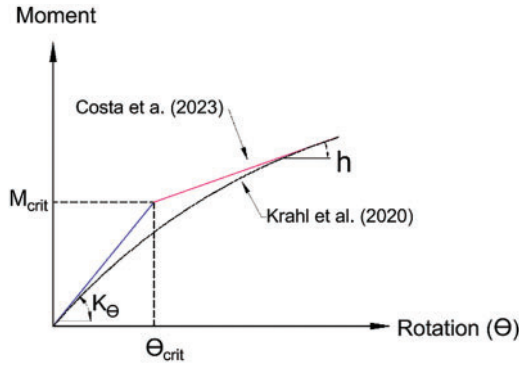
where  $W$  and  $L$  denote the width and length plan dimensions of the bearing, respectively;  $H$  is the bearing thickness;  $E_{\text{pad}}$  is the effective elastic modulus of the elastomeric bearing in compression;  $P$  is the vertical load on the bearing resulting from the girder self-weight; and  $x_0$  is the width of contact loss between the girder and the bearing. The model was validated by comparing its predictions with the experimental measurements published by Consolazio and Hamilton.<sup>12</sup> By incorporating the lift-off behavior, the proposed formulation provided improved predictions of bearing rotational stiffness compared to prior analytical models.

In a recent study, Costa et al.<sup>39</sup> proposed equilibrium equations to evaluate the lateral stability of precast girders supported on bearings during the erection stage. A simplified approach was proposed, wherein the nonlinear moment–rotation relationship developed by Krahel et al.<sup>35</sup> was approximated using a bilinear function, with separate solutions defined for  $\theta < \theta_{\text{crit}}$  and  $\theta > \theta_{\text{crit}}$  (Fig. 6). Using this bilinear relationship in combination with the energy-based approach, analytical expressions for the critical load were developed. In these expressions, geometric imperfections were coupled with the nonlinear contact interaction between the girder and the bearing to evaluate different conditions. The proposed approach was applied to evaluate the equilibrium states of a PCI BT-54 girder for different cases, including a perfect geometry, pure sweep, sweep combined with rotation, and camber without sweep, and the results were compared with the analytical studies of Oliveira<sup>40</sup> and Krahel et al.<sup>41</sup> It was revealed that linear rotational spring stiffness assumptions, such as those suggested by current design codes and guidelines, result in an overestimation of the rollover capacity by neglecting the softening effect of contact nonlinearity during lift-off.

Van Engelen<sup>28</sup> developed analytical equations for predicting lift-off initiation in infinite strip, rectangular, and circular elastomeric bearings, considering the effects of elastomer



**Figure 5.** Assumptions adopted by Krahl et al.<sup>35</sup>: a) equivalent stiffness distribution; b) stress distribution



**Figure 6.** Bi-linear approximation of moment-rotation relationship proposed by Costa et al.<sup>39</sup>

compressibility and reinforcement extensibility. For rectangular bearings, the lift-off rotation was expressed by

$$\frac{\varepsilon_c t}{\theta_0 b} = \frac{\sum_{n=1}^{\infty} \frac{1}{\xi_{rn}^2} \left(1 - \frac{1}{\cosh(\xi_{rn})}\right)}{\sum_{n=1,3,5,\dots}^{\infty} \frac{1}{\xi_{cn}^2} \left(1 - \frac{1}{\cosh(\xi_{cn})}\right)} \quad (12)$$

where

$$\xi_{cn}^2 = \lambda^2 \frac{(\rho + 1)^2}{\rho^2} + \frac{n^2 \pi^2}{4\rho^2} \quad (13)$$

$$\xi_{rn}^2 = \lambda^2 \frac{(\rho + 1)^2}{\rho^2} + \frac{n^2 \pi^2}{\rho^2} \quad (14)$$

$$\frac{1}{K_e(e)} = \frac{1}{K} + e \frac{t}{E_f t_f} \quad (15)$$

$$\lambda^2 = \frac{12GS^2}{K_e(2)} \quad (16)$$

where  $\theta_0$  denotes the rotation at initiation of lift-off;  $\lambda$  is the compressibility–extensibility parameter;  $a$  and  $b$  are the half-dimensions of the bearing plan;  $\rho = \frac{b}{a}$  is the aspect ratio of the rectangular bearing;  $S = \frac{ab}{t(a+b)}$  is the shape factor;  $K$

is the bulk modulus of the elastomer,  $t$  is the thickness of a single elastomer layer,  $t_f$  is the thickness of the reinforcement layer,  $E_f$  is the effective elastic modulus of the reinforcement, and  $\varepsilon_c$  is the compressive strain. The coefficient  $e$  depends on the bearing geometry and loading conditions.

