

Handling and Shipping of Long Span Bridge Beams



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In the early history of the prestressed concrete industry (up to 1960), bridge beams were very bulky (heavy) and their length seldom exceeded 100 ft (30.5 m). In fact, at that time, 80 ft (24.4 m) beams were considered quite long.

With advancing prestressing technology, together with the improvement of materials (especially high strength concrete and high strength prestressing steels), beam sections became progressively more structurally efficient. As a result, beam sections became more slender and the spans much longer.

Currently, on the West Coast, 148 ft (45.1 m) beams are common and 130 to 140 ft (39.7 to 42.7 m) bulb T beams and I beams are used frequently. Today, the length limit of bridge members is determined mainly by the mode of transportation (truck steering trailer) and allowable gross weight rather than any arbitrary span restriction.

Over the years, as beam sections became more slender and their spans longer, producers soon discovered that these long beams had a tendency to crack or even collapse during handling or shipping unless the lifting points (shipping points) were moved away from the ends of the members, or special braces were attached to the beam.

The lateral stability of these types of beams was discussed in the 1960s (see Refs. 1, 2 and 3). Further information on this topic may also be found in Refs. 4 and 5 (published in 1971).

Currently, the PCI Design Handbook, in Section 5.2.9, Lateral Stability, briefly describes the problem and suggests solutions. Ref. 4 is the basis for this section.

Lateral instability occurs during the handling and shipping of long prestressed bridge beams. This problem arises because of the imperfections

during production (slight horizontal eccentricity in prestress from the Y-Y axis, or the lifting loops not centered in the section or thermal gradient from one side of the beam to the other). Such variations cause the beam to bow horizontally during handling, thus shifting the center of the mass away from the original centroid of the beam. When the beam is lifted, the combination of the horizontal bow with the tilting action causes the beam to bend and deflect progressively in the weak axis.

As soon as the moment of inertia of the weak axis becomes cracked, the phenomenon rapidly increases until the beam fails in compression or tension, depending on the configuration of the beam in the Y-Y axis. Such a phenomenon may occur even where no lateral loads or direct forces are applied.

From the above brief discussion and Refs. 4, 5 and 6, it is shown that failure due to lateral instability is related to deflection:

$$\Delta = K \frac{wl^4}{E_c I_y} \quad (1)$$

where $K = 1/120$ for the mass center of a simply supported prismatic beam.

Assuming that the design engineer has already established the beam cross section and prestress level, the options available to the producer to reduce the deflection Δ (and thus improve lateral stability) are as follows:

1. Shorten the handling and shipping span.
2. Improve the modulus of elasticity of concrete (E_c) (increase concrete strengths f'_{ci} and f'_c).
3. Brace the member (thereby increasing the effective I_y).

The above options are now briefly discussed:

1. Shortening of the handling and shipping span can be impractical because most engineers design bridge beams for in place load and in place supports. Since the economical design

Synopsis

The stability and handling stresses of long span prestressed concrete bridge beams are discussed. Special attention is given to the location of lifting points, shipping supports, effect of road conditions (impact) and superelevation (beam tilt). Various bracing systems are discussed and new proposals are put forth.

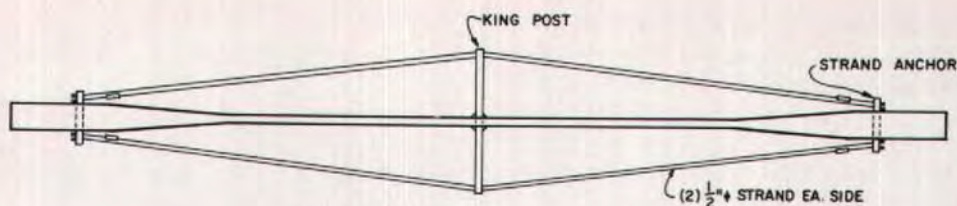
A suggested analytical procedure is presented whereby a long span bridge beam can be designed for stability during handling and shipping. To illustrate the method, a sample design of a 136 ft (41.5 m) long PCI 72 in. (1829 mm) bulb T bridge beam for handling and shipping is included.

for a simply supported beam requires maximum allowed compression in the bottom fiber and maximum allowed tension in the top fiber at the midspan of the beam due to its own dead load at transfer stresses, it is extremely difficult in some cases to shift the lifting points away from the end without significantly increasing the concrete strength.

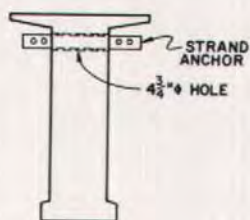
2. There is a practical (economical) limit to increasing the concrete strength and improving E_c especially for early transfer strength and for handling of the beam from the casting bed.

3. Bracing the member has some merit and was the most commonly used method in handling and shipping beams in the past.

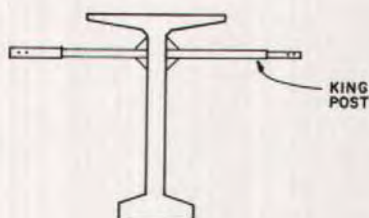
Each producer developed a bracing system to fit the particular plant requirements. The basic method included stiffening the weak part of the beam (most often the top flange) with pipe frame, temporary trusses or other methods. Since every long beam has to be stiffened, this type of temporary bracing system can be very expensive.



BEAM PLAN w/ CABLE STAY



SECTION AT END BLOCK



SECTION AT MID-SPAN

Fig. 1. Bracing system (king post truss) used for shipping long span bridge beams.

For shipping the beams the most commonly used bracing system is the king post truss system (see Fig. 1), where the posts are attached to the beam sides at midspan and several prestressing strands are stressed over the king post and anchored near or at the end of the beam. Some producers have used heavy cable up to 1 in. (25.4 mm) diameter instead of prestressing strand, the advantage being that the cables can be adjusted by heavy duty turnbuckles.

