Sweep in Precast, Prestressed Concrete Bridge Girders—Part II

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This article is the second in a series of three articles on sweep, or bowing, in prestressed concrete bridge girders. The first article focused on potential causes of sweep and provided recommendations for actions that can be taken at the prestressing plant to mitigate its effects (see the Spring 2019 issue of *ASPIRE*®).[1] This article addresses the effects of sweep during the lifting, transportation, and erection of girders and describes actions that can be taken to increase factors of safety for lifting and hauling. The third article will focus on whether permanent sweep in girders should cause concern for long-term stresses, strength, or performance of bridges.

Design Example Describing the Effects of Sweep

To provide an example for discussion, a PCI-American Association of State Highway and Transportation Officials (AASHTO) bulb-tee BT-72 girder with a span length of 130 ft 6 in. is used. The girder cross section and material properties, prestressing, and initial camber are listed in **Table 1**. For this example, the girder is assumed to have a midspan sweep f of 1.631 in., which is equal to the PCI recommended sweep tolerance of ⅛ in. per 10 ft in length.[2] Calculations in this article assume that the girder is being lifted at the time of transport, so later-age material properties are used. Although the effect of wind loads is considered in PCI's *Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*,[3] it is not considered in this example.

Table 1. Girder Design Details for Example

Girder Design:	Bruce W. Russell, PhD, PE	
Length:	130.5 ft	
Type of Girder:	PCI-AASHTO BT-72	
A =	767	In.^{2}
h =	72.0	in.
c_b =	36.6	in.
c_t =	35.4	in.
I_{xx} =	545,113	in.^{4}
I_{yy} =	37,543	in.^{4}
S_t =	15,420	in.^{3}
w_b =	0.799	kip/ft
f'_c =	10.0	ksi
f'_{ci} =	7.0	ksi
E_{ci} =	4820	ksi
E_c =	5760	ksi
Width of bottom flange	26	in.
Width of top flange	42	in.
N =	38	0.6-in.-diameter Gr. 270 ASTM A416, low-relaxation strands
Strand eccentricity =	29.02	in.
Δ_{camber} =	2.72	in. ↑ estimated at time of handling and includes girder self-weight

Lifting Girders with Sweep and the Calculation of Secondary Effects Related to Roll Equilibrium

When a bridge girder exhibits sweep, the center of mass of the girder (CG) is eccentric to the roll axis.[3] While other effects can also contribute to this eccentricity, only sweep will be considered in this article. A generalized representation for sweep is shown in **Fig. 1**, where the sweep at midspan is defined by the symbol f. The initial eccentricity e_i of the center of mass of the girder with sweep, which can be modeled as a circular arc, is located at approximately ⅔f from the roll axis of the girder and given by:

$$e_i = \frac{2}{3}f = \frac{2}{3}(1.631 \text{ in.}) = 1.087 \text{ in.}$$

If we assume that the girder is lifted at its ends to simplify analysis and is lifted at the top surface (lifting loops are assumed to be flexible, so y_{lift} = 0 in **Fig. 2**), then y_r, the height of roll axis above the CG of the hanging girder, is defined as[4]:

$$y_r = c_t - 0.64\Delta_{camber} = 35.4 - (0.64)(2.72)$$

$$= 33.66 \text{ in.}$$

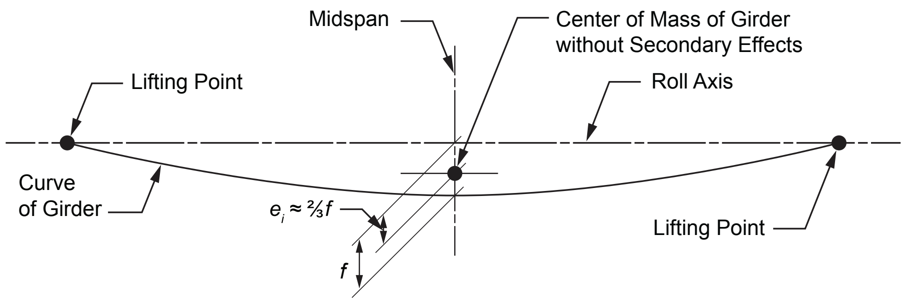

Figure 1. Schematic plan view of girder with sweep when supported at its ends. Figure: PCI.

