Precast Pretensioned Trapezoidal Box Beam for Short Span Bridges

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This paper describes a new trapezoidal precast, pretensioned beam that can span up to 100 ft (30.5 m). The beam has a maximum weight of 55 tons (50 t). The new beam is presented in two different shapes: a closed totally precast concrete shape and an open-top shape requiring a cast-in-place composite topping. To maintain continuity between adjacent beams and to eliminate the potential of reflective cracks, both shapes have shear keys and continuity reinforcement in the transverse direction. The new beam has a high span-to-depth ratio, ranging between 30 and 40, in comparison to an I-beam system, which makes it suitable for low clearance sites. It can cover a large surface area with fewer beams than the adjacent AASHTO box beams, reducing erection time and cost. The new beam also produces an aesthetically pleasing closed superstructure soffit.

Adjacent box beams have been widely used in the United States for the construction of new bridges as well as for the replacement of old bridges. The National Bridge Inventory[1] shows that box beams represented about one-third of all prestressed concrete bridges constructed in the United States between 1979 and 1989. Box beams can span up to 100 ft (30.5 m) while maintaining a high span-to-depth ratio.[2] Also, they produce an aesthetically pleasing closed superstructure soffit.

Adjacent box beams are generally connected at their interfaces by grouted shear keys. A 2 in. (51 mm) thick wearing surface is commonly used to provide a smooth riding surface. However, in some cases, a 5 to 6 in. (127 to

152 mm) structurally composite concrete overlay is used.

Bridges built with adjacent box beams have been reported[3] to experience longitudinal "reflective" cracks in the topping directly over the shear key joints. Water and deicing chemicals penetrate through the cracks causing concrete staining and spalling, and reinforcement corrosion. Subsequent repairs increase maintenance and traffic disruption.

Longitudinal cracks are usually caused by the large torsional stiffness of the adjacent boxes and by the lack of an adequate transverse connection to account for the significant forces needed to be transferred between boxes. El-Remaily et al.[4] have proposed a diaphragm and transverse post-tensioning system to account for these forces. However, the relatively large amount of transverse post-tensioning required to restrain the torsionally stiff boxes may significantly increase the cost of the system. In addition to the problem of longitudinal cracking, constructing bridges with adjacent boxes requires shipping and handling of a relatively large number of pieces.

Some attempts have been successfully made to develop trapezoidal box beams. In 1973, Batchelor et al.[5] and Campbell et al.[6] recommended to the Ontario Precast Concrete Manufacturers Association the adoption of a new precast trapezoidal girder to replace the I-beam in relatively long spans. It consisted of a U-shaped precast beam and cast-in-place deck slab. The precast beams were erected on temporary bents and made continuous by means of post-tensioning.

In 1991, the Texas Department of Transportation developed a new precast, prestressed U-beam.[7] This system has similar features to those in the Ontario beams except that the beams are not post-tensioned and are erected without the need of temporary supports. The Texas U-beam has been successfully used in a number of bridges. The Texas U-beams are considered heavy beams and have a span-to-depth ratio of about 29. They are generally used for spans in the range of 100 to 150 ft (30.5 to 45.7 m).

The objective of this paper is to present a new trapezoidal precast, prestressed concrete system that can span up to 100 ft (30.5 m), has a maximum weight of 55 tons (50 t), and controls the problem of longitudinal cracking occurring in adjacent box beams. The proposed beam has a high span-to-depth ratio (ranging between 30 and 40), covers a large bridge deck surface area with fewer precast pieces than the adjacent box beams, is aesthetically pleasing, and eliminates field forming.

The new trapezoidal beam is developed in two different shapes. The first is a closed totally precast concrete shape and the second is an open-top shape with a cast-in-place composite topping. This paper discusses the evolution of the new beam, connection details, span capacities, and production issues. A comparison between the new trapezoidal beam and the existing AASHTO box beams is also provided.

EVOLUTION OF PROPOSED SYSTEM

A survey[8] concerning the development of a new precast, prestressed system for short to medium span bridges up to 100 ft (30.5 m) was sent to bridge owners, general contractors,