During shipping the beams may be subjected to their most severe stress conditions. Impact forces depending on the road conditions can be in the range of 20 to 30 percent in both directions (up or down). The superelevation in the road curves or job site conditions may be as much as 10 percent. Therefore, the horizontal component of the beam weight and the weak axis bending moment are increased accordingly. The combined stresses due to the prestress and horizontal bending may reach well beyond the cracking or compression

limit of the concrete (see Fig. 2).

Unfortunately, the king post and strand system has limitations. More than one prestressed concrete beam producer learned the hard way, that beyond a certain horizontal deflection of the beam, the system is useless and cannot prevent the collapse of the beam.

Most producers used the king post strand truss system with one or two strands on each side of the beam. The analysis of the statically indeterminate composite king post truss, by the method of consistent deformation, would indicate that for cases of long beams more than one or two strands (or cables) would be needed to prevent critical lateral deflection.

On the other hand, this system could be effective for short durations (moving on the superelevated road where the curve changes) because the beam deflection is not instantaneous. It is gradual and can be observed visually due to the plastic characteristic and creep of the concrete.

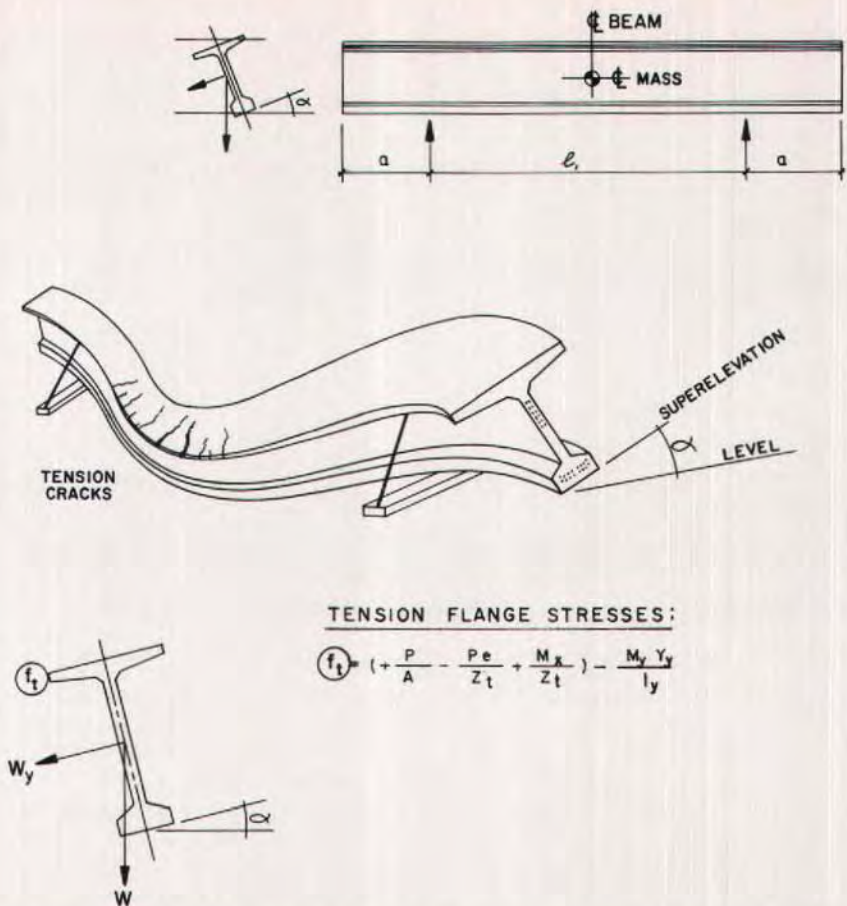


Fig. 2. Tilted beam (isometric view distorted) showing formation of tension cracks.

The situation becomes critical when the truck must stop and stay on the superelevation (or on an uneven surface), where the gradual horizontal deflection can not be adjusted or stopped.

One of the authors observed a 130.5 ft (40 m) long, 84 in. (2134 mm) deep I beam which was lifted from the truck trailer for erection and later had to be replaced because the crane could not handle the load. Upon being replaced, due to road superelevation and the beam offset on the truck, the beam had about 15 percent (8.67 degrees) tilt. It took about 20 minutes to reach the critical deflection, about 12 in. (305 mm)

horizontal bow, before the beam collapsed. (This beam had five strands on each side of the king posts.) Other producers across the country have had similar experiences.

Our company re-evaluated the beam handling and shipping problem during the past two years. The final conclusion was a simple one.

Handling the beam in the plant must be done under very strict conditions and constant supervision. Impact and tilting forces can be avoided whereby the analysis given in the PCI Design Handbook⁸ to evaluate stability can be applied directly.

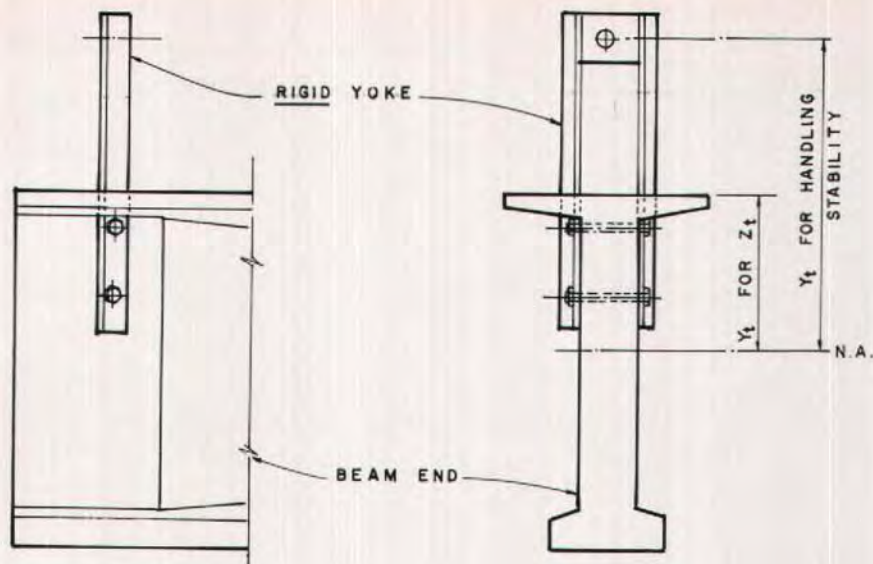


Fig. 3. Beam lifting device used to increase top fiber distance (y_t) of beam.