where

c_t	=	distance from the CG to the top surface of the girder
Δ_{camber}	=	girder camber at midspan including self-weight
0.64	=	coefficient that accounts for the CG of a polynomial shape describing the cambered girder

Once the girder is lifted, the initial angle of inclination θ_i (using small-angle theory [θ < 0.400 rad] and not considering any secondary effects), as shown in **Fig. 2**, is given by:

$$\theta_i = \tan\theta_i = \frac{e_i}{y_r} = \frac{1.087 \text{ in.}}{33.66 \text{ in.}} = 0.0323 \text{ rad}$$

When lifted, the girder rotates by an angle θ_i, causing a secondary effect—bending about its weak axis. This effect results in additional eccentricity caused by the deflection of the self-weight component of the girder bending about its weak axis and more rotation. The final eccentricity e is:

$$e = e_i + 0.64\left(\frac{5w_bL^4}{384E_cI_{yy}}\right)\sin\theta$$

After tilting, the girder's final angle θ at its "roll equilibrium" is derived directly from equilibrium and is expressed by:

$$y_r \tan\theta = y_r \tan\theta_i + z_0 \sin\theta$$

The term z_0, which is the lateral deflection of center of gravity of the girder with the full self-weight applied laterally, is computed by the following equation (see explanation in Mast[4]):

$$z_0 = 0.64\left(\frac{5w_bL^4}{384E_cI_{yy}}\right) = \frac{w_bL^4}{120E_cI_{yy}}$$

$$= \frac{\left[\frac{(0.799 \text{ kip/ft})}{(12 \text{ in./ft})}\right]\left[(130.5 \text{ ft})(12 \text{ in./ft})\right]^4}{120(5760 \text{ ksi})(37{,}543 \text{ in.}^4)}$$

$$= 15.43 \text{ in.}$$

By rearranging these equations and using small-angle theory, the angle of inclination at roll equilibrium can be determined by the following equation[4]:

$$\theta = \theta_i + \frac{z_0}{y_r}\theta$$

Solving for θ yields:

$$\theta = \frac{\theta_i}{\left[1 - \left(\frac{z_0}{y_r}\right)\right]}$$

The equation shows that the final angle of inclination is dependent solely on the initial angle of inclination θ_i, whether caused by sweep or other imperfection, and the ratio of z_0 to y_r. Furthermore, the inverse of the denominator quantifies directly the magnification of the initial angle of inclination.

For the BT-72 example girder, the rotation at roll equilibrium is:

$$\theta = \frac{0.0323 \text{ rad}}{\left[1 - \left(\frac{15.43 \text{ in.}}{33.66 \text{ in.}}\right)\right]} = 0.0596 \text{ rad}$$

Table 2 shows the same calculations for varying amounts of sweep from no sweep to a sweep equal to twice the sweep. The design example is represented by the highlighted row, where sweep f is 1.631 in. and the final roll angle θ is 0.0596 rad (which, for reference, equals 3.4 degrees of tilt).

Roll Stability

Roll stability of girders directly impacts the lifting, transportation, and erection of prestressed bridge girders. It should not be ignored or omitted in a discussion regarding treatment of girders with initial imperfections such as sweep because these imperfections are multiplied by the effects of girder instability. Roll instability is created when the deflection of the center of mass of the girder bent about its weak axis z_o is greater than the distance from the CG of the girder to the roll axis y_r.