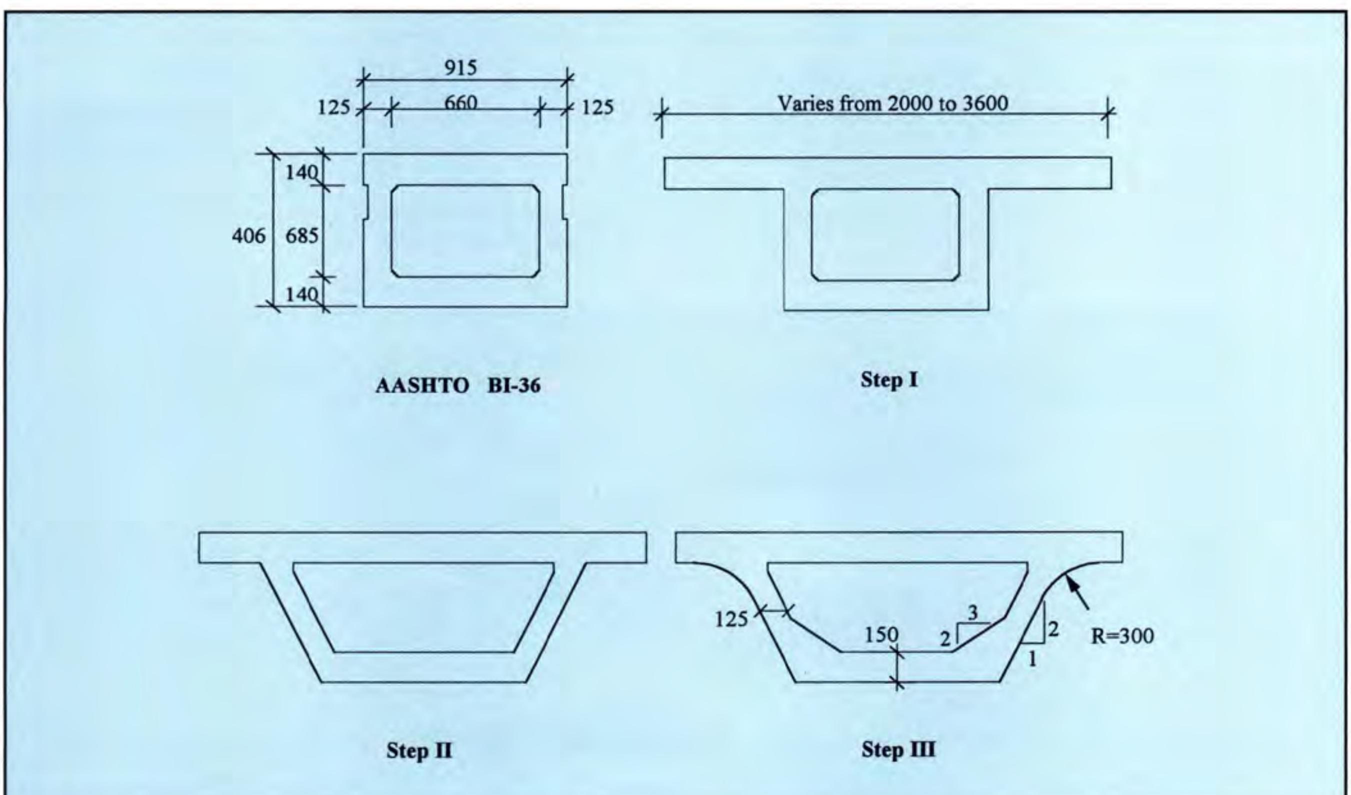
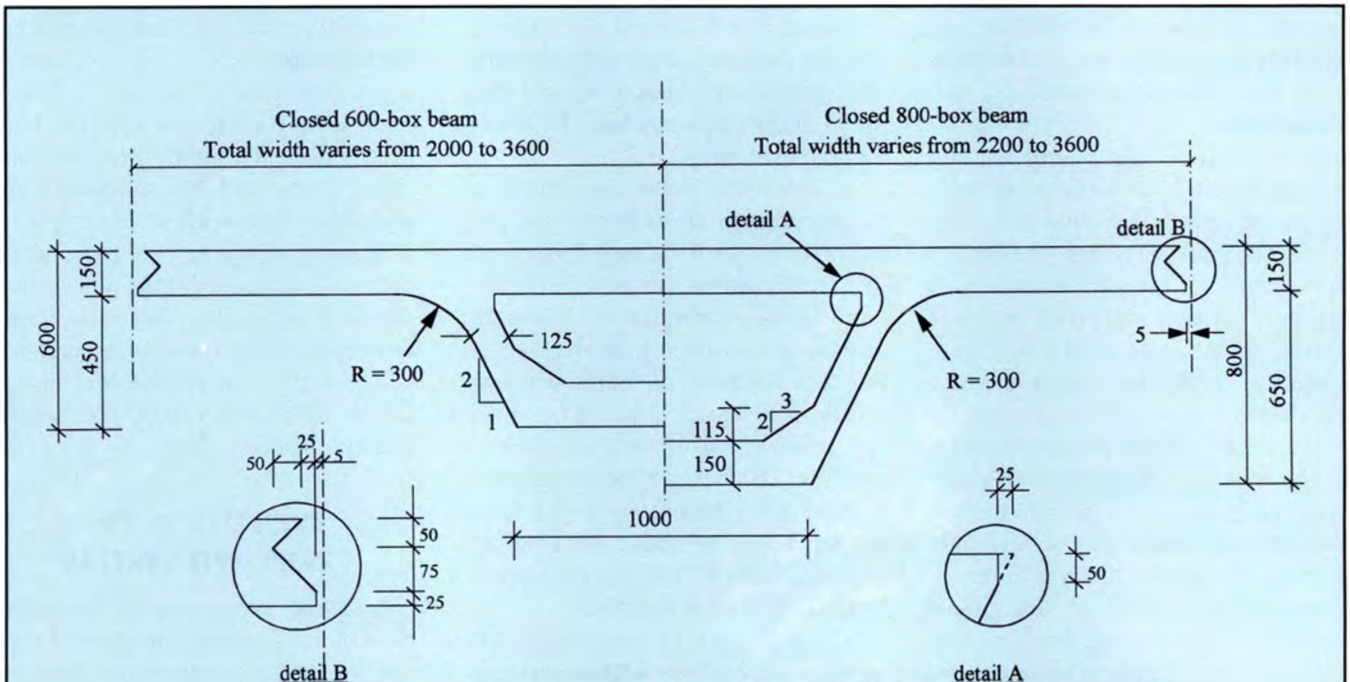


Fig. 1. Evolution of proposed trapezoidal box beam. **Note:** 100 mm = 3.937 in.

precast concrete producers, and consultants across the United States. The results of this survey showed that the use of the channel beam with sloped sides or the box beam is preferred. This is because these systems are easy to construct and have aesthetic appeal.