The study further investigated the post lift-off response of unbonded bearings by considering the reduction in effective contact area. Using the effective contact width,  $b_i = \eta b$ , analytical expressions were developed for the instantaneous bending modulus (Eq. 17), and the corresponding moment-rotation relationship (Eq. 18) after lift-off. In these equations,  $(E_b I)_i$  is the instantaneous bending stiffness after lift-off,  $(E_b I)_{eff}$  is the effective bending stiffness before lift-off. The results indicated that current design provisions do not accurately predict the rotational capacity of elastomeric bearings prior to lift-off or the development of tensile hydrostatic stresses. The results also showed that the bending modulus decreases after lift-off while the rotation continues to increase, resulting in a nonlinear moment-rotation response.

$$\frac{(E_b I)_i}{(E_b I)_{eff}} = \frac{\eta^3 \sum_{n=1}^{\infty} \frac{1}{n^2 \pi^2 \xi_{rni}^2} \left(1 - \frac{\tanh(\xi_{rni})}{\xi_{rni}}\right)}{\sum_{n=1}^{\infty} \frac{1}{n^2 \pi^2 \xi_{rn}^2} \left(1 - \frac{\tanh(\xi_{rn})}{\xi_{rn}}\right)} \quad (17)$$

$$M = \int \frac{(E_b I)_i}{t} d\theta \quad (18)$$

The analytical solutions developed by Van Engelen<sup>28</sup> were verified by Bai et al.<sup>33</sup> using finite element models of infinite strip elastomeric bearings with different numbers of layers. The study examined the influence of lift-off on the instantaneous bearing geometry and moment–rotation response under combined compression and rotation. The analytical predictions showed good agreement with the finite element results, indicating that the proposed formulations can accurately predict lift-off behavior of unbonded reinforced elastomeric bearings.

**Table 2.** Geometric, material, and loading properties of the elastomeric bearing used in illustrative comparison

| Property                             | Value       |
|--------------------------------------|-------------|
| Bearing length, $L$                  | 508 mm      |
| Bearing width, $W$                   | 508 mm      |
| Total bearing thickness, $H$         | 60.3 mm     |
| Number of elastomer layers           | 4           |
| Elastomer layer thickness, $t$       | 12.7 mm     |
| Steel reinforcement thickness, $t_f$ | 3.18 mm     |
| Elastomer shear modulus, $G$         | 0.758 MPa   |
| Elastomer bulk modulus, $K$          | 3102.6 MPa  |
| Reinforcement elastic modulus, $E_f$ | 200,000 MPa |
| Applied compressive load, $P$        | 444.8 kN    |

**Table 3.** Comparison of predicted rotation at initiation of lift-off and corresponding moment

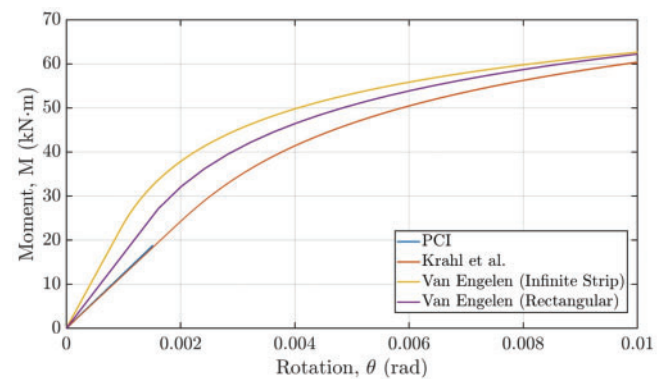
| Method                                    | $\theta_{\text{lift-off}}$ (rad) | $M_{\text{lift-off}}$ (kN · m) |
|-------------------------------------------|----------------------------------|--------------------------------|
| PCI <sup>6</sup>                          | 0.00152                          | 18.83                          |
| Stanton et al. <sup>30</sup>              | 0.00123                          | 20.90                          |
| Krahl et al. <sup>35</sup>                | 0.00187                          | 22.65                          |
| Van Engelen <sup>28</sup> -Infinite-strip | 0.00100                          | 23.59                          |
| Van Engelen <sup>28</sup> -Rectangular    | 0.00161                          | 27.16                          |

### Comparison of predictions for rotation at lift-off and moment–rotation resistance

This section presents a comparison of predictions for the rotation at initiation of lift-off and moment–rotation resistance obtained by existing methods for a representative unbonded steel-reinforced elastomeric bearing. The geometric and material properties of the bearing considered in this illustrative example are summarized in Table 2. The calculated rotation at the initiation of lift-off and corresponding lift-off moments determined using the methods previously reviewed are presented in Table 3. Initial inclination of the support and eccentricity of the bearing were neglected in determining equilibrium with the PCI<sup>6</sup> method, since none of the other methods account for such geometric imperfections. The results indicate significant variation among the analytical methods, with predicted lift-off rotations ranging from 0.00100 rad to 0.00187 rad. Differences among the predictions can be attributed to the assumptions used in each method. As discussed earlier, the Krahl et al.<sup>35</sup> approach is based on an energy method in which lift-off is represented by a reduction in the contact length between the bearing and girder. The Stanton et al.<sup>30</sup> and Van Engelen<sup>28</sup> formulations are based on a pressure solution. In contrast, the PCI<sup>6</sup> method is based on force equilibrium and determines lift-off from the location of the resultant reaction within the bearing kern point. The PCI<sup>6</sup> method is found to produce a conservative estimate of the rotation and moment resistance

at the initiation of lift-off compared to the Krahl et al.<sup>35</sup> and Van Engelen<sup>28</sup> formulations for rectangular bearings, underestimating the lift-off moment by 17% and 31%, respectively.