A factor of safety (FS) against roll instability becomes an important concept when discussing improvements to lateral stability when lifting, hauling, and transporting girders. For the example BT-72 girder, which is 130.5 ft long but without initial sweep or other

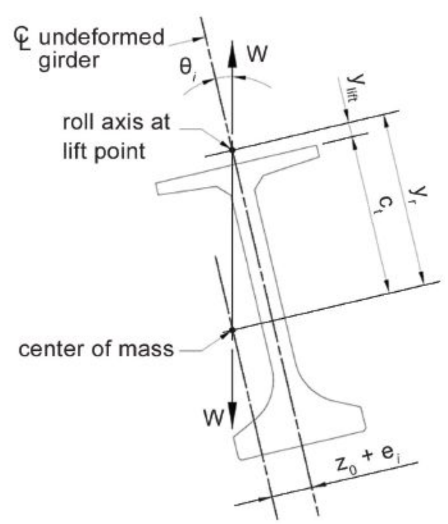

Figure 2. Schematic end view of rotated girder with sweep when lifted. Figure: PCI.

Table 2. Effects of Varying Sweep when Lifting for Example Girder

f	f, in.	e_i, in.	θ_i, rad	θ, rad	FS_θ
0.00	0.000	0.000	0.0000	0.0000	2.18
0.50 f_{tol}	0.816	0.544	0.0162	0.0298	1.89
1.00 f_{tol}	1.631	1.087	0.0323	0.0596	1.60
1.50 f_{tol}	2.447	1.631	0.0485	0.0895	1.31
2.00 f_{tol}	3.263	2.175	0.0646	0.1193	1.02

Notes:
1. Calculations are based on a BT-72 with length L = 130.5 ft.
2. Sweep tolerance f_{tol} = 1.631 in. is computed from a PCI standard practice[1] where sweep tolerance is ⅛ in. per 10 ft of length.
3. FS_θ is the factor of safety against cracking and is computed from θ_{max} = 0.1218 rad, which is the angle of tilt that is expected to cause cracking.

imperfections, and therefore has no secondary effects, the *FS* is:

$$FS = \frac{y_r}{z_0} = \frac{33.66 \text{ in.}}{15.43 \text{ in.}} = 2.182$$

Any steps to improve the roll stability of a girder without sweep—such as increasing y_r by raising the lifting point above the top of the girder or increasing the moment of inertia in the weak direction (see the Creative Concrete Construction article on long girders in this issue of *ASPIRE*)—help mitigate the secondary effects of sweep. Note that typical lifting loops are flexible, and the stability of the girder is not improved by increasing the length or height of typical lifting loops. The factor of safety against roll instability is not affected by initial sweep because the girder's theoretical roll stability is independent of initial imperfections.

Additional Stresses and Possible Cracking Caused by Sweep in Long Girders

As the girder is lifted, sweep will cause the girder to tilt, which creates new stresses from bending about its weak axis that increase the tensile stress at one corner of the girder's top flange. Considering this added stress and typical patterns of prestressing, the top of a girder is more likely to be affected by cracking than the bottom. Small-angle approximations are used to simplify the equations. The additional stresses (tension is positive) are computed as follows:

1. Calculate the top fiber stress considering the girder without tilt. For this computation, it is estimated (from normal design procedures) that the effective prestressing force at erection F_{se} is 1197 kip after all losses, and that the eccentricity of the prestressing force e_{ps} is 29.02 in. For purposes of this article, $f_{t,m}$ is defined as the stress at the top fiber at midspan due to prestressing and self-weight:

$$f_{t,m} = -F_{se}\left(\frac{1}{A} - \frac{e_{ps}}{S_t}\right) - \frac{M_B}{S_t}$$

$$f_{t,m} = -1197 \text{ kip}\left(\frac{1}{767 \text{ in}^2} - \frac{29.02 \text{ in.}}{15{,}420 \text{ in.}^3}\right)$$

$$-\left(\frac{(1700.9 \text{ kip-ft})(12\text{in./ft})}{15{,}420 \text{ in}^3}\right) = -0.632 \text{ ksi}$$

where

M_B = the self-weight moment of the girder at midspan when supported at the ends
= 1700.9 kip-ft