For simply supported beams, use Eqs. (5.2.2) and (5.2.3):

$$\beta_v = \frac{5}{384} \frac{wl^4}{E_c I_y} \quad (2)$$

with a factor of safety of:

$$\text{F.S.} = \frac{y_t}{\beta_v} \geq 2 \quad (3)$$

Note that Eq. (5.2.2) includes an additional safety factor because the true mass shift is:

$$\beta_v = \frac{wl^4}{120 E_c I_y} \quad (4)$$

Therefore, the true safety factor and Eq. (5.2.3) become:

$$\text{F.S.} = \frac{y_t}{0.64 \beta_v} \quad (5)$$

For the details, see Ref. 5.

Since the factor of safety is a function of y_t and β_v , it is logical to increase y_t or reduce β_v .

It is possible to increase the vertical

distance between the center of mass and lifting points (y_t) by using a rigid yoke. This technique is sometimes used in plants (see Fig. 3).

As mentioned earlier, the modulus of elasticity of concrete (E_c), i.e., the concrete strength, may be increased or the lifting points shifted away from the ends. In this case the stability factor at midspan may be expressed as:

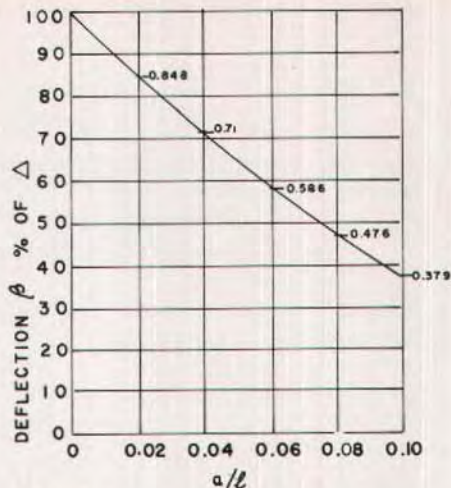
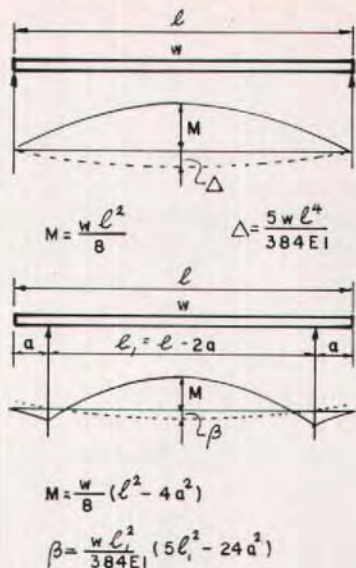
$$\beta_v = \frac{wl^2}{384 E_c I_y} (5l^2 - 24a^2) \quad (6)$$

Fig. 4 shows the relation between the a/l ratio and deflection.

Based on plant and field experience (and the actual value of β_v), we use the following safety factors:

1. For plant handling: F.S. > 1.5
2. For field handling (erection): F.S. > 1.75

For transportation stability, the support (bunking) points must be known and the impact factors estimated (20 to 30 percent recommended). It is important that the roadway superelevations (especially at the jobsite) be checked



EXAMPLE:

100 FT. END SUPPORTED BEAM $\Delta = 1.00$ in.
 SAME BM. SUPP. 6 FT. FROM ENDS $\beta = 0.58$ in.

Fig. 4. Design aid for determining beam support influence on deflection.

and that the beam lie on a level surface and vertical position prior to erection.

Using the above assumptions, the combined stresses of a laterally deflected beam at any point can be calculated.

It can be quickly determined that the critical points are the downward top flange under high tension and the upward bottom flange under high compression at the midspan of a bulb T or I beam (see Fig. 2). These stresses can be counteracted or limited by mild steel reinforcement or prestressing steel. If the stresses are below cracking, the section may be conventionally reinforced with supplementary reinforcing bars near the outer edges of the flange. If the stresses are above the allowable, temporary post-tensioning may be used advantageously to reduce them to an acceptable level (see Fig. 5).

Our experience in the past 2 years shows that, by using nearly the same location for shipping as for yard handling, highly stressed 72 in. (1829 mm) bulb T beams in the 140 to 150 ft (42.7 to 45.7 m) range may be safely shipped with

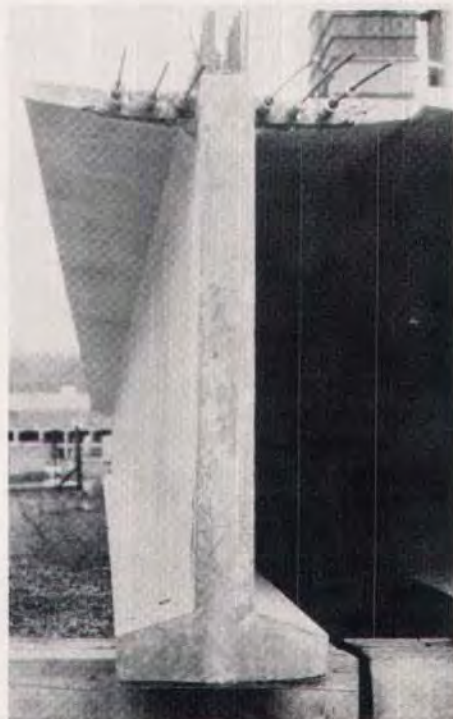


Fig. 5. To reduce high tensile stresses, temporary post-tensioning may be used to brace a long slender beam.

