Sweep in Precast, Prestressed Concrete Bridge Girders

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Sweep is defined in the *Manual for Quality Control for Plants and Production of Structural Precast Concrete Products* (PCI MNL-116)[1] as "a variation in horizontal alignment from a straight line parallel to centerline of member (horizontal bowing)." A generalized representation for sweep is shown in **Fig. 1**.

Decades of industry experience inform us that very few girders are produced with noticeable or out-of-tolerance sweep. However, when sweep is large enough to be noticed—or when the amount of sweep exceeds tolerance—producers, contractors, and owners may be understandably concerned about how sweep could occur in production, and what corrective actions can, or should be taken. Regardless the amount of sweep, the truth is this: most prestressed concrete bridge girders, once they are in place with composite concrete decks cast upon them, will function effectively for the design life of the bridge without concern for limits on strength, durability, or serviceability.

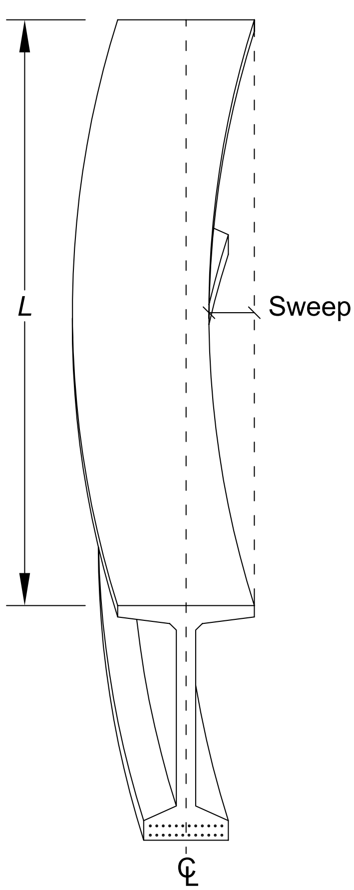

Figure 1. A generalized representation for sweep in a girder. Figure: Dr. Bruce Russell.

Prestressed concrete bridge girders that are built in accordance with our design standards, and are made from conforming materials (concrete and steel) within a geometry described by the contract documents, will support the intended design loads for millions of cycles, in all kinds of climates, for the design service life of the structure. This article focuses on the sweep of bridge girders that may occur during initial fabrication, lifting, or storage in the yard. One probable cause is explored with a hypothetical example and corrective actions that can be taken while the girder is still in the precast producer's yard. Subsequent articles will cover transportation, erection, and construction issues and discuss whether permanent sweep in girders should cause concern for long-term stresses, strength, or performance.

Measurements and Tolerances

The initial measurement of sweep is made after the side forms are removed and prestressing force is transferred, or after the girder is removed from the forms and is placed on dunnage in the precast producer's yard. When measuring sweep, it is important that the girder is level, the sun is not shining on one side, and the actual flange widths have been verified at the ends and middle. Commonly, sweep is measured at the midspan of the girder. Admittedly, accurate measurement may be difficult for long girders. However, a measurement to ¼ in. precision should be sufficient (⅛ in. would be preferable). The measurement(s) should be recorded even if zero.

Alternatively, it may be easier to measure the sweep at approximately 20 ft increments. In this case, measurements should be made accurate to ±1⁄16 in. A sweep measurement made at the center of a 20.0-ft length, or the average of several such measurements, can be converted to an overall sweep by the following:

$$f = f_{20}\left(\frac{L}{20.0\text{ ft}}\right)^2$$

where

f = sweep projected over the entire girder length L

f_{20} = sweep measured over a 20.0 ft length

Tolerances for precast, prestressed concrete members have been established to allow for production and erection variances, as well as the interface of the member with the overall construction of the structure. Tolerances are to be used for guidelines and not as reasons for rejection. If the girder can be brought within tolerance in an acceptable manner, or if exceeding the tolerance does not affect the integrity or performance of the girder, the girder should be accepted. Later articles will show that girders with sweep in excess of tolerances can function without compromising the completed bridge system.

The tolerance for sweep for bridge girders given in MNL 116-99[1] is ⅛ in. per 10 ft. For example, a bridge girder with a length of 130.5 ft would have a sweep tolerance of 1.63 in. The calculation for sweep tolerance follows:

$$\text{Sweep Tolerance} = 130.5\text{ ft}\left(\frac{\frac{1}{8}\text{ in.}}{10\text{ ft}}\right)$$

$$= 1.63\text{ in.}$$

What Causes Sweep and What Should Be Done?