A parametric study conducted on bridge girders[9] showed that to have an efficient section, the area of the cross section should be concentrated in the two flanges as far apart as possible and the web should be made as thin as possible. Moreover, the haunch between the web and the flanges should be kept as horizontal as possible while still permitting placement of concrete and easy stripping of formwork.



	Closed 600-box beam				Closed 800-box beam			
Width mm (in.)	2000	(78.74)	3600	(141.73)	2200	(86.61)	3600	(141.73)
Area mm^2(in^2)	580,000	(899)	819,590	(1271)	660,000	(1023)	870,000	(1348)
Inertia mm^4 (in^4)	2.3437x10^{10}	(56,308)	2.8720x10^{10}	(69,000)	5.2126x10^{10}	(125,233)	6.1470x10^{10}	(147,701)
y_b mm (in)	356	(14.03)	406	(15.97)	488	(19.21)	545	(21.46)
Wt. kN/m (kip/ft)	13.65	(0.936)	19.303	(1.324)	15.44	(1.065)	20.48	(1.404)

Fig. 2. Cross-sectional dimensions and properties of closed box beams. **Note:** 100 mm = 3.937 in.

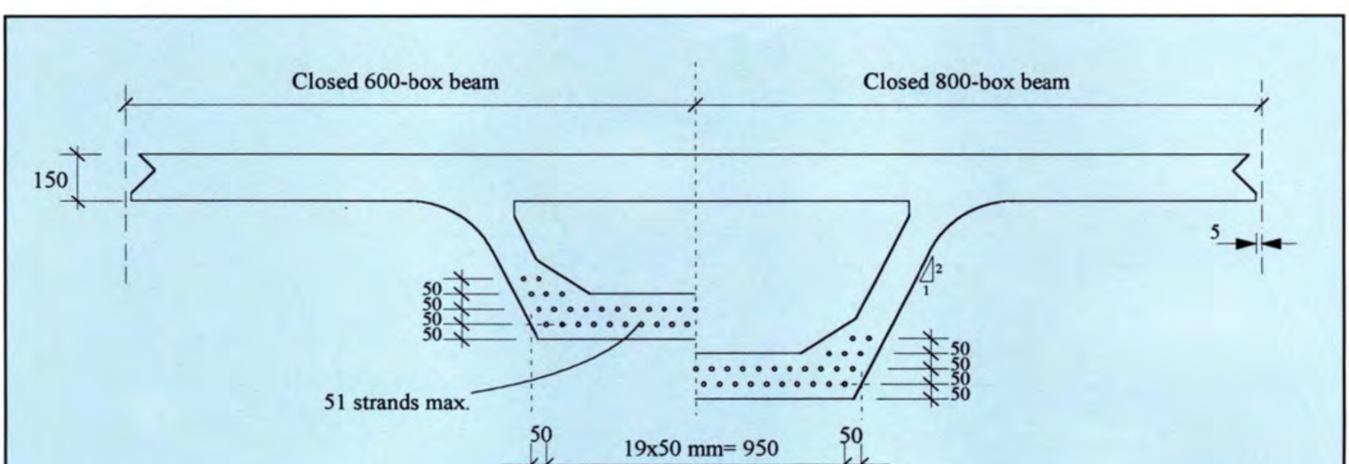


Fig. 3. Strand template of closed box beams. **Note:** 100 mm = 3.937 in.

Proposed Totally Precast Closed Beam

Following these recommendations, the development of the proposed beam started with modifying the shape of the existing AASHTO box beam by extending the top flange outside the webs. This was done for two reasons. The first reason was to provide a structurally flexible beam-to-beam connection that minimizes the effect of differential rotation between adjacent boxes and consequently reduces the potential for longitudinal cracks. The second reason was to minimize the number of beams to be handled to increase construction speed.

To improve the aesthetic appearance of the section, the webs were given two-to-one slopes and curved corners were added between the top flange and the webs. The web thickness was kept at 5 in. (125 mm), the same as in the AASHTO box beams. The bottom flange thickness was set at 6 in. (150 mm) to allow for two rows of strands and haunches were added to increase the number of strands that can be accommodated.

Fig. 1 shows the steps considered in modifying the AASHTO box beam. Fig. 2 gives the dimensions and properties of the proposed closed box beam. The beam is provided in two depths, 23.6 and 31.5 in. (600 and 800 mm). The width of the top flange varies from 6 ft 7 in. to 11 ft 10 in. (2000 to 3600 mm). The 11 ft 10 in. (3600 mm) maximum width has been chosen to cover one lane with one beam. The bottom flange can accommodate up to 51 strands with a minimum concrete cover of 2 in. (50 mm) and a strand spacing of 2 in. (50 mm), as shown in Fig. 3. In situations where smaller concrete cover and/or strand spacing is allowed, the bottom flange thickness may be reduced.