2. Calculate the concrete stress at the extreme fiber caused by bending about the weak axis. This is the additional stress that can be anticipated when the girder with sweep is lifted by the lifting loops. For this article, $f_{t,\theta}$ is the stress at the outside edge of the top fiber due to weak axis bending:

$$f_{t,\theta} = \pm\left(\frac{M_B\theta}{I_{yy}}\right)\left(\frac{b_f}{2}\right) =$$

$$\pm\left[\frac{(1700.9 \text{ kip-ft})(12 \text{ in./ft})(0.0596 \text{ rad})}{37{,}543 \text{ in.}^3}\right]$$

$$\times\left(\frac{42 \text{ in.}}{2}\right) = \pm 0.680 \text{ ksi}$$

3. The calculated tension (or compression) can be determined by adding the two computed stresses together. In this example, the top corner of the BT-72 will have a combined stress of 0.680 ksi – 0.632 ksi = 0.048 ksi (tension). In this particular case, the sweep in the girder coupled with secondary effects creates only a slight tension in the top corner of the BT-72. However, these calculations should be performed for other locations along the length of the girder. For harped strand designs, the harp location should be checked. A check should also be made of maximum compressive stresses at the bottom fibers.

When Is Sweep a Serious Consideration?

To summarize the conditions computed for the example, the initial sweep was taken to be equal to the sweep tolerance of 1.631 in. These results demonstrate that the additional roll from sweep is unlikely to cause cracking in the girder. Therefore, the engineer could, and perhaps should, conclude that the 1.631 in. of sweep is acceptable when lifting and handling the girder, and similar computations can be made by the specialty engineer for each case where an owner or other stakeholder raises concerns about observed sweep.

While the reduced cross-sectional properties associated with cracking of the prestressed concrete bridge girder are considered in both Mast[5] and the PCI Recommended Practice,[3] this author recommends that cracking be used as a performance limit for stability calculations. This can be implemented by computing the rotation θ_{max}, which is the tilt angle at which cracking is expected. A suitable factor of safety similar to that described in the PCI Recommended Practice can be applied to θ_{max}.

Cracking in the top flange of the girder can be avoided by satisfying the following equation, where cracking is assumed to occur when the tensile stress in concrete is equal to the modulus of rupture from the *AASHTO LRFD Bridge Design Specifications*[6] Article 5.4.2.6, which is $0.24\lambda = \sqrt{f'_c}$. Note that compressive stresses are taken as negative, f'_c is measured in ksi, and λ is taken as 1.0 for normalweight concrete.

$$f_{t,m} + f_{t,\theta} \le 0.24\sqrt{f'_c} = 0.24\sqrt{10 \text{ ksi}} = 0.759 \text{ ksi}$$

For the example girder, the 0.048 ksi tension computed earlier satisfies this inequality.

The inequality can also be used to determine θ_{max}, the tilt angle at which cracking would theoretically occur, by substituting θ_{max} into the expanded form of the equation as follows:

$$\left[-F_{se}\left(\frac{1}{A} - \frac{e}{S_t}\right) - \frac{M_B}{S_t}\cos\theta_{max}\right]$$

$$+\left[\frac{M_B \sin\theta_{max}}{I_{yy}}\left(\frac{b_f}{2}\right)\right] \le 0.24\sqrt{f'_c}$$

Using small-angle approximations of $\cos\theta_{max} = 1$ and $\sin\theta_{max} = \theta_{max}$, and substituting the values for $f_{t,m}$ and $f_{t,\theta}$ the equation can be solved for θ_{max}:

$$\theta_{max} = \frac{\left[F_{se}\left(\frac{1}{A} - \frac{e}{S_t}\right) + \frac{M_B}{S_t}\cos\theta_{max}\right] + 0.24\sqrt{f'_c}}{\left[\left(\frac{M_B}{I_{yy}}\right)\left(\frac{b_f}{2}\right)\right]}$$

$$\theta_{max} = \frac{-f_{t,m} + 0.24\sqrt{f'_c}}{\frac{f_{t,\theta}}{\theta}}$$

$$= \frac{\left[-(-0.632 \text{ ksi}) + 0.759 \text{ ksi}\right]}{\frac{0.680 \text{ ksi}}{0.0596 \text{ rad}}}$$