Fig. 7 compares the moment–rotation relationships predicted by the PCI<sup>6</sup> method, Krahl et al.<sup>35</sup> approach, and Van Engelen<sup>28</sup> formulations for both infinite-strip and rectangular bearing geometries. The comparison highlights the significant conservatism inherent in the PCI<sup>6</sup> method, which predicted lower rotation and corresponding moment at lift-off than the more refined approaches and, more significantly, does not leverage the nonlinear resistance offered by the bearing after initiation of lift-off. Incorporating nonlinear rotational resistance into stability assessments using the Krahl or Van Engelen formulations could reduce the conservatism associated with the PCI<sup>6</sup> method and potentially allow greater sweep tolerances for seated girders. However, given the apparent discrepancies between the resistance predicted by these models for this illustrative bearing example, further research should be directed toward experimental validation of the techniques before adopting a formulation for practical implementation.



**Figure 7.** Comparison of predicted moment–rotation relationships for illustrative bearing example

## Experimental and Analytical Studies on Girder Rollover

### Rollover stability under gravity

The influence of geometric imperfections and support flexibility under gravity has been the foundation of most analytical and experimental investigations for rollover stability. The first comprehensive analytical and experimental investigation of rollover stability in prestressed concrete girders supported on elastic bearings was conducted by Mast.<sup>7</sup> As previously discussed, Mast developed simplified equations to estimate factors of safety against cracking and rollover failure, assuming that the girder behaves torsionally rigid. The proposed equations account for the influence of initial sweep, bearing stiffness, and initial bearing inclination. His analytical work was validated through full-scale lateral bending tests of 45.5 m long prestressed I-girders with initial sweep supported on steel supports.<sup>42</sup> Although this girder was not seated on elastomeric bearings, it is

included in this review due to the scarcity of experimental tests on rollover instability and due to important findings related to the fundamental behavior of the girders during rollover. The experimental observations confirmed that torsional deformation was minimal, supporting the assumption that torsional flexibility could be neglected, as the midspan twist remained small relative to the overall roll angle.

Building on Mast's framework, Burgoyne and Stratford<sup>43</sup> developed an analytical relationship between the critical self-weight producing rollover and the rotational stiffness of flexible supports. Their findings indicated that initial imperfections generated increased tensile stresses and promoted cracking, thereby reducing the effective minor-axis bending stiffness. The key difference between their method and Mast's lies in how imperfections were incorporated. Mast<sup>7</sup> introduced initial imperfections directly into the equilibrium equations, whereas Burgoyne and Stratford assumed a geometrically perfect beam and then computed the stresses induced by initial sweep. By evaluating the resulting tensile stresses at critical locations, they concluded that the minor-axis flexural stiffness should be reduced once cracking is expected to occur.

Further developments were presented by Consolazio and Hamilton<sup>11</sup> through an extensive parametric study evaluating the influence of sweep, girder type and cross-sectional properties, span length, and bracing stiffness on the lateral stability of seated girders. It was demonstrated that buckling capacity was highly sensitive to girder cross-sectional properties and span length, and decreased rapidly as span length increased. In addition, sweep and insufficient bracing substantially reduced the rollover and buckling capacities.

Hurff and Kahn<sup>44</sup> conducted full-scale experimental and numerical investigations on the rollover stability of a PCI BT-54 girder with a 30.5 m span. The effects of initial sweep, initial bearing inclination, and bearing stiffness were evaluated. The girder was supported on two steel-reinforced elastomeric bearings and subjected to a concentrated vertical load at the midspan. The vertical, lateral, and rotational response of the girder was monitored at the midspan and at the bearing supports using string potentiometers and strain gauges. Surface-mounted LVDTs were used to estimate effective prestress and measure the strain distribution through the cross section at the midspan. Initial lateral displacements at the top and bottom of the girder were also measured at different locations along the span to characterize the sweep. Prior to testing, a layer of epoxy was applied at the bearing surfaces to mitigate gaps caused by initial out-of-flatness and camber-induced end slope. The test program was performed with an initial bearing inclination of 0.05 radians, which resulted in amplification of the initial sweep. Rollover was the governing instability mode exhibited by the girder during the experiment, occurring before cracking or lateral-torsional buckling, and the results indicated that geometric imperfections and bearing rotation significantly influenced rollover stability. Test measurements indicated significant shear deformation in the bearings, which reduced the vertical stiffness near the compressed edge. In addition, loss of contact occurred prior to rollover, leading to a reduction in rotational stiffness and a more nonlinear response.

The numerical model developed by the authors did not reproduce the experimental behavior, particularly at higher load levels, and instead predicted a stiffer, nearly linear response. This discrepancy was due to neglecting bearing shear deformation and idealizing the supports as linearly elastic.