Proposed Open-Top Beam with Cast-in-Place Topping

Because of difficulty forming the void of the closed box beam and because some bridge owners prefer a cast-in-place riding surface, an open box section was also developed. Fig. 4 gives the dimensions of the proposed open beam. The open box beam has the same bottom flange and web dimensions as the closed box beam but with a thinner top flange of 2.56 in. (65 mm). Thus, the same forms can be used in fabricating the open and closed beams.

After the beams are installed in the field and connected transversely as discussed in the following section, they receive a 4.9 in. (125 mm) thick composite cast-in-place (CIP) concrete topping. The CIP topping provides a smoother riding surface and simpler adjustment of the cross slope for water drainage than for a totally precast, untopped, bridge deck. A 1.4 in. (35 mm) thick ferrocement panel or another cost-effective material may be used as a stay-in-place (SIP) form for the CIP topping.

The CIP topping is reinforced with one layer of epoxy-coated welded wire reinforcement with a 2.5 in. (64 mm) clear concrete cover, which functions as the negative moment reinforcement in the deck slab. The positive moment reinforcement of the deck slab is provided in the top flange of the precast beam. To maintain continuity of the positive reinforcement, the precast beams are transversely connected as discussed in the following section.

The concrete properties of the precast open 600 and 800 box beams are given in Fig. 4. Fig. 5 shows the strand template. Up to 51 strands can be placed in the bottom flange. Top strands can be provided to control tensile stresses at release at end sections of the beam.

TRANSVERSE CONNECTIONS

To maintain continuity between the adjacent beams in the transverse direction, the flange sides are shaped to create a continuous shear key that can be filled with non-shrink grout, as shown in Detail B in Fig. 2 and Detail A in Fig. 4. In addition to the shear key, blockouts are provided at intervals of 23.4 in. (600 mm). Fig. 6 shows three types of transverse connections. Connection Type I and Type II can be used only with the closed box beam while Connection Type III can be used with either the open or closed box beams.

In Connection Type I, a $^3/_8$ x 3.9 x 3.9 in. (10 x 100 x 100 mm) steel plate is embedded at the end of the flange and fabricated with the precast beam. The plate is welded in the field to its adjacent plate using a $^3/_8$ x 2 x 3.9 in. (10 x 50 x 100 mm) plate. Finally, the pocket is filled with non-shrink grout.

Connection Type II requires fabricating the top flange with a 15.7 in. (400 mm) long pocket from one side and a 7.9 in. (200 mm) long pocket in the other side. A 15.7 in. (400 mm) long #6 (#19) bar, confined with a spiral, is embedded in the 15.7 in. (400 mm) long pocket. After setting the adjacent beam, the bar is pulled across the joint to fit into the 7.9 in. (200 mm) long pocket on the other side. A non-shrink grout is used to fill the pockets. With Connection Type II, care is needed during fabricating and installing the precast beams in place because the two ends of the top flange are not identical.

For Connection Type III, a full-depth blockout of 3.9 in. (100 mm) width and 7.9 in. (200 mm) long is provided. In order to avoid forming in the field for the blockout, a 20-gauge, 5.9 x 9.8 in. (150 x 250 mm) metal sheet is used as a stay-in-place form at the blockouts. The metal sheet is secured into the concrete by bending its corners. A #6 (#19) bar is embedded in the concrete for a distance to fully develop the bar in tension while protruding a distance of 7 in. (175 mm) in the blockout, as shown in Fig. 6. This bar is spliced with the adjacent bar by a 14.7 in. (375 mm) long #6 (#19) splice bar. To fully develop the #6 (#19) bar, it is confined with a high strength spiral.

The confining technique, used in Connection Type III, was tested in stay-in-panels used for a bridge deck at the University of Nebraska.[10,11] The panels were loaded over the transverse joint and tested for 2 million cycles of repeated load and also for ultimate load. No signs of slippage or failure were observed in the connections. The results showed that confining the #6 (#19) bars for a distance of 5 in. (127 mm) fully developed the bar in tension.