Table 1. State of Washington DOT specification for stability.

CRITERIA FOR CHECKING GIRDER STRESSES AT TIME OF LIFTING OR TRANSPORTING

Stresses at both support and harping points must be satisfied based on:

1. Specify concrete strength at time of lifting or transporting, f'_{cm}
 f'_{cm} = compressive strength at time of lifting or transporting verified by test but shall not exceed design compressive strength (f'_c) at 28 days in psi +1000 psi.
2. Allowable compression stress, $f_c = 0.60 f'_{cm}$
3. Allowable tension stress, f_t
 - a. With no bonded reinforcement = $3 \sqrt{f'_{cm}}$
 - b. With bonded reinforcement to resist total tension force in the concrete computed on the basis of an uncracked section = $7.5 f'_{cm}$
The allowable tensile stress in reinforcement is 30 ksi (ASTM A 615 Grade 60).
4. Prestress losses
 - 1 day — 1 month = 20,000 psi
 - 1 month — 1 year = 25,000 psi
 - 1 year or more = 35,000 psi (max.)
5. Impact
10 to 30% depending on road and field conditions, acting up or down.

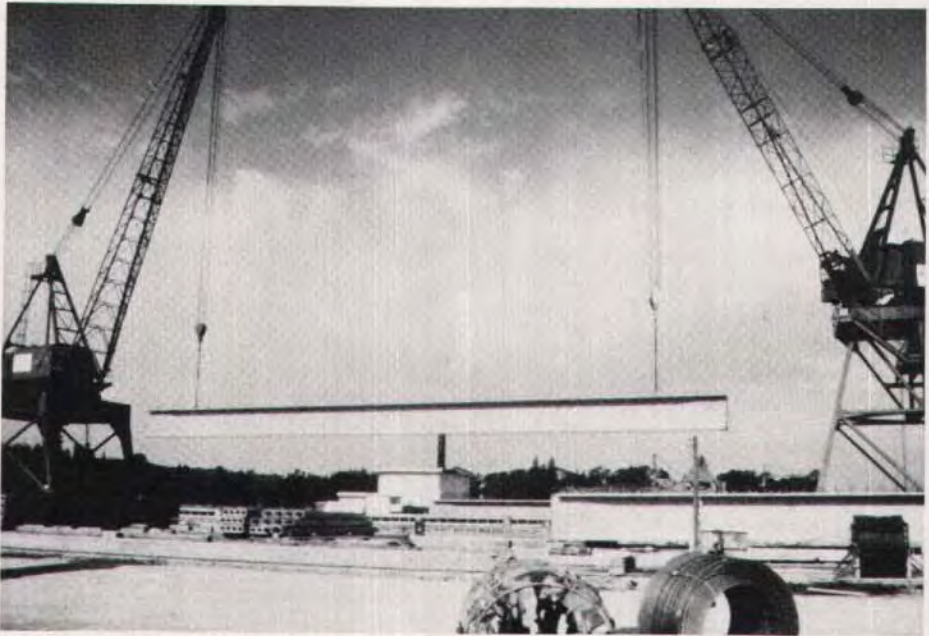


Fig. 6a. Handling of long span beam at plant.

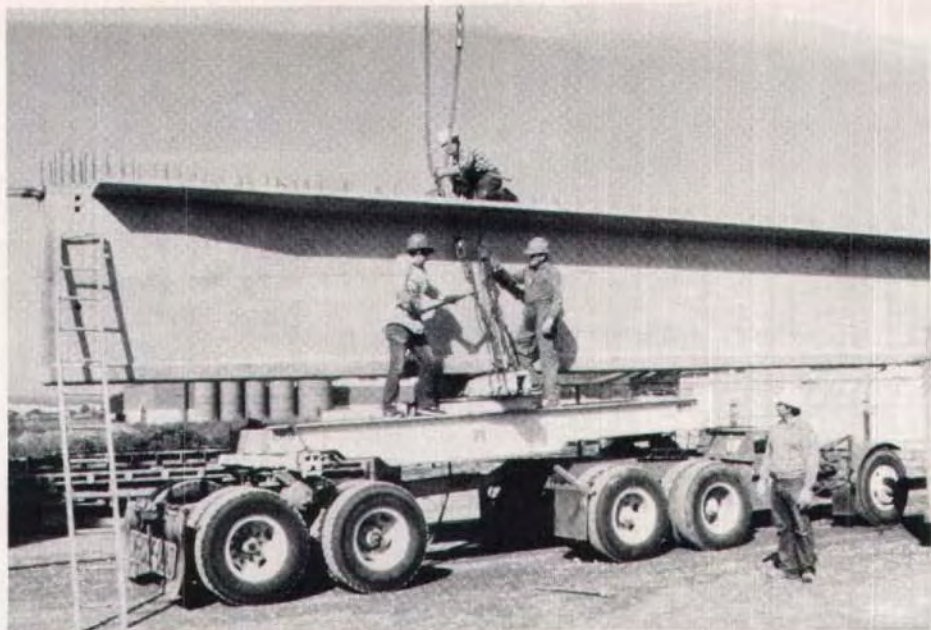


Fig. 6b. Long span beam being braced prior to shipping.



Fig. 6c. Transportation of long span beam.



Fig. 7. Collapse of long span beam.

only two, or a maximum of four, unbonded post-tensioned strands placed in the top flange. These strands can be released and recovered after erection of the beams.

We use $\frac{1}{2}$ in. (13 mm) diameter 270K low relaxation strands in a greased plastic tube, anchored with steel plates and standard barrel anchors (chucks) at each end of the top flange. The stress is released by a hydraulic jack, or by burning the strands through a small hole provided in the flange about 6 ft (1.83 m) from one end. After releasing the strand, it is pulled out manually.