Chamorro-Varilla and Aristizábal-Ochoa<sup>45</sup> investigated the static response of a long-span elastic girder with initial sweep and overhangs at both ends, supported on elastomeric bearings with initial inclination and subjected to a concentrated vertical load at the midspan. An analytical model was developed to predict deflections, stresses, internal forces, twist, and rigid-body rotation of the girder. Although the cross section considered in the study was doubly symmetric, the proposed approach was generalized to the static analysis of typical precast bridge girders. To evaluate the accuracy and efficiency of the method, a finite element model was developed based on the girder in the experimental study by Hurff and Kahn<sup>44</sup> and the results were compared. While the analytical model predicted well the overall structural response, differences were observed relative to the experimental results. These discrepancies were attributed to the omission of prestressing effects, shear deformation of the bearing, and uncertainty in the assumed bearing stiffness used in the analytical formulation.

Lee<sup>46</sup> proposed analytical expressions to estimate the critical weight and lateral displacement of both perfect and imperfect girders, accounting for initial sweep and elastomeric bearing stiffness. The formulation was based on the critical weight equation developed by Burgoyne and Stratford,<sup>43</sup> with modifications to incorporate the additional lateral displacement associated with rotation along the girder. To evaluate the influence of initial sweep and slenderness on lateral stability, numerical models of AASHTO BT-54, BT-63, and BT-72 girders with a 30~m span were analyzed using the Abaqus finite element software. The girders were modeled with linear beam elements, while the bearings were represented as compression-only springs connected to the girder through rigid link elements. The results indicated that initial sweep reduced both the critical weight and the lateral displacement at which instability occurs. In addition, increasing slenderness further reduced the critical weight.

Cardoso and Lima<sup>37</sup> investigated the effect of bearing stiffness, concrete strength and material nonlinearity of the girder on the lateral stability of precast beams supported on elastomeric bearings using finite element simulations conducted with ANSYS. The results showed that increased concrete strength and, consequently, beam stiffness reduced beam displacements and limited the loss of contact area between the beam and the bearings.

Krahl and colleagues conducted a series of analytical studies using the Rayleigh–Ritz method and Monte Carlo simulation. Krahl et al.<sup>47</sup> numerically and analytically studied the rollover instability of precast concrete girders supported on elastomers by developing a finite element model of a PCI BT54 that had been previously tested by Hurff and Kahn.<sup>44</sup> The nonlinear behavior of the elastomeric

bearings was represented using the grillage model with non-linear compression springs. A parametric study assessing the influences of different parameters, including sweep, bearing inclination, concrete elastic modulus, top flange width, and span length, on instability load was carried out. While concrete elastic modulus had only a minor influence, the remaining parameters significantly affected the instability load, with increased bearing skew and sweep and reduced top-flange width leading to lower capacity. Krahle et al.<sup>48</sup> developed closed-form equations to estimate rollover load for beams on flexible supports under various loading conditions. However, the formulation was based on linear analysis to develop closed-form solutions for elastic buckling and did not account for initial inclination of the girder as a possible geometric imperfection. Subsequently, Krahle et al.<sup>49</sup> extended the approach to incorporate nonlinear rollover behavior and examined the effects of sweep, camber, and support inclination. Their results demonstrated that bearing inclination was the most influential geometric imperfection, and that the most critical rollover condition occurred when initial sweep and rotation were combined with camber. Oliveira et al.<sup>38</sup> further combined the Rayleigh–Ritz method with the Minimum Potential Energy approach to estimate the rollover capacity of precast beams supported on bearing pads. A parametric study was conducted to evaluate the influence of initial sweep, initial support inclination, concrete compressive strength, bearings geometry, and geometry of the cross-section on beam stability. The results indicated that beam geometry and bearing stiffness were among the most influential parameters controlling the critical rollover load. The rollover capacity increased with higher concrete strength and larger top flange width, whereas it decreased with larger initial sweep and support inclination. Moreover, the initial cracking load was found to be close to the critical load associated with rollover instability.

Recently, Costa et al.<sup>39</sup> analytically evaluated the lateral stability of slender ultra-high-performance concrete (UHPC) beams supported on elastomeric bearings, considering geometric imperfections and the nonlinear behavior of the bearings. It was found that ordinary concrete beams were more sensitive to initial imperfections, although the more slender cross-section of UHPC girders still made them vulnerable to lateral instability despite their higher strength.

### ***Influence of wind loading on rollover stability***

Wind loading introduces additional lateral forces and overturning moments that amplify existing eccentricities and reduce available safety margins during erection. Mast<sup>7</sup> evaluated wind effects and showed that wind loading increased the initial eccentricity, generating an overturning moment about the bottom edge of the bearings. Long span prestressed girders were found to be highly vulnerable to rollover under wind loading unless adequate lateral bracing was provided.

Plaut and Moen<sup>50</sup> investigated the lateral stability of unbraced, horizontally curved prestressed concrete girders supported on bearings under wind loading, considering both rollover and sliding behavior. A modified factor of safety incorporating wind effects was introduced, and it was shown

that PCI design equations, which were developed primarily for straight girders and small roll angles, may overestimate the factor of safety against cracking. A sliding-instability criterion based on wind force and friction was also established, demonstrating that low-friction bearings significantly increased the risk of sliding failure. Their analyses further indicated that roll angle increased with decreased bearing stiffness, increased sweep, reduced weak-axis stiffness due to cracking, and higher wind loads.