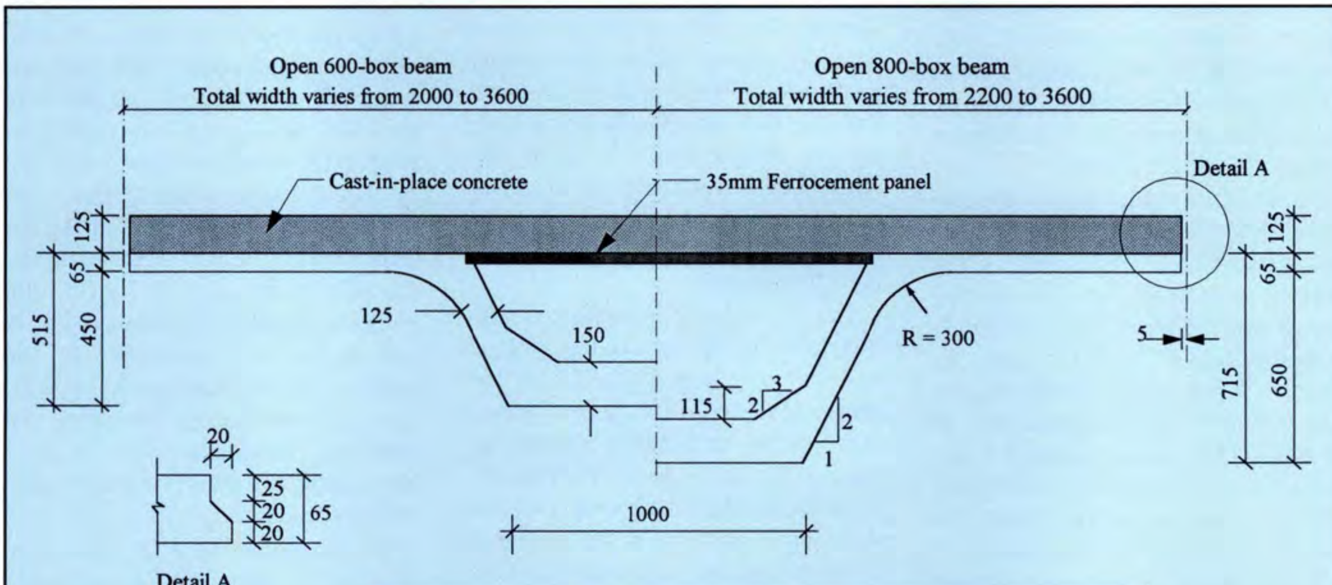
SPAN CAPACITIES

Span capacities for both a totally precast closed beam and an open-top box beam with CIP topping will be discussed.

Proposed Totally Precast Closed Beam

A 35.4 ft (10.8 m) wide simple span bridge was considered. Concrete strength of the precast beam at release and at 28 days was 5500 and 7500 psi (38 and 52 MPa) respectively, and 1/2-in. (12.7 mm) diameter, low relaxation strands of 270 ksi (1862 MPa) ultimate strength were used. Initial prestressing of three-quarters of the ultimate strength was considered. Guidelines given by Article 5.11.4.2 in the AASHTO LRFD Specifications[12] regarding debonding of strands were used.

Thus, the total number of debonded strands was limited to 25 percent of the total number of strands, and the number of debonded strands in any horizontal line was limited to 40 percent of the strands in that row. The maximum shielded length was limited



	Open 600-box beam				Open 800-box beam			
Width mm (in.)	2000	(78.74)	3600	(141.73)	2200	(86.61)	3600	(141.73)
Area mm²(in²)	330,000	(511)	434,100	(673)	380,000	(589)	471,000	(730)
Inertia mm⁴ (in⁴)	0.9103x10¹⁰	(21,869)	1.4473x10¹⁰	(37,771)	2.2359x10¹⁰	(53,718)	3.2673x10¹⁰	(78,497)
y_b mm (in)	223	(8.77)	285	(11.22)	308	(12.14)	380	(14.98)
Wt. kN/m (kip/ft)	7.76	(0.532)	10.22	(0.701)	8.94	(0.613)	11.09	(0.761)

Fig. 4. Cross-sectional dimensions and properties of open box beams. **Note:** 100 mm = 3.937 in.

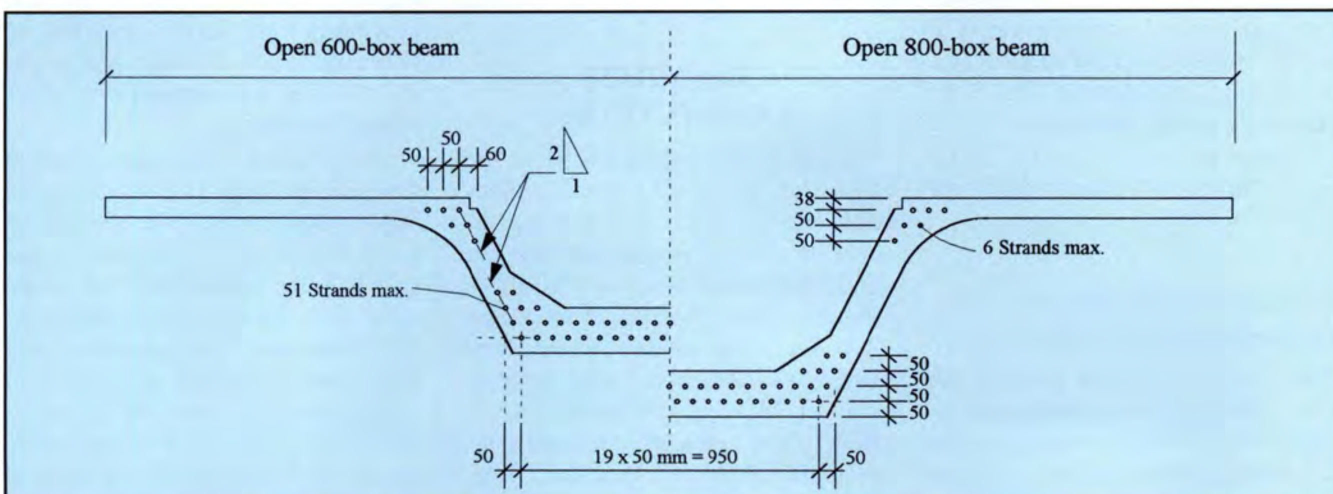


Fig. 5. Strand template of open box beams. **Note:** 100 mm = 3.937 in.

to 20 percent of the span on each side.

The bridge was analyzed under its own weight and a superimposed dead load of 45 psf (2.2 kPa). Because some state agencies are moving toward higher live loads than that specified by the AASHTO Standard Specifications,[13] span capacities were determined for two different live loads, i.e., HS20 and HS25 truck levels.