For shorter beams [less than 130 ft (39.6)], only additional mild reinforcing steel may be required in the top flange.

Both methods are simpler to use, easy to calculate, and much less expensive than any other technique we have used in the past.

Only a few codes of practice address allowable stresses and other parameters in handling and shipping of long prestressed concrete beams. For example,

AASHTO, under "Allowed Temporary Stresses," specifies $0.6 f'_c$ for compression and $7.5 \sqrt{f'_c}$ for tension.

Table 1 shows the State of Washington DOT specification on criteria for checking girder stresses at time of handling or shipping.

Figs. 6a through 6c show the handling and shipping of a long span beam.

Fig. 7 shows a vivid example of the disastrous collapse of another long span beam. The importance of following sound handling and shipping procedures for long span members cannot be over-emphasized.

Appendix A presents a step by step analytical procedure for dealing with stability when handling and shipping long span prestressed concrete bridge beams.

Appendix B gives, with the aid of an example, the detailed calculations needed for carrying out such an analysis.

Appendix C summarizes the meaning of each mathematical symbol used in alphabetical order.

CLOSING REMARKS

The proposed procedure presented in this article is a straightforward method for dealing with three troublesome conditions involved in handling and shipping long span prestressed concrete bridge beams:

- (a) Safe handling at the time of stripping when concrete strengths are at their lowest and forces in the prestressing strand are at their highest.
- (b) Safe truck delivery with the uncertainties of superelevated roads and dynamics of travel.
- (c) Adequate safety factor during erection where handling of precast members by a contractor may not be as well controlled as the precaster might assume.

Conditions (a) and (c) represent the classical lateral stability problem when the beam is hanging from pickup loops from the top of the beam. The method given in the PCI Design Handbook, Section 5.2.9, is used with new proposed safety factors together with a design aid shown in Fig. 4. Lateral stability is dramatically improved by moving the pickup points in from the ends of the beam, subject to avoiding overstress in the beam. This is particularly critical in the net top flange tensile stresses at the harp point near 0.4l.

Condition (b) represents a combined stress analysis of vertical bending of the

beam on truck bunks, plus lateral bending due to an assumed superelevated road. In critical cases, surveying the road and measuring superelevation is important. When combined stresses exceed allowable values for short term loading, the use of temporary post-tensioned strands in the top flange, and/or higher strength concrete are shown to be effective in improving the safety of the beam.

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3. Laszlo, George, "A Prestressed Lightweight Concrete Bridge 131 ft. Long," *Civil Engineering - ASCE*, V. 37, No. 4, April 1967, pp. 64-65.
4. Anderson, Arthur R., "Lateral Stability of Long Prestressed Concrete Beams," *PCI JOURNAL*, V. 16, No. 3, May-June 1971, pp. 7-9.
5. Swann, R. A., Readers' Comment to "Lateral Stability of Long Prestressed Concrete Beams" (Ref. 4), *PCI JOURNAL*, V. 16, No. 6, November-December 1971, pp. 85-87.
6. *PCI Design Handbook*, Third Edition, Prestressed Concrete Institute, 175 W. Jackson Blvd., Chicago, Illinois, 1985.

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METRIC (SI) CONVERSION FACTORS

1 ft = 0.305 m	1 psi = 0.006895 MPa
1 in. = 25.4 mm	1 kip-ft = 1356 N-m
1 pcf = 16.02 kg/m ³	1 kip = 4448 N
1 lb/ft = 1.488 kg/m	

APPENDIX A — CALCULATION STEPS

Detailed below are the calculation steps needed to carry out a stability check for handling and shipping long span bridge beams.

Plant and Field Handling

1. Select the factor of safety (F.S.). Note that minimum F.S. for plant handling = 1.5; for field handling = 1.75.
2. Calculate the beam deflection as a simply supported span in the Y axis:

$$\Delta_y = \frac{5 w l^4}{384 E_c I_y}$$

3. Compute $y_y/F.S. = \beta$ in order to find the optimum beam stability factor (deflection).
4. From the ratio of β_y/Δ_y , find a/l from Fig. 4, which gives the optimum cantilever and center span lengths.
5. Round out the center span and cantilever lengths to the nearest foot. Check the safety factor with the conventional deflection formula at midspan for equal cantilevered beams in the Y axis:

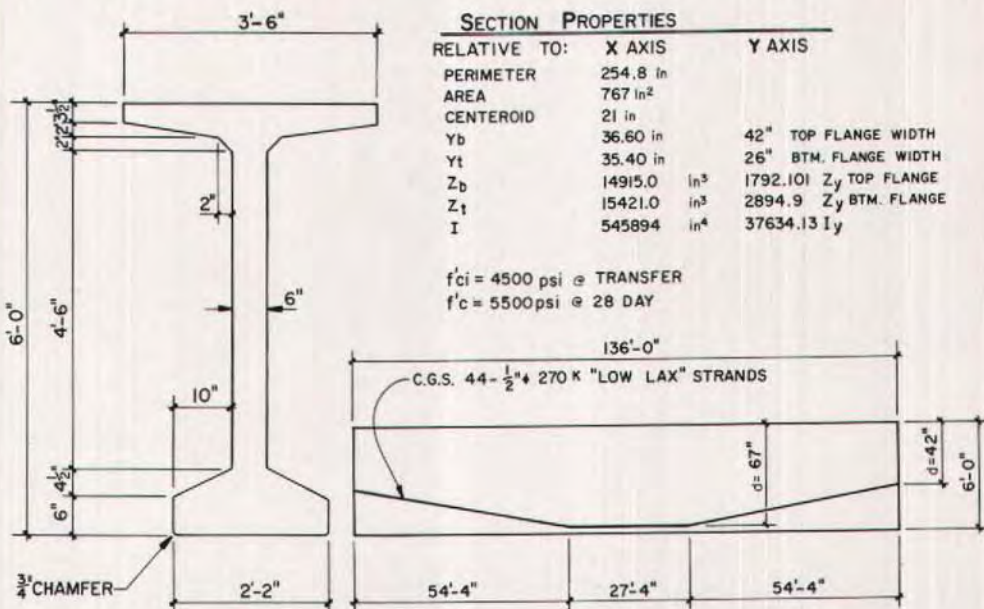
$$\beta_y = \frac{w l^4}{384 E_c I_y} (5 l_1^2 - 24 a^2)$$

6. With the new support locations, check the handling stresses at critical points (at the harp point which is generally near $0.4l$ and support).
7. Check the required concrete strength and revise the value accordingly.