Sweep can be caused by a number of factors, including eccentric prestressing force, the misalignment of forms, anomalies in locations or positions of lifting devices, differences in material properties within the girder, variation in concrete maturity at early ages, exposure to sunlight, out-of-level supports, or differing curing conditions.

Based on previous experience, each producer should be aware of what amount of sweep is normal for a particular girder type. When the initial measured sweep is larger than this "experience" value, or if measured sweep exceeds tolerance or is projected to exceed tolerance, then an investigation should be undertaken immediately by the precaster and sweep should be monitored on a regular basis while the girder is stored. The investigation might uncover a problem that can be corrected before subsequent girders are produced or, if mitigating or corrective action on the existing girder is required, lead to a preferred course of action. As time goes by, measured sweep may worsen because of creep and concrete maturity, with fewer opportunities for corrective action. An investigation by the producer should include checking or reviewing the following:

- Form alignment.
- Cross-section dimensions in several locations along the length of the forms.
- Strand locations—ensure templates are centered and that holes have not elongated.
- Uniform pretensioning of strands and uniform application of prestressing forces.
- Plumbness of girder and level bearing surfaces in storage—a girder that is stored out of plumb can develop sweep.
- Exposure to sun—thermal differences between the sides of the girder in storage can cause sweep.
- Curing temperatures—if heat is applied, ensure uniform application of elevated temperatures.
- Quality control records—search for differences in concrete batches.
- The design—strand pattern and items such as blockouts in a flange or localized changes in the web.

In many cases, the cause of sweep is not easily identified. It could involve a combination of two or more of the listed items.

Table 1. Girder Design Details for Example

Bridge:	SH 99 over Deep Fork River, Lincoln Co., Okla.	
Design Engineer:	Bruce W. Russell	
Span:	130.5	ft
Type of Girder:	PCI-AASHTO BT-72	
Spacing, s =	7.17	ft
A =	767	in.^{2}
h =	72.0	in.
c_b =	36.60	in.
I_{xx} =	545,113	in.^{4}
I_{yy} =	37,543	in.^{4}
w_b =	0.799	kip/ft
f'_c =	10.0	ksi
f'_{ci} =	7.0	ksi
E_{ci} =	4821	ksi
Width of bottom flange	26	in.
Width of top flange	42	in.
Strand type:	0.6-in.-diameter Gr. 270 ASTM A416, low relaxation	
N =	38	strands
e =	29.02	in.

Calculating Sweep for Eccentrically Located Strands

For the purposes of this discussion, one possible cause of sweep is explored. The example is based on a PCI-AASHTO bulb-tee BT-72 girder[2] designed for State Highway 99 (SH 99) over the Deep Fork River in Lincoln County, Okla. The original designs were performed by the author. Spans for this bridge were 130 ft 6 in., measured from center-to-center of bearings. Girders were spaced at 7 ft 2 in. Each BT-72 girder was made with thirty-eight 0.6-in.-diameter Grade 270 prestressing strands conforming to ASTM A416. Design details are listed in **Table 1**. Please note that the example used for this article is hypothetical and created only for purposes of illustration. During fabrication of the actual girders for the SH 99 Bridge, there were no reports of sweep in the bridge girders.

For purposes of illustration, let us compute the sweep as if all strands in the girder were located ¼ in. off center, or with a lateral eccentricity e_x of ¼ in., which is the tolerance in PCI MNL-116 for strand placement. The following calculations compute the amount of sweep f that results from the minor-axis bending moment induced by the ¼ in. eccentricity of strands assuming thirty-eight 0.6-in.-diameter strands with an effective prestressing force of 1512 kip after elastic shortening loss:

$$F_{pe}e_x = (1512\text{ kip})(0.25\text{ in.}) = 378\text{ kip} - \text{in.}$$

$$\phi_y = \frac{F_{pe}e_x}{E_{ci}I_{yy}} = \frac{378\text{ kip} - \text{in.}}{(4821\text{ ksi})(37{,}543\text{ in.}^4)} = 2.088 \times 10^{-6}\text{ rad/in.}$$

$$f = \frac{\phi_y L^2}{8}$$

$$= \frac{(2.088 \times 10^{-6}\text{ rad/in.})(130.5\text{ ft})^2\left(144\frac{\text{in.}^2}{\text{ft}^2}\right)}{8} = 0.640\text{ in.}$$

From these calculations, one can see that a strand pattern that is placed eccentrically by ¼ in. can produce an estimated sweep of 0.64 in. immediately after transfer. This sweep is less than the sweep tolerance of 1.63 in. for a 130.5 ft girder, which was calculated earlier in this article.