The distribution factor for concrete box girders, as given by Table 3.23.1 in the AASHTO Standard Specifications,[13] i.e., *S*/7.0, was used. Although Articles 3.23.4 and 3.28 in AASHTO Specifications[13] indicate possible use of a different moment distribution factor, the authors prefer to use *S*/7.0. The moment distribution factor for the proposed beams according to Articles 3.23.4 and 3.28 can be higher than unity. This was felt to be unreasonable as the widest beam cannot cover more than one lane. In addition, they do not give any guidelines for calculating the shear distribution factor.

The authors examined the distribution factor equations for shear and moment given by the AASHTO LRFD Specifications[12] and found that these

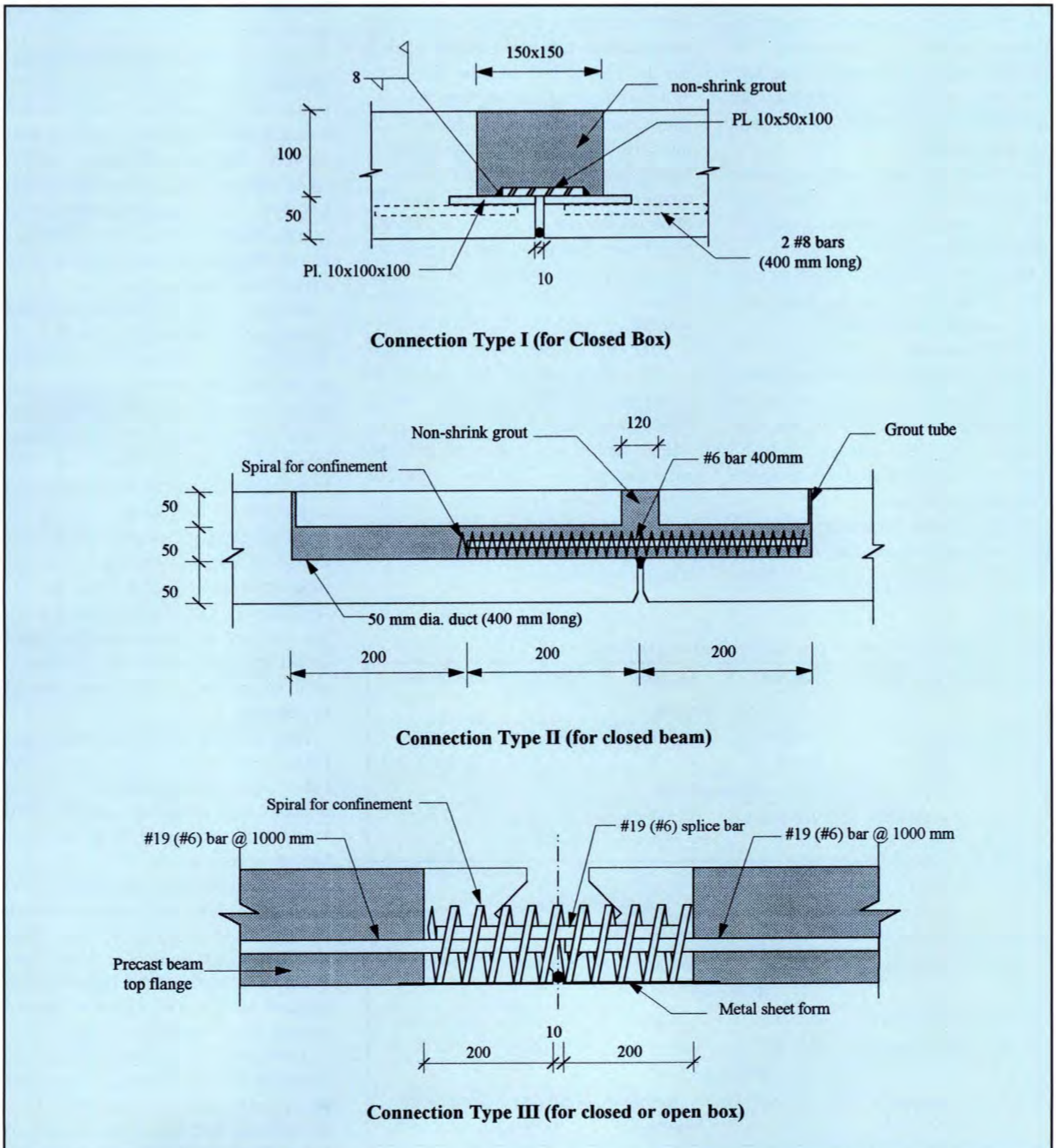


Fig. 6. Transverse connection details. **Note:** 100 mm = 3.937 in.

equations gave almost the same values as using $S/7.0$. However, the LRFD distribution factor equations could not be applied to the widest proposed beam, i.e., 11.81 ft (3600 mm), because its width exceeded the limit specified by the AASHTO LRFD Specifications.

To determine the maximum span, the following design scheme was used to establish the maximum span capacity:

1. Utilize the maximum number of bottom strands that maximizes the nominal ultimate strength of the section, ϕM_n, while not exceeding the maximum allowable tensile stresses at midspan at service.