Consolazio and Hamilton<sup>11</sup> conducted a parametric study to evaluate the lateral stability of prestressed concrete girders under wind loading. The study examined the effects of girder section type, span length, skew angle, bearing slope, and initial sweep on the rollover capacity of the girders under lateral wind pressure and developed empirical equations to estimate wind capacity. The results demonstrated that wind capacity linearly decreased with span length. Later, Lee et al.<sup>51</sup> conducted analytical and numerical studies to estimate the critical wind load, lateral displacement, and rotational angle that cause rollover. The effects of girder length and cross-sectional properties were examined, and the results showed that girder length strongly influenced critical wind load and support rotation, whereas cross-sectional properties had comparatively minor influence.

In a recent study, Cardoso and Lima<sup>52</sup> numerically investigated the influence of wind loading on the lateral stability of precast concrete girders supported on elastomeric bearings. In addition, the effects of concrete strength and bearing compression stiffness were evaluated by developing a finite element model, in which the nonlinear bearing response was represented using a grillage system composed of compression-only springs. The results showed that concrete strength significantly influenced lateral stability, and that wind loading increased the overturning moment, resulting in loss of contact between the girder and the bearing, a reduction in the effective roll stiffness, and a corresponding decrease in rollover stability.

### ***Thermal effects on rollover stability***

The influence of thermal effects on rollover behavior were examined by Lee,<sup>13</sup> by developing vertical and transverse thermal gradients and carrying out a 3D nonlinear finite element analysis of a PCI BT-63 girder with a 30.5 m span length. The girder remained stable under self-weight and thermal loading in the absence of initial sweep and support rotation. However, instability occurred when thermal gradients were combined with an initial sweep of 114 mm and a bearing inclination of 5°. Honing et al.<sup>53</sup> further improved the thermal-gradient model proposed by Lee to evaluate the effect of thermal sweep on the rollover stability of precast girders under lateral wind loading using FE simulations. A parametric study was carried out to assess the influence of girder type, span length, and environmental conditions. The results indicated that thermal sweep reduced wind resistance, and this reduction became more pronounced for longer spans. Hurff<sup>54</sup> provided additional insight through full-scale experimental and analytical investigations of a PCI BT-54

girder with 30.5 m span length subject to solar radiation on the top and sides of the girder. Wind speed, internal strain, air temperature, internal temperature, and surface temperature were monitored to evaluate additional sweep and rotation resulting from non-uniform thermal effects. It was found that despite a thermally induced increase in sweep of approximately 40%, non-uniform heating had a negligible effect on rotation of the girder cross section.

## Comparative Synthesis

Table 4 provides a comparative synthesis of the studies reviewed in this section, highlighting differences in modeling approaches, parameters considered, treatment of cracking and lift-off, validation or verification methods, key findings, limitations, and recommendations. This comparison

helps identify common modeling assumptions and remaining research needs discussed in the following section.

## Gaps and Future Research

The research gaps identified in the literature can be organized into four priority areas: (1) analytical modeling and experimental validation, (2) bearing behavior and girder–bearing interaction, (3) construction tolerances and lateral restraint, and (4) girder-specific and time-dependent effects.

### Analytical modeling and experimental validation

Existing analytical models of rollover stability rely on several simplified assumptions that require further evaluation Mast.<sup>4,7</sup> idealized prestressed concrete girders as torsionally rigid based on their relatively high torsional stiffness, and