$$= 0.1218 \text{ rad}$$

From this result, the eccentricity of the CG of the girder associated with cracking and, by inference, the sweep that would be expected to cause cracking can be computed (again, note that compressive stresses are negative):

$$\theta_{i,\max} = \theta_{\max}\left(1-\frac{z_0}{y_r}\right)$$

$$= 0.1218 \text{ rad}\left[1-\left(\frac{15.43 \text{ in.}}{33.66 \text{ in.}}\right)\right]$$

$$= 0.06629 \text{ rad}$$

$$e_{i.max} = y_r\theta_i = 33.66 \text{ in.}(0.06629 \text{ rad})$$

$$= 2.231 \text{ in.}$$

$$f_{max} = \left(\frac{3}{2}\right)e_i = \left(\frac{3}{2}\right)2.231 \text{ in.} = 3.346 \text{ in.}$$

These simple calculations show that a BT-72 with a length of 130.5 ft could possess a sweep at midspan prior to lifting of 3.346 in. without cracking when lifted by rigging located at the girder's ends. Note that this sweep of 3.346 in. represents more than twice the sweep tolerance of 1.631 in. Most importantly, these computations show that girders with sweep exceeding the tolerance published by PCI[2] may be lifted and erected without damage to the bridge girders. By way of comparison to standard practice, the 2014 *PCI Bridge Design Manual*[7] states that sweep equal to one-half the tolerance should be used during girder design for considering the effects of lifting; however, for many cases, it is apparent that sweep equal to or exceeding the published sweep tolerance can be accepted.

Maximum Tilt Angle and Factors of Safety

For the purpose of this article, we have adopted a factor of safety that assigns θ_{max} to be equal to the tilt angle that causes cracking. Accordingly, the term FS_θ is used in this article to distinguish it from the factor of safety related to roll instability *FS*. The limiting value of *FS*, or the critical ratio as defined by Mast,[4] is computed by:

$$\left(\frac{y_r}{z_0}\right)_{cr} = \frac{1}{\left(1-\frac{\theta_i}{\theta_{max}}\right)} = \frac{1}{\left[1-\left(\frac{0.0323}{0.1218}\right)\right]} = 1.361$$

The FS_θ against cracking for this example is computed using this equation, which is equivalent to one developed by Mast[5]:

$$FS_\theta = \frac{\frac{y_r}{z_0}}{\left(\frac{y_r}{z_0}\right)_{cr}} = \frac{FS}{\left(\frac{y_r}{z_0}\right)_{cr}} = \frac{2.182}{1.361} = 1.600$$

Table 2 shows computations for FS_θ for varying amounts of sweep. The design example with sweep equal to the sweep tolerance is included with its FS_θ equal to 1.600, which corresponds to the computation shown in this article. The changes in FS_θ as initial sweep increases are also reported, showing that as the initial sweep increases, the likelihood of cracking the beam upon lifting also increases. Nevertheless, the results in **Table 2** show that a BT-72 girder with sweep equal to twice the tolerance can be lifted safely and, theoretically, without the girder cracking.

Note that the calculation of FS_θ is dependent on both the initial sweep and secondary effects. While analysis in this article is limited to uncracked sections, industry experience, and testing performed by Mast[5] demonstrate that precast, prestressed concrete girders can provide additional safety for roll or tilt beyond that computed for first cracking. The engineer should work with the owner and contractor to determine acceptable factors of safety.

Considerations for Hauling Girders

The transportation of bridge girders requires special attention or special considerations when transportation involves superelevation and curvature of roadways, which is almost always the case. During transport, girders are supported at the bottom on specialized hauling equipment that has different equilibrium conditions and resists rotation differently than when girders are lifted. Analysis methods developed and presented in Imper and Laszlo,[8] Mast,[5] and the PCI Recommended Practice[3] can be used to evaluate the effects of stability during the transportation of a girder. An article by Brice, Khaleghi, and Seguirant[9] provides a detailed design example that gives an approach for incorporating lateral stability considerations into the design of a bridge girder rather that checking lateral stability after the design is completed. Information on actual girder sweep, initial imperfections, and hauling equipment are required for the analysis. The reader is referred to these other references for details on the inputs required and analysis methods used for stability of girders during transportation. The differences in analysis apply, however, whether the bridge girders exhibit sweep or not.