The sweep created by the eccentric prestressing force creates a theoretically uniform minor-axis curvature ϕ_y over the length of the bridge girder. As can be seen in the calculations, sweep is proportional to the square of the girder length. Therefore, in the author's opinion, for longer girders, it may be more appropriate to set a larger tolerance for sweep than the ⅛ in. in 10 ft provided in MNL 116-99. For example, the same strand eccentricity that creates a ¾ in. sweep for a 100 ft girder (which exceeds the tolerance of 1.25 in.) also produces a 3.0 in. sweep for a 200 ft girder, which exceeds the tolerance of 2.50 in. The point is that longer girders are more susceptible to noticeable or out-of-tolerance sweep simply because they are longer, and the effect that may have caused sweep in the first place is squared in proportion to length.

Stresses Caused by Sweep

Generally, if sweep exists, it is most often small, and its effects on stresses can be ignored. Also when considering the magnitude of the stresses, readers should be aware that the stresses computed in this manner are temporary stresses and, accordingly, the importance of temporary stresses should not be overemphasized in judging the performance of precast, prestressed concrete bridge girders.

The earlier computations of the sweep caused by an eccentric prestressing force resulted in a lateral curvature of 2.088×10^{-6} rad/in. If this curvature is extended to the outer edges of the bottom fiber, strains at the extreme fibers would be:

$$\varepsilon = \pm\ 2.088 \times 10^{-6} \frac{\text{rad}}{\text{in.}} \times 13 \text{ in}$$
$$= \pm\ 27 \times 10^{-6} \frac{\text{in.}}{\text{in.}}$$

This strain would produce 131 psi of additional compressive stress on one side of the bottom flange and reduces the compressive stress on the opposite side by 131 psi. At the top flange, an additional tensile stress of 211 psi will theoretically be produced on one side.

Now, some engineers may be tempted to include additional sources of tension in their calculations. However, one must bear in mind that these calculations are approximations and represent mere estimates for the stresses and strains that may actually occur within bridge girders. Accordingly, I argue that additional calculations for stress and strain based on possible sweep deformations are relatively unimportant and should not be used to make additional requirements for computation, for load conditions, or for handling. Instead, this calculation serves as a reminder *to place reinforcement where tension exists* in order to control cracking and provide better distribution of stresses and strains throughout the cross section. It is my firm opinion that if the engineer has provided sufficient reinforcement in the tensile zone of a precast, prestressed concrete bridge girder, and if that design is in accordance with current American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[3] for temporary stresses, the additional tensile stresses created by sweep in girders can be ignored.

Creep Considerations

Because of concrete's relative immaturity at early ages, we know that the concrete will experience the largest creep strains at early ages. Creep also can have significant effects on prestressed concrete because the prestressing forces remain active over the life of the bridge. Similarly, the girder sweep measured initially is affected by the creep properties of concrete, and so discussion of creep within this article is important.

In the example provided, the estimated sweep of 0.64 in. that would be caused by a ¼ in. eccentricity of prestressing force is less than the 1.63 in. tolerance. Those involved must draw from their own experience to judge whether sweep is "normal," but this author will argue that the estimated sweep is not "excessive." Nonetheless, even "normal" amounts of sweep may merit consideration for a proactive approach when considering the effects of creep. Immediately after transfer, and upon initial storage at the precast producer's yard, the concrete is young and the internal crystalline structures that provide concrete strength are maturing rapidly. As the concrete creeps with time, the sweep is also expected to increase.

Table 2a provides a summary of assumptions and **Table 2b** are the calculations performed to estimate the increase in sweep caused by creep at various ages. Data in the table show the additional sweep that can occur within the first 28 and 90 days for the BT-72 girder being used as an example in this article. Considering only the "within tolerance" sweep of 0.64 in. caused by offset prestressing strands, and using provisions in the current AASHTO LRFD specifications[3] for creep calculations, we can see that the sweep deformation nearly doubles in 90 days, to 1.24 in. At this level of sweep, the bridge girder is approaching the tolerance limit of ⅛ in. per 10 ft. of length (that is, 1.63 in., as computed previously). Additionally, various other potential effects may combine to increase sweep, and many of these effects may be unknown. Therefore, we should conclude that it is possible that tolerance for sweep may be reached and exceeded, although, as mentioned earlier, the project from which the example girder is taken had no reported issues with sweep, which is typical of the great majority of bridge projects.