**Table 4.** Comparative synthesis of previous research on rollover stability

| Study                                             | Analysis type                                             | Girder type                              | Bearing model                                    | Parameters considered                                                                                                                                                             | Validation                                        | Main limitations                                                                                                                                                                                                                    |
|---------------------------------------------------|-----------------------------------------------------------|------------------------------------------|--------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mast <sup>7</sup><br>(Journal)                    | Analytical & Numerical.<br>(No FEA model)                 | PCI BT72                                 | Linear elastic bearing rotational stiffness      | Initial sweep; Bearing inclination; Bearing stiffness; Cracking; Girder self-weight; Wind                                                                                         | Test of girders with rigid supports               | Idealized torsionally rigid girder; Twist and major-axis bending deformation neglected; Simplified bearing rotational stiffness; Thermal effects, bearing shear deformation and lift-off not considered                             |
| Mast <sup>42</sup><br>(Journal)                   | Experimental                                              | PCI BT72                                 | Steel cradles                                    | Initial sweep; Cracking; Girder self-weight                                                                                                                                       | Full-scale test                                   | Steel-cradle supports rather than elastomeric bearings; Bearing inclination, bearing shear deformation, thermal effects, lift-off and wind not considered                                                                           |
| Burgoyne and Stratford <sup>43</sup><br>(Journal) | Analytical<br>(No FEA model)                              | Prestressed concrete beams (M10 and SY6) | Equivalent rotational springs                    | Initial sweep; Cracking; Girder self-weight                                                                                                                                       | None                                              | Bearing represented by equivalent rotational stiffness; Torsional deformation ignored; Stiffness degradation due to cracking neglected; Bearing inclination, bearing shear deformation, thermal effects and lift-off not considered |
| Consolazio & Hamilton <sup>11</sup><br>(Report)   | Analytical & Numerical (FEA model developed with ADINA)   | FBT54,63,72,78                           | Simplified linear springs                        | Initial sweep; Girder type; Girder cross-sectional properties; Span length; Bracing stiffness; Skew angle; Bearing inclination; Bearing creep; Lift-off; Girder self-weight; Wind | None                                              | Simplified bearing representation; Bearing shear deformation, cracking and thermal effects not considered                                                                                                                           |
| Lee <sup>13</sup><br>(Thesis)                     | Analytical (3D nonlinear FEA model developed with ABAQUS) | PCI BT63                                 | A series of nonlinear springs                    | Initial sweep; Bearing inclination; Thermal effects; Girder self-weight                                                                                                           | None                                              | Bearing behavior simplified using vertical springs; Bearing shear deformation, lift-off, cracking and wind not considered; Limited girder type and length                                                                           |
| Hurff <sup>54</sup><br>(Thesis)                   | Analytical & Experimental (No FEA model)                  | PCI BT54                                 | Discrete strips with bilinear vertical stiffness | Initial sweep; Bearing inclination; Bearing stiffness; Lift-off; Girder self-weight & midspan vertical load; Thermal effects                                                      | Full-scale test of girder on elastomeric bearings | Bearing model did not fully reproduce nonuniform contact; Bearing shear deformation and wind not considered; Overly stiff analytical response at large rotations                                                                    |

**Table 4.** (Continued)

| Study                                                             | Analysis type                                            | Girder type                                          | Bearing model                                                                       | Parameters considered                                                                                                                                                                    | Validation                                         | Main limitations                                                                                                                                                                                                      |
|-------------------------------------------------------------------|----------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hurff and Kahn <sup>44</sup><br>(Journal)                         | Numerical (No FEA model)                                 | PCI BT54                                             | Discrete strips with bilinear vertical stiffness                                    | Initial sweep; Bearing inclination; Bearing stiffness; Lift-off; Girder self-weight & midspan vertical load; Thermal effects                                                             | Hurff <sup>54</sup> data                           | Bearing shear deformation neglected; Idealized support contact behavior; Bearing model did not fully reproduce nonuniform contact; Overprediction of stiffness at larger rotations; Cracking and wind not considered  |
| Plaut and Moen <sup>50</sup><br>(Journal)                         | Analytical & Numerical (No FEA model)                    | Horizontally curved prestressed concrete girders     | Elastic rotational springs                                                          | Initial sweep; Bearing stiffness; Bearing friction; Girder self-weight; Wind                                                                                                             | None                                               | Linear-elastic girder response; Linear bearing rotational stiffness; Cracking, lift-off; bearing shear deformation and thermal effects not considered                                                                 |
| Chamorro-Varilla and Aristizábal-Ochoa <sup>45</sup><br>(Journal) | Analytical & Numerical (FEA model developed with ABAQUS) | PCI BT54                                             | Nonlinear elastic rotational supports (Richard–Abbott model)                        | Initial sweep; Bearing inclination; Overhang effects; Girder self-weight & midspan vertical load                                                                                         | Hurff <sup>54</sup> data                           | Prestressing effects, concrete cracking, bearing shear deformation, girder vertical curvature, lift-off, thermal effects and wind not considered; Residual stresses neglected                                         |
| Lee et al. <sup>51</sup><br>(Journal)                             | Analytical & Numerical (FEA model developed with ABAQUS) | AASHTO girders type IV, V, VI                        | Nonlinear compression only springs (Grillage method)                                | Girder length and cross-sectional properties; Girder self-weight; Wind                                                                                                                   | None                                               | Initial sweep, bearing inclination, bearing shear deformation, thermal effects, lift-off and cracking not considered                                                                                                  |
| Lee <sup>46</sup><br>(Journal)                                    | Analytical & Numerical (FEA model developed with ABAQUS) | PCI BT54,63,72                                       | Distributed nonlinear compression-only springs, with bilinear compressive stiffness | Initial sweep; Lift-off; Girder self-weight                                                                                                                                              | None                                               | Limited to girder sections and sweep range; Simplified bearing behavior; Bearing inclination, bearing shear deformation, thermal effects, cracking and wind not considered                                            |
| Krahl et al. <sup>47</sup><br>(Journal)                           | Analytical & Numerical (FEA model developed with ABAQUS) | PCI BT54                                             | Nonlinear compression only springs (Grillage method)                                | Initial sweep; Skew angle; Concrete elastic modulus; Top flange width; Span length; Lift-off; Girder self-weight                                                                         | Hurff <sup>54</sup> data                           | Linear-elastic concrete behavior; Bearing shear deformation, thermal effects, cracking and wind not considered                                                                                                        |
| Honing et al. <sup>53</sup><br>(Journal)                          | Analytical & Numerical (FEA model developed with ADINA)  | PCI BT63, AASHTO Type V, FIB36,45,54,63, 72,78,84,96 | 6-DOF elastic springs                                                               | Initial sweep and camber; Girder type; Length; Environmental conditions; Lift-off; Girder self-weight; Wind                                                                              | None                                               | Bearings represented by equivalent 6-DOF springs; Nonlinear contact degradation not directly captured; Limited parametric study; Lift-off, cracking, bearing shear deformation and bearing inclination not considered |
| Krahl et al. <sup>48</sup><br>(Journal)                           | Analytical (No FEA model)                                | PCI BT54 & rectangular section                       | Nonlinear compression only springs (Grillage method)                                | Initial sweep; Concrete modulus of elasticity; Top flange width; Span length; Skew angle; Lift-off; Girder self-weight and concentrated load at midspan, and symmetrical two-point loads | Hurff, Consolazio & Hamilton <sup>12,54</sup> data | Simplified equivalent bearing rotational stiffness; Linear analytical solution; Pre-buckling and post-buckling behavior not captured; Bearing shear deformation, thermal effects and cracking not considered          |
| Cardoso and Lima <sup>37</sup><br>(Journal)                       | Numerical (No FEA model)                                 | AASHTO Type IV                                       | Nonlinear compression only springs (Grillage method)                                | Initial geometric imperfection; Concrete strength and material-nonlinearity; Bearing stiffness; Cracking; Lift-off; Girder self-weight                                                   | None                                               | Limited to one girder; Limited bearing configurations; Bearing shear deformation, girder vertical curvature, thermal effects and wind not considered                                                                  |