The standard of care for girder transportation calls for the bracing of the ends of the girder during transportation and secure attachment of the girder to the truck, tractor, or hauling platform. Three of the four stability improvement strategies described in the following section can be used to mitigate the effects of sweep in girders during transport.

Mitigating Effects of Sweep During Lifting, Transportation, and Erection

There are four primary ways to decrease the effects of sweep and other imperfections that affect the lifting and transportation of prestressed concrete bridge girders:

- Move the lifting location toward the center of the girder.
- Increase the height of the lifting point.
- Incorporate fully tensioned top strands.
- Provide bracing along the length of the bridge girder.

The following discussion can be augmented by the works by Mast[4,5] and Imper and Laszlo[8].

Move the Lifting Location Toward the Center of the Girder

The engineer and owner should be concerned about adding tension to the top of the girder during lifting and erection, but they must address this concern while also considering the need to lift and transport the bridge girder safely and without damage. Computations for this BT-72 girder show that by moving the lifting locations inward by 6% of its length, the magnification of the tilt angle is reduced by 50% and factors of safety are increased.

Mast[4] also discusses the effect of moving the lifting locations. His calculations demonstrate that moving the lifting location as mentioned above for the BT-72 will give the same result for any type of girder and will also double the factory of safety. This method must be

Figure 3. Example of extended rigid lifting system. Photo: The Lane Construction Corporation.

considered during initial design because lifting devices must be located during fabrication and the design must consider additional tension in the top of the girder.

Increase the Height of the Lifting Point

This technique requires a frame sufficiently stiff (that is, rigid) to raise the hinge point for lifting above the top of the cross section. The frame must maintain its horizontal location with respect to the girder cross section during lifting. The frame will increase y_r, the distance between the roll axis and the centroid of the girder.

The photograph shown in **Fig. 3** shows one method that can be used to raise the lifting point for a long bridge girder. Other methods are available. **Table 3** reports the results of computations where the girder is lifted by rigid devices that have pick points at varying heights above the top of the cross section. All calculation results in **Table 3** are based on an initial sweep equal to the sweep tolerance of 1.631 in. **Table 3** shows that by raising the lifting point (hinge point) for a BT-72 from the top of the girder cross section to a height 24 in. above it, the *FS* against roll instability increases from 2.18 to 3.74 and the FS_θ increases from 1.60 to 3.16. The tabulations demonstrate that raising the lifting point is an effective means of improving girder stability for a girder that exhibits sweep.

Incorporate Fully Tensioned Top Strands

These strands can be internal and fully bonded as shown by Russell,[1] internal and debonded over the center portion of the girder (temporary top strands), or external and not bonded. The fully tensioned top strands increase precompression in the top fibers of the girder and effectively improve the girder's resistance to cracking if and when tilting occurs.

Analysis results in **Table 4** indicate modest improvements in FS_θ for the example BT-72 by adding fully tensioned top strands 4 in. below the top of the girder. In the event that cracking occurs at the top fibers of a girder, for any reasons, fully tensioned top strands effectively limit both the width and number of cracks that may occur.

Provide Bracing Along the Length of the Bridge Girder

Several bracing arrangements can be employed, such as a stiffening truss connected to the top or bottom flange of the girder or the web, or a post-tensioned king- or queen-post arrangement. Mast[4] also discusses the issue of king posts for bracing girders.

A king-post arrangement is shown in **Fig. 4**.[8] In this figure, the king post supports fully tensioned strands as outriggers that effectively add stiffness to the cross section and resist lateral bending. Note that for the arrangement shown, strands are not required to be fully tensioned. Instead it is sufficient to post-tension external tendons to the level where they remain in tension through all possible girder deformations.