2. Satisfy the maximum allowable tensile stresses at the end section at release by using the following steps in order of preference:

- Shield some of the bottom strands up to the maximum allowed number, as indicated earlier.
- Add top strands.
- Finally, if shielding bottom strands and using top strands do not satisfy the design criteria, increase the concrete strength at release, up to 85 percent of the specified concrete strength at 28 days.

Following this procedure, the concrete strength at release was raised from 5500 to 6200 psi (38 to 43 MPa), which was about 82 percent of the 28-day concrete strength. Table 1 shows the span capacities for the proposed closed box beams. Note that the span capacities can be increased by 5 percent if the proposed beams are used for a continuous span structure.

Proposed Open-Top Box Beam with Cast-in-Place Topping

The first trials to determine the maximum spans were done using the same design data and procedure used for the closed box beams. The concrete strength of the topping was assumed to be 5000 psi (34 MPa) at 28 days. However, it was apparent that a higher concrete strength of the precast beam should be used because the compression stresses in the bottom flange at release controlled the design, and the maximum number of bottom strands, 58 strands, was not fully utilized.

Thus, the 28-day concrete strength of the precast beam was raised to 9000 psi (62 MPa) and the release stress was raised to 7400 psi (51 MPa), which was approximately 82 percent of the 28-day concrete strength. Table 2 gives the span capacities of the proposed open box beams for HS20 and HS25 Design Trucks, respectively.

Table 1. Span capacities for proposed closed box beams.

Proposed closed box	600/2000	600/3600	800/2200	800/3600
HS20 truck load				
Maximum span, m (ft)	23.8 (78)	18.3 (60)	29.0 (95)	23.2 (76)
Girder weight, t (ton)	33.1 (36.5)	36.0 (39.7)	45.9 (50.6)	48.3 (53.3)
HS25 truck load				
Maximum span, m (ft)	21.9 (72)	16.2 (53)	27.1 (89)	21.3 (70)
Girder weight, t (ton)	30.6 (33.7)	31.8 (35.1)	43.0 (47.4)	44.6 (49.1)

Note: 1 ton = 2000 lbs; 1 t = 9.81 kN.

Table 2. Span capacities for proposed open box beams.

Proposed open box	600/2000	600/3600	800/2200	800/3600
HS20 truck load				
Maximum span, m (ft)	21.3 (70)	17.1 (56)	26.2 (86)	21.6 (71)
Girder weight,* t (ton)	16.9 (18.7)	17.8 (19.7)	24.0 (26.4)	24.5 (27.0)
HS25 truck load				
Maximum span, m (ft)	20.1 (66)	15.9 (52)	25.0 (82)	20.4 (67)
Girder weight,* t (ton)	15.9 (17.6)	16.6 (18.3)	22.8 (25.2)	23.1 (25.5)

Note: 1 ton = 2000 lbs; 1 t = 9.81 kN.
* Girder weight does not include the weight of the cast-in-place topping.

TRANSVERSE REINFORCEMENT

To determine the transverse reinforcement needed for the section, a three-dimensional finite element analysis was used for a 35.4 ft (10.8 m) wide and 90 ft (27.4 m) simple span bridge. The precast beams were modeled using eight-node isoparametric cubic elements. A 350 lbs per ft (5.1 N/m) barrier weight and 20 lbs per sq ft (0.96 kPa) superimposed dead load were assumed.

Two HS25 Design Trucks were considered, as shown in Fig. 7. They were positioned to give maximum positive and maximum negative bending moment at each critical location in the cross section of the beam. These values were used to design the transverse reinforcement of the girder. No transverse diaphragms were assumed to exist except at the supports.

Results of the analysis showed that changing the bridge span from 70 to 90 ft (21.3 to 27.4 m) had a small effect on the transverse reinforcement (less than 2 percent). Therefore, the transverse reinforcement was determined based on the 90 ft (27.4 m) span. The transverse reinforcement was designed to provide for the required strength for three different stages of loading: handling and shipping, casting of the topping concrete, and service. For bridges significantly wider than 35 ft (10.8 m), the standard transverse reinforcement shown may not be adequate. Structural analysis similar to that shown would be required.

Figs. 8 and 9 give the details of the transverse reinforcement for the closed and open top proposed beams. Welded wire reinforcement was used to simplify and speed up the production process. One layer of reinforcement in the middle thickness of the web and the bottom flange was used in the closed beam. However, this could not be achieved in the web of the open beam as a result of the high moment applied to the web sections during casting of the topping concrete.

To reduce this moment, the authors investigated the idea of tying the webs of the open beam using steel rods. However, it was found that the cost of the tie rods with their anchors would be higher than using two layers of