**Table 4.** (Continued)

| Study                                       | Analysis type                | Girder type              | Bearing model                                                                                | Parameters considered                                                                                                                                                  | Validation                               | Main limitations                                                                                                                                                                                                                          |
|---------------------------------------------|------------------------------|--------------------------|----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cardoso and Lima <sup>52</sup><br>(Journal) | Numerical<br>(No FEA model)  | AASHTO Type IV           | Nonlinear compression only springs (Grillage method)                                         | Initial sweep; Concrete strength; bearing stiffness; Cracking; Lift-off; Girder self-weight; Wind                                                                      | None                                     | Limited to one girder; Limited bearing configurations; Bearing shear deformation and thermal effects not considered; Convergence limitations in highly nonlinear cases                                                                    |
| Krahl et al. <sup>35</sup><br>(Journal)     | Analytical<br>(No FEA model) | PCI BT54, BT63, BT72     | Nonuniform elastic springs                                                                   | Bearing stiffness; Lift-off; Girder self-weight                                                                                                                        | Consolazio & Hamilton <sup>12</sup> data | Initial sweep, bearing inclination, thermal effects, wind and cracking not considered; Torsional deformation neglected                                                                                                                    |
| Krahl et al. <sup>49</sup><br>(Journal)     | Analytical<br>(No FEA model) | PCI BT54                 | Rotational springs using secant rotational stiffness with nonlinear moment–rotation behavior | Initial sweep and camber; Bearing inclination; Lift-off; Girder self-weight                                                                                            | None                                     | Bearing vertical and shear deformation, thermal effects, wind and cracking not considered; Torsional and warping effects neglected                                                                                                        |
| Oliveira et al. <sup>38</sup><br>(Journal)  | Analytical<br>(No FEA model) | PCI BT54, BT63, BT72     | Equivalent rotational springs                                                                | Initial sweep; Initial bearing inclination; Concrete compressive strength; Girder cross-section; Bearing dimension & stiffness; Cracking; Lift-off; Girder self-weight | None                                     | Simplified bearing model; Bearing shear deformation, wind and thermal effects not considered; Torsional and warping effects neglected; Limited girder and bearing configurations, sweep ranges, bearing inclination and concrete strength |
| Costa et al. <sup>39</sup><br>(Journal)     | Analytical<br>(No FEA model) | UHPC I-girder & PCI BT54 | Nonlinear compression-only springs with bilinear moment–rotation relationship                | Initial sweep and camber; Bearing inclination; Lift-off; Girder self-weight & construction loads                                                                       | None                                     | Idealized bearing contact; Torsional and warping deformation neglected; Bearing shear deformation, cracking, wind and thermal effects not considered; Limited UHPC girder                                                                 |

therefore neglected both twist deformation and major-axis bending in his analysis. This assumption has been retained by nearly all analytical models used to assess rollover factors of safety. However, under rollover conditions, excluding deformation modes that may influence the initiation of cracking and the loss of equilibrium can lead to non-conservative stability estimates<sup>55</sup>). Mast<sup>42</sup> also investigated the rollover behavior of prestressed concrete girders supported on rigid supports rather than flexible bearings. Unlike flexible supports, which provide rotational flexibility that allows the girder to roll laterally and develop lateral bending, rigid supports restrain such movements and alter the rollover response. Currently, experimental testing of rollover instability of girders seated on elastomeric bearings is limited to the single test reported by Hurff.<sup>54</sup> Additional full-scale experimental testing, and high-fidelity finite element modeling validated against the experimental observations, are needed to validate rollover capacity equations and refine analytical models for reliable use in design.<sup>11,54</sup>