Beam Shipping (Handling)

8. Establish the transportation support points. It is prudent to check this operation prior to yard handling and shipping.
9. Check the stresses at critical locations (at the harp point which is generally near $0.4l$ and support) with (a) no impact and (b) impact up and down.
10. Check the road superelevation or assume an arbitrary beam tilt. Calculate the weak (Y-Y axis) moment due to beam tilt.
11. Calculate the top and bottom flange stresses due to beam tilt only.
12. Combine (add) the shipping stresses (Step 9a) to the flange stresses (Step 11). Note that no impact is assumed at combined stresses. It would be extremely conservative to add the most adverse conditions unless the road is extremely rough at superelevations.
13. If the combined stresses at any point exceed the allowable stresses, post-tension or reinforce the required part of the section.
14. If stresses are below cracking, reinforce the section according to usual stress relations (compression-tension).
15. If combined stresses are above the crack level, use post-tensioning.
16. When supplementary strands are added, revise (a) total prestress force and (b) prestress eccentricity.
17. With the new prestressing force (P) and eccentricity (e), check the stresses at the critical locations similar to Step 9.
18. Combine these stresses (Step 17) with the stresses in Step 11.
19. Check the concrete strength, increase it if required, or add more post-tensioning.
20. Post-tensioning can be very helpful as the need arises. For example, if a very high stability is required, or the concrete strength cannot be increased, post-tensioning can be applied before yard handling (in the prestressing bed) and can then be postponed until the beam is erected.

APPENDIX B — SAMPLE CALCULATIONS



PCI BT-72 BRIDGE BEAM (7 FT. SPACING 8" DECK)

Given: PCI BT-72 bridge beam with following data (see also diagram):

Unit weight of concrete = 155 pcf

$w = 825.6$ lb/ft

$l = 136.0$ ft

$a = 0$ ft

$E_c = 4.07 \times 10^6$ psi

$f'_{ci} = 4500$ psi

$I_y = 37634$ in.⁴

Step 2 — Calculate beam deflection.

$$\begin{aligned} \Delta_v &= \frac{5 w l^4}{384 E_c I_y} \\ &= \frac{5 \times 825.6 \times 136^4 \times 1728}{384 \times 4.07 \times 10^6 \times 37634} \\ &= 41.48 \text{ in.} \end{aligned}$$

Step 3 — Compute stability factor.

$$\begin{aligned} \beta_v &= \frac{y_t}{1.5} = \frac{35.4}{1.5} = 23.6 \text{ in.} \\ \frac{\beta_v}{\Delta_v} &= \frac{23.6}{41.48} = 0.57 \end{aligned}$$

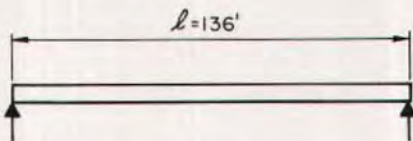
Step 4 — Determine optimum cantilever and span lengths.

For $\beta_v/\Delta_v = 0.57$, $all = 0.063$ (see Fig. 4).

Therefore,

$a = 0.063 \times 136 = 8.57$ ft

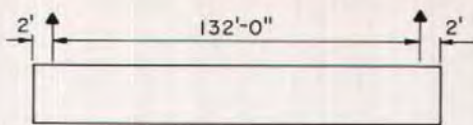
$l_1 = 136 - 2 \times 8.57 = 118.86$ ft



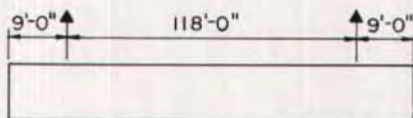
A. BEAM HANDLING IN PRODUCTION YARD

Step 1 — Select factor of safety

(a) Assume factor of safety (F.S.) = 1.5



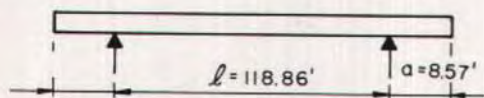
UNSTABLE (MAY BUCKLE)
F.S.=0.96



F.S.=1.55

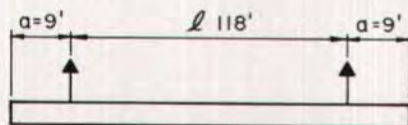
LATERAL STABILITY AT HANDLING

Supports for F.S. = 1.5; $\beta_y = 23.6$ in.



Step 5 — Round out span lengths.

$a = 9$ ft; $l_1 = 118$ ft



(b) Check pickup point 9 ft from ends.

$$\beta_y = \frac{wl_1^4}{384 E_c I_y} (5l_1^2 - 24a^2)$$

$$= \left[\frac{825.6 \times 118^2}{384 \times 4.07 \times 10^6 \times 37634} \times (5 \times 118^2 - 24 \times 9^2) \times 1728 \right]$$

$$= 22.85 \text{ in.}$$

$$\text{F.S.} = \frac{35.4}{22.85} = 1.55 > 1.5 \text{ (ok)}$$

Step 6 — Check handling stresses.