For girders with sweep, a fully tensioned, one-sided king-post arrangement can be employed to help straighten the girder and reduce the amount of sweep.

Table 5 includes computations for the BT-72 example girder where a king-post with external post-tensioning is provided on one side only. The table shows the effects of adding external tendons in a king-post arrangement where the post deflects the tendons 36 in. Increasing the number of tendons provides a modest increase in lateral (weak-axis) stiffness. This has the direct effect of improving the roll stability of the girder, which is shown in the table as increasing *FS*. Perhaps more important in this discussion about lifting and transporting girders with sweep is the computation showing the straightening effect of

Table 3. Effects of Raising the Lifting Point Above the Top of the Example Girder Using a Rigid Frame

Distance Above Top Fiber, in.	y_r, in.	$FS = y_r/z_o$	θ_i, rad	θ_{max}, rad	FS_θ
0	33.66	2.18	0.0323	0.1218	1.60
4	37.66	2.44	0.0289	0.1218	1.86
8	41.66	2.70	0.0261	0.1218	2.12
12	45.66	2.96	0.0238	0.1218	2.38
16	49.66	3.22	0.0219	0.1218	2.64
20	53.66	3.48	0.0203	0.1218	2.90
24	57.66	3.74	0.0189	0.1218	3.16

Table 4. Effects of Fully Tensioned Top Strands (Internal or External) Located 4 in. Below the Top of the Example Girder

No. Top Strands	e_{top}, in.	ΔF_{pe}, kip	Δf_{top}, ksi	$f_{t,m}$, ksi	θ_i, rad	θ_{max}, rad	FS_θ
2	-31.40	0.0	0.000	-0.632	0.0323	0.1218	1.60
4	-31.40	62.9	-0.046	-0.678	0.0323	0.1258	1.62
6	-31.40	125.9	-0.093	-0.724	0.0323	0.1299	1.64
8	-31.40	188.8	-0.139	-0.770	0.0323	0.1340	1.66

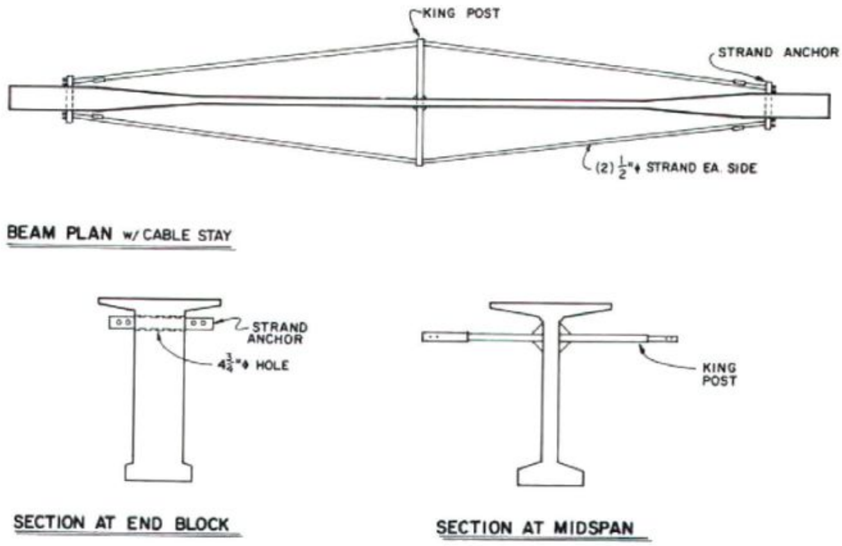

Figure 4. Example of king post bracing system used for shipping long-span bridge beams. Figure: Reference 8.

eccentric post-tensioning of the king post. The king-post arrangement with four strands tensioned to 30 ksi deflects the center of the girder 0.89 in., which is a sizable amount of the original sweep used in this example. Moreover, largely because of the straightening effects, the factor of safety against cracking FS_θ is increased from 1.60 (without the king post) to 2.35 with eight 0.6-in.-diameter strands tensioned to 30 ksi. These computations assume the external post-tensioned strands are located at the vertical centroidal axis, so the benefit of increasing top fiber precompression is only a result of axial compression.