### **Bearing behavior and girder-bearing interaction**

The nonlinear response of elastomeric bearings under girder self-weight remains a major source of uncertainty in rollover stability assessment. Current bearing stiffness estimates are generally based on service-level loading, whereas rollover failure typically occurs under self-weight alone. As a result,

experimental studies are needed to quantify the axial and rotational stiffness of elastomeric bearing pads under self-weight conditions.<sup>54</sup> Additional research is also required to evaluate how bearing pad roll stiffness influences rollover behavior across different girder types, span lengths, and loading conditions<sup>13,56,12</sup>. All existing approaches for estimating the nonlinear rotational stiffness of elastomeric bearings neglect potential softening due to interaction with shear deformations in the bearing, which may be significant if there is initial support inclination. Further experimental and analytical studies are needed to better characterize this behavior and incorporate it into rollover stability assessments. The influence of bottom-flange flatness imperfections represents another important issue that requires further investigation, as it may help identify situations in which the use of an embedded steel plate is necessary.<sup>48,54</sup>

### **Construction tolerances and lateral restraint**

The review of current codes and guidelines indicates that a defined limit for initial rotation of prestressed concrete bridge girders is still needed.<sup>54</sup> While the PCI Bridge Design Manual<sup>8</sup> specifies allowable tolerances for initial sweep, it does not clearly define corresponding limits for initial rotation of girders associated with construction. In addition, the required strength and stiffness of lateral bracing needed to prevent rollover instability are not explicitly specified.<sup>13,54</sup>

The PCI Bridge Design Manual<sup>8</sup> recommends the use of lateral bracing but provides limited guidance on requirements for the design of temporary bracing. Most existing studies have focused on the effectiveness of bracing at girder end supports. Further analytical and experimental research is needed to evaluate the role of intermediate bracing systems that connect multiple girders and allow them to act together as a system, particularly during construction stages.<sup>11</sup>

### **Girder specific and time-dependent effects**

Costa et al.<sup>39</sup> showed that UHPC girders are more sensitive to initial geometric imperfections than conventional concrete beams. As a result, allowable limits for imperfections in UHPC girders, including sweep and initial inclination of the girder, should be carefully evaluated and clearly defined. Additional factors that remain insufficiently addressed include prestress losses, nonuniform stress distribution in strands, time-dependent effects such as creep and shrinkage, and impact loads during construction. Further research is needed to determine the influence of these factors on rollover stability.

### **Conclusion**

This state-of-the-art review discussed existing research regarding the rollover behavior of prestressed concrete bridge girders supported on flexible supports. First, the fundamental theories of rollover stability and key controlling parameters were introduced. Then, the specifications in current design codes and guidelines related to rollover stability and their limitations were discussed. In addition, the influence of initial geometric imperfections, skew and slope angle, initial bearing inclination, and thermal sweep on rollover stability under self-weight and lateral wind loading, acting both individually and in combination, was discussed, and the related analytical, numerical, and experimental studies were comprehensively reviewed. It is shown that initial sweep and support inclination are the primary imperfections that reduce lateral stability by increasing tensile stresses and promoting cracking, thereby lowering effective weak-axis stiffness. Bearing behavior has a major influence on rollover stability; reductions in rotational stiffness, increases in support inclination, and the combined effects of skew angle and end slope decrease rollover capacity. Wider bearing pads provide greater stability, while bearings with low stiffness or low friction increase rotational and sliding demands. In addition, bottom-flange flatness imperfections may introduce unintended initial rotation, contributing to earlier onset of instability. Lateral wind loading increases the overturning moment and reduces the vertical load capacity, especially for long-span girders, while thermal effects become critical primarily when combined with sweep or support inclination. The effects of girder length and cross-sectional properties on lateral stability vary depending on the loading and failure conditions considered. Under wind loading, girder length was found to have a greater influence on critical wind load than cross-sectional properties. However, other studies showed that cross-sectional properties significantly affect

rollover and buckling capacity. Thus, the effects of these parameters should be evaluated based on the specific stability condition considered. Cracking reduces both flexural and torsional stiffness, confirming the need to consider stiffness degradation during construction.

Overall, the reviewed studies demonstrate that rollover instability is governed largely by support flexibility and geometric imperfections rather than material strength. However, differences remain among the existing analytical models, particularly in the representation of bearing lift-off and nonlinear rotational resistance. Current design provisions also provide limited guidance on initial support inclination, nonlinear bearing behavior, and temporary bracing requirements. These limitations can affect the assessment of rollover stability during transportation and erection. Further experimental studies are needed to validate nonlinear bearing models, establish acceptable limits for support inclination, and evaluate the stiffness and strength requirements of temporary and intermediate bracing systems.

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### **Data Availability Statement**

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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