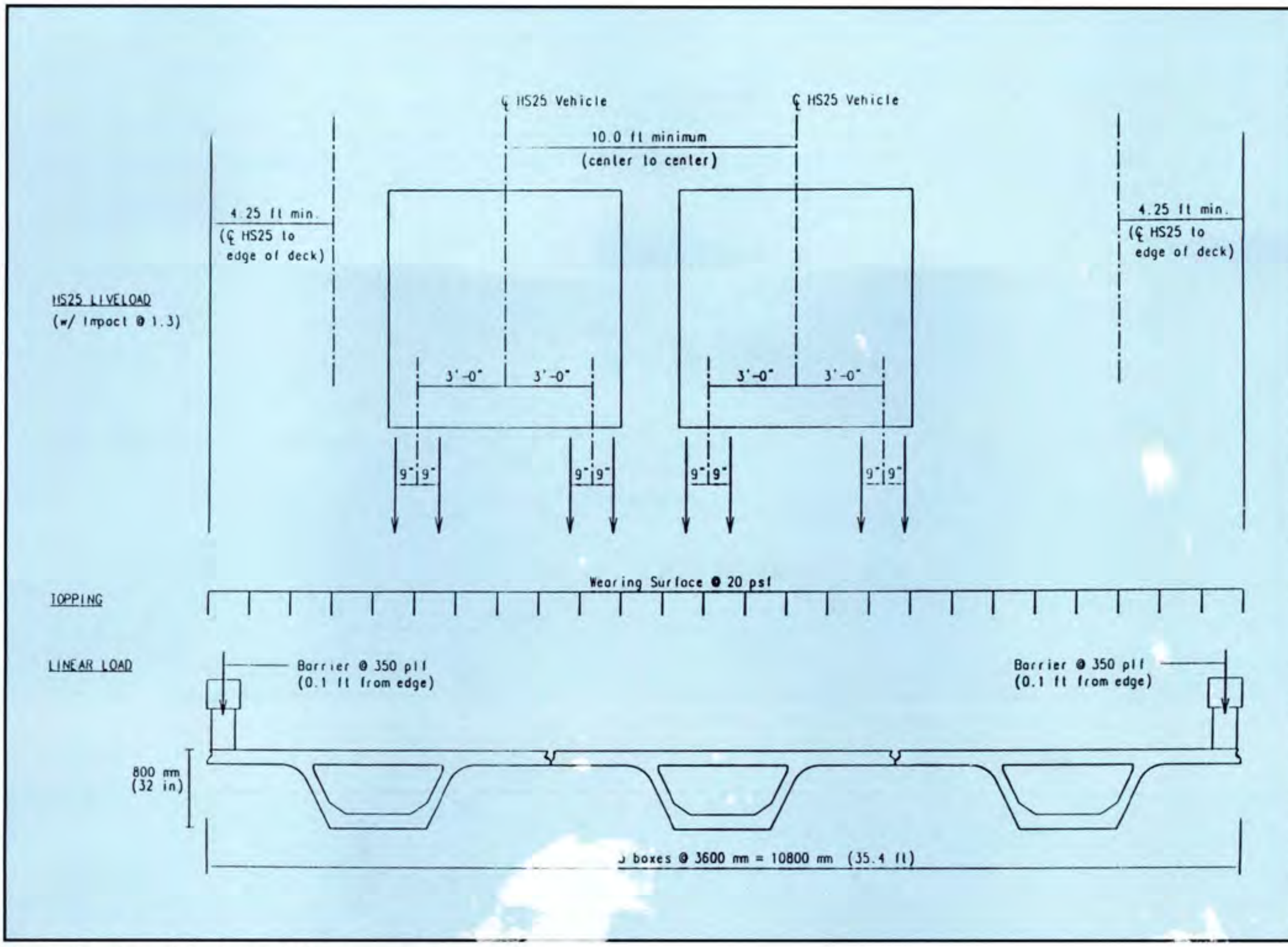


Fig. 7. Loads used in determining transverse reinforcement.

welded wire reinforcement. In addition, using tie rods would complicate the beam fabrication.

BEAM FABRICATION

Beam fabrication details for both a totally precast closed beam and an open-top beam with a CIP topping are given.

Proposed Totally Precast Closed Beam

Fabrication of the proposed box beams can be achieved by two approaches: (1) using expanded polystyrene void forms or (2) using recoverable steel void forms.

In the first approach, steel forms are used to form the outside surface of the box. Strands and welded wire reinforcement are installed in the bottom flange and webs. Expanded polystyrene void forms are then placed. The void forms should be secured in position to avoid floating during concrete placement. Top flange reinforcement is then installed. Concrete is placed in one web of the beam and vibrated until it appears in the bottom of the other web. Then, the concrete is placed uniformly over the entire beam until the forms are filled.

This approach gives a relatively fast production cycle. However, some producers[7,14] have expressed concern that the buoyancy forces of the vibrated concrete may displace the expanded polystyrene form upward. In addition, if the concrete is not adequately flowable, or adequately consolidated, voids may develop in the bottom flange, where they cannot be visibly inspected because of the expanded polystyrene forms.

The second approach is the same as the first, except that recoverable steel void forms are used. In this situation, no intermediate diaphragms, if required, could be cast. The authors believe, however, that no intermediate diaphragms should be used in this system.

Proposed Open-Top Beam with Cast-in-Place Topping

Fabrication of the open box beam is quite simple. Steel forms would be used for both the exterior and interior surface. The web slopes make form removal simple. Also, a good feature of the open box is the ability to visually inspect the interior surface of the box. Note that steel forms for the outside surface of the beam can be stationary in contrast to the I-beam forming, which requires moving the side forms in and out. This technique is widely used in Mexico in producing box beams where the side forms are permanently placed under the ground surface. It has been shown that this technique makes the production of box beams in Mexico competitive with the fabrication of I-beams.

Note that for both types, the closed and open beam, the box geometry is developed such that it is possible to use one set of forms for various box depths. The forms