(c) Check handling stresses at 0.4 l (harping point)

$$+ M_{(x)}(\text{beam}) = \frac{W}{2} (l_1 x - x^2 - a^2)$$

$$= \frac{825.6}{2000} (118 \times 45.33 - 45.33^2 - 9^2)$$

$$= 1326.4 \text{ kip-ft}$$

P (transfer)/strand = 28.0 kips
(10 percent losses)

$$P_t = 44 \times 28 = 1232 \text{ kips}$$

$$e_{\text{harping}} = d - y_t = 67 - 35.4 = 31.6 \text{ in.}$$

$$f_{\text{top}} = + \frac{1232}{0.767} - \frac{1232 \times 31.6}{15.421}$$

$$+ \frac{12 \times 1326.4}{15.421}$$

$$= + 114 \text{ psi (compression)}$$

$$f_{\text{bottom}} = + \frac{1232}{0.767} + \frac{1232 \times 31.6}{14.915}$$

$$- \frac{12 \times 1326.4}{14.915}$$

$$= + 3149 \text{ psi (compression)}$$

Step 7 — Check required concrete strength.

Required handling strength:

$$\frac{3149}{0.6} = 5250 \text{ psi}$$

New factor of safety for modulus of elasticity of concrete, E_c ($f_{ci} = 5250$ psi) = 4.39×10^6 psi

$$\text{New F.S.} = 1.55 \times \frac{4.39}{4.07} = 1.67$$

Note: If cantilever is rounded to 8 ft, new F.S. would be 1.53.

Stresses at pickup point and midspan may be calculated in a similar way (usually will not govern).

Conclusion: If beam is handled 9 ft from ends, then concrete strength must be 5250 psi > 4500 psi release.

B. BEAM SHIPPING (HAULING)

Step 8 — Determine transportation support points.

Assume the same support points as for handling, i.e., 9 ft from each end.

$$f'_c = 5500 \text{ psi}; E_c = 4.496 \times 10^6 \text{ psi}$$

$$P = 27.17 \text{ kips/strand (25 ksi losses)}$$

$$P = 44 \times 27.17 = 1195.48 \text{ kips}$$

Impact = 20 percent up or down

Superelevation = 8 percent

Step 9 — Evaluate stresses at critical locations.

(a) Check stresses at 0.4 l (harping point) without impact.

$$M_{beam} = 1326.4 \text{ kip-ft (see Step 6)}$$

$$f_{top} = \frac{1195.5}{0.767} - \frac{1195.5 \times 31.6}{15.421} + \frac{1326.4 \times 12}{15.421}$$

$$= + 141 \text{ psi (compression)}$$

$$f_{bottom} = + \frac{1195.5}{0.767} + \frac{1195.5 \times 31.6}{14.915} - \frac{1326.4 \times 12}{14.915}$$

$$= + 3024 \text{ psi (compression)}$$

Required concrete strength:

$$f'_c = \frac{3024}{0.6} = 5040 \text{ psi}$$

< 5500 psi furnished (ok)

(b) Check stresses with 20 percent impact up.

$$M_{beam} = 0.8 \times 1326.4$$

$$= 1061 \text{ kip-ft}$$

$$f_{top} = + 65 \text{ psi}$$

$$f_{bottom} = + 3238 \text{ psi}$$

$$\text{Required } f'_c = \frac{3238}{0.6} = 5397 \text{ psi}$$

< 5500 psi (ok)

(c) Check stresses with 20 percent impact down.

Values will be less than the above stresses, due to increased beam weight.

Check at support:

$$d = \left[\left(\frac{67 - 42}{54.33} \right) \times 9 \right] + 42 = 46.14 \text{ in.}$$

$$e = 46.14 - 35.4 = 10.74 \text{ in.}$$

$$M_{beam} = \frac{9^2}{2} \times 1.2 \times \frac{825.6}{1000} = 40.12 \text{ kip-ft}$$

$$f_{top} = + 1559 - \frac{1195.5 \times 10.74}{15.421} - \frac{40.12 \times 12}{15.421}$$

$$= + 696 \text{ psi (compression)}$$

$$f_{bottom} = + 1559 + \frac{1195.5 \times 10.74}{14.915} + \frac{40.12 \times 12}{14.915}$$

$$= + 2452 \text{ psi (compression)}$$

$$\text{Required } f'_c = \frac{2452}{0.6} = 4087 \text{ psi}$$

< 5500 psi (ok)

Step 10 — Check superelevation and compute weak axis section moduli.

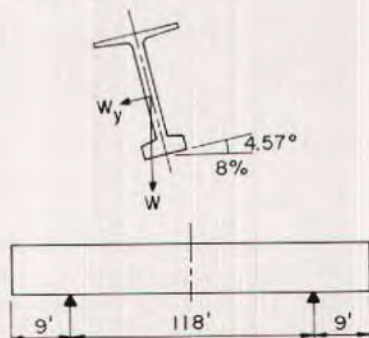
(d) Check stresses with 8 percent superelevation (no impact).

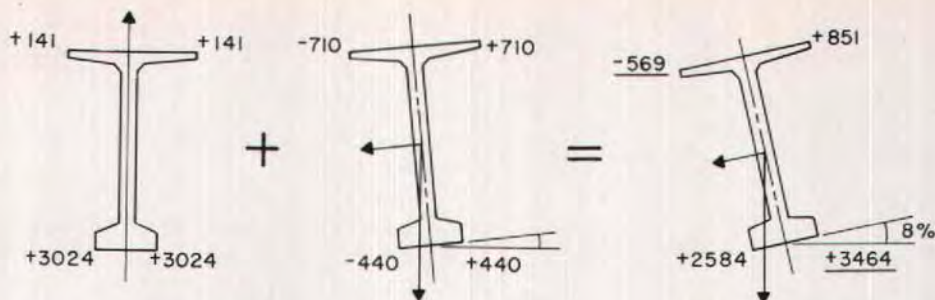
$$W_y = 0.08 W$$

$$M_y = 0.08 M$$

$$= 0.08 \times 1326.4$$

$$= 106.11 \text{ kip-ft}$$





$$Z_v(\text{top flange}) = 1792 \text{ in.}^3$$

$$Z_v(\text{bottom flange}) = 2895 \text{ in.}^3$$

Step 11 — Determine stresses in top and bottom flange due to superelevation (W_v component).