Recommendations to Mitigate Sweep

Sweep in a girder is not typically a large concern, but it can affect handling, transportation, erection, and stability issues even when the measured sweep is within tolerance.[4] For many reasons, the engineer, owner, or precaster may want to reduce the sweep of the girder to ease any handling, lifting, transportation, or erection issues. When a decrease in the amount of sweep in a girder is desired, the early age of the concrete and its self-weight enable corrective actions. The recommendations for corrective action fall into two categories:

1. Straighten the girder with bracing and forces, or
2. Store the girder on slightly sloped supports and allow its self-weight to straighten the girder.

To straighten the girder using direct application of force, the girder must be braced at the ends to provide a reaction to the straightening force applied at midspan or intermediate points. A structural frame will likely be required to provide both straightening forces and reactions, or the girder with sweep can be braced against other girders. It is also important that the straightening force be applied through the centroid of the cross section; if it is not, the application of force will cause torsional deformations. In the example provided for the 130.5-ft-long BT-72 girder, the lateral midspan force required to straighten the girder would be about 1450 lb. The sweep must continue to be monitored, and it is likely that the force will have to be maintained over the full time of storage to straighten the girder prior to transportation.

Alternatively, the girder can be straightened by storing the bridge girder on a slight

Table 2a. Summary of assumptions.

RH =	70	%
V/S =	3.01	in.
k_f =	0.625	
k_s =	1.06	≥ 1.0
k_{hc} =	1.00	

Table 2b. Effects of Creep at 28 and 90 Days Using AASHTO LRFD Article 5.4.2.3.2.

Age (days)	Creep coefficients Time Development Factor k_{td}	Creep Coefficient $\Psi(t, t_i)$	Sweep *f* from ±¼ in. eccentric prestressing force and creep (in.)
1	–	–	0.64
28	0.467	0.587	1.02
90	0.738	0.929	1.23

angle. In this method, the girder's self-weight will work over time to straighten the beam. At the very least, storing the girder with a slight tilt will prevent creep effects from worsening the initial sweep.

The method for straightening a girder by storing on canted dunnage is described as follows. (Calculations shown are for the BT-72 beam with an initial sweep of 0.64 in.)

1. Calculate the required slope of the support to produce a tilt to counteract the measured sweep. For the BT-72 girder, the uniform load (amount of lateral self-weight) w_y to cause a midspan deflection equal to the 0.64 in. sweep is:

$$w_y = \frac{384 E_{ci} I_{yy}}{5L^4} f(\text{sweep})$$

$$= \frac{384(4821\text{ ksi})(37{,}543\text{ in.}^4)}{5(130.5\text{ ft})^4\left(1728\frac{\text{in.}^3}{\text{ft}^3}\right)}(0.64\text{ in.})$$

$$= 0.0178\text{ kip/ft}$$

The slope of the supports required to straighten the 130.5-ft-long BT-72 beam during storage can then be computed as the ratio of w_y to the weight of the girder w_b:

$$\theta = \frac{w_y}{w_b} = \frac{0.0178\text{ kip/ft}}{0.799\text{ kip/ft}} = 0.0223\text{ rad}$$

Using this procedure, the supports for this bridge girder in storage should be sloped at θ, or approximately ¼ in. per 12 in., or approximately ½ in. for every 24 in. (about the width of the bottom flange). My recommendation is to measure the angle against the web of the girder using a 2- or 4-ft level.

2. Monitor the sweep regularly during storage to ensure that sweep is sufficiently reduced before transportation.

Conclusion

In most bridge girders, sweep, if it exists, is likely to remain small and unnoticed. However, as longer and lighter bridge girders are fabricated, sweep may become more noticeable. This article provides an example for one cause of sweep in a girder, discusses increase in sweep that can occur at early ages when the girder is most susceptible to time-dependent changes, and provides an outline for corrective action, if that is desired.

References

1. 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.
2. PCI. 2014. *PCI Bridge Design Manual*. 3rd ed. 2nd release. (PCI MNL 133-14). Chicago, IL: PCI.
3. AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.
4. PCI. 2016. *Recommended Practice of Lateral Stability of Precast, Prestressed Concrete Bridge Girders* (PCI CB-02-16-E). Chicago, IL: PCI.

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