The king post is effective in accomplishing two important things at once: increasing the *FS* against roll instability and cracking and removing sweep from the girder during transportation and erection.

Conclusion

In most bridge girders, sweep, if it exists, is likely to remain small and unnoticed. However, as longer bridge girders are fabricated, sweep may become more noticeable. This article presents simple calculations that can be performed by the specialty engineer and shows that the angle of inclination, or the angle for roll equilibrium, can increase dramatically for longer girders. The calculations demonstrate that for girders possessing modest amounts of sweep within the tolerance, the lifting and transportation of the bridge girders can usually be performed safely and without damage to the girder. If the design of the girder considers an allowance for sweep, it is unlikely that a problem will arise during lifting, transporting, and erection. Where measured sweep exceeds the PCI tolerance, engineers and owners will want to retain a qualified engineer to help with rigging, transportation, and erection.

Table 5. Increasing Lateral Stiffness and Straightening the Girder with a One-Sided, External King Post at a 36 in. Standoff

No. of External Strands	A_{sx}, in.^{2}	Lateral Stiffness Factor	z_0, in.	*FS*	F_{px}, kip	Δ_x, in.	θ_i, rad	FS_θ
0	0	1.00	15.43	2.18	0.00	0.00	0.0323	1.60
1	0.217	1.01	15.26	2.21	0.60	0.22	0.0281	1.69
2	0.434	1.02	15.09	2.23	1.20	0.44	0.0239	1.79
4	0.868	1.05	14.76	2.28	2.39	0.89	0.0155	1.99
6	1.302	1.07	14.45	2.33	3.59	1.33	0.0070	2.19
8	1.736	1.10	14.16	2.38	4.79	1.77	-0.0014	2.35

Notes:
1. External 0.6-in.-diameter strands are tensioned to 30 ksi each.
2. The lateral stiffness factor reflects the relative stiffness at midspan of the girder with the king post to the bare girder.
3. F_{px} is the lateral force transmitted to the bridge girder at the midpoint through the king post.
4. The straightening effect is the computed lateral deflection Δ_x.

References

1. Russell, B.W. 2018. "Using Fully Bonded Top Strands in Pretensioned Concrete Bridge Girders." *ASPIRE* Summer 2018: 26–28.
2. Precast/Prestressed Concrete Institute (PCI). 1999. *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products*, 4th ed. (PCI MNL-116–99). Chicago, IL: PCI.
3. PCI. 2016. *Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*. PCI Publication CB-02-16-E. Chicago, IL: PCI.
4. Mast, R.F. 1989. "Lateral Stability of Long Prestressed Concrete Beams—Part I." *PCI Journal* 34(1): 34–53.
5. Mast, R.F. 1993. "Lateral Stability of Long Prestressed Concrete Beams—Part II." *PCI Journal* 38(1): 70–88.
6. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.
7. PCI. 2014. *Bridge Design Manual*, 3rd ed, 2nd release (MNL-133-14). Chicago, IL: PCI.
8. Imper, R.R., and G. Laszlo. 1987. "Handling and Shipping of Long Span Bridge Beams." *PCI Journal* 32(6): 86–101.
9. Brice, R., B. Khaleghi, and S. Seguirant. 2009. "Design Optimization for Fabrication of Pretensioned Concrete Bridge Girders: An Example Problem." *PCI Journal* 54(4): 73–111.

EDITOR'S NOTE

Some of the approach and notation in this article differ from those in the PCI Recommended Practice.[3] This article will be considered by the PCI committees as they develop the 2nd edition of the Recommended Practice. While the author proposes a different factor of safety against cracking, the PCI Recommended Practice also requires consideration of the factor of safety against failure.

After the original article was published an error was found in the calculations for the girder braced using a king post. The author has revised the text in the first column on page 43 and the values in Table 5. The revised values do not alter the author's conclusion.