Top flange stresses:

$$\begin{aligned} f(\text{uphill flange}) &= + \frac{12 \times 106.11}{1.792} \\ &= + 710 \text{ psi} \\ &\quad (\text{compression}) \end{aligned}$$

$$\begin{aligned} f(\text{downhill flange}) &= - \frac{12 \times 106.11}{1.792} \\ &= - 710 \text{ psi} \\ &\quad (\text{tension}) \end{aligned}$$

Bottom flange stresses:

$$\begin{aligned} f(\text{uphill flange}) &= + \frac{12 \times 106.11}{2.895} \\ &= + 440 \text{ psi} \\ &\quad (\text{compression}) \end{aligned}$$

$$\begin{aligned} f(\text{downhill flange}) &= - \frac{12 \times 106.11}{2.895} \\ &= - 440 \text{ psi} \\ &\quad (\text{tension}) \end{aligned}$$

Step 12 — Check combined stresses.

Critical stresses

$$\begin{aligned} f(\text{downhill top flange}) &= -569 \text{ psi (tension)} \\ &> 7.5 \sqrt{5500} = -556 \text{ psi (ok)} \end{aligned}$$

$$\begin{aligned} f(\text{uphill bottom flange}) &= +3464 \text{ psi (comp)} \\ &> 0.6 \times 5500 = 3300 \text{ psi (ok)} \end{aligned}$$

Step 13 — Study the various corrective options for maintaining stability.

(a) Increase the concrete strength and reinforce the section.

(b) Post-tension the top flange.

Step 14 — In this particular case, Option (a) is not used.

Step 15 — For this case, use Option (b), namely, apply post-tensioning to top flange.

Try two $\frac{1}{2}$ in. diameter 270K strands in top flange.

F (final force) = $2 \times 28 = 56$ kips located 2 in. from top of beam.

Step 16 — Determine new prestress force and eccentricity.

$$56 \times 2 = 112.0 \text{ in.-kips}$$

$$\frac{1195.5 \times 67}{67} = 80,098.5 \text{ in.-kips}$$

$$\frac{1251.5 \text{ kips}}{67} = 80,210.5 \text{ in.-kips}$$

$$\text{New } P = 1251.5 \text{ kips}$$

$$\text{New } d = \frac{80,210.5}{1251.5} = 64.09 \text{ in.}$$

$$\text{New } e = 64.09 - 35.4 = 28.69 \text{ in.}$$

Step 17 — Check the shipping stresses.

$$f_{top} = + \frac{1251.5}{0.767} - \frac{1251.5 \times 28.69}{15.421}$$

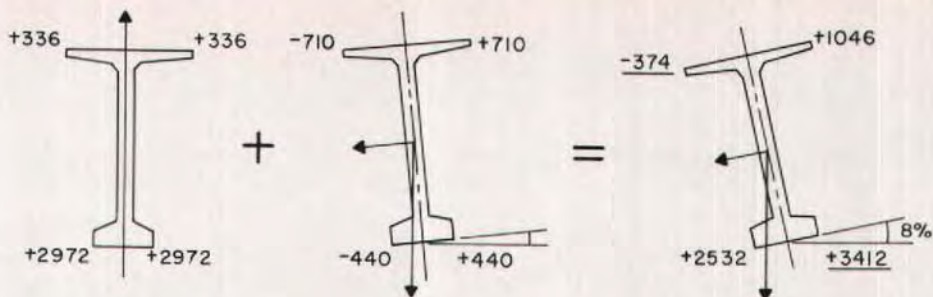
$$+ \frac{1326.4 \times 12}{15.421}$$

$$= + 336 \text{ psi (compression)}$$

$$f_{bottom} = + \frac{1251.5}{0.767} + \frac{1251.5 \times 28.69}{14.915}$$

$$- \frac{1326.4 \times 12}{14.915}$$

$$= + 2972 \text{ psi (compression)}$$



Step 18 — Check the combined stresses (see above diagram).

Use two post-tensioning strands in top flange.

Critical stresses:

$$f(\text{downhill top flange}) = -374 \text{ psi (tension)}$$

$$< 6 \sqrt{5500} = -445 \text{ psi (ok)}$$

$$f(\text{uphill bottom flange}) = +3412 \text{ psi (comp)}$$

$$> 0.6 \times 5500 = 3300 \text{ psi (unsatisfactory)}$$

Step 19 — Increase the required concrete strength. In this case to $3412/0.6 = 5700$ psi. Alternatively, increase the post-tensioning final force.

APPENDIX C — NOTATION

A = cross-sectional area
 d = distance from extreme compression fiber to centroid of prestressed tension reinforcement
 E_c = modulus of elasticity of concrete
 e = eccentricity of prestress force parallel to axis measured from the centroid of the section
 f_b = stress in the bottom fiber of the cross section
 f_c = unit stress in concrete
 f'_c = specified compressive strength of concrete
 f_r = modulus of rupture of concrete
 I = moment of inertia
 l = span length

M = unfactored moment
 P = prestress force after losses
 w = weight per unit length
 y_b = distance from bottom fiber to center of gravity of the section
 y_t = distance from top fiber to center of gravity of the section (distance from rigid lifting point to center of gravity of section)
 Z = section modulus
 Z_b = section modulus with respect to the bottom fiber of a cross section
 Z_t = section modulus with respect to the top fiber of a cross section
 Δ = deflection (with subscripts)
 β_v = stability factor

NOTE: Discussion of this article is invited. Please submit your comments to PCI Headquarters by August 1, 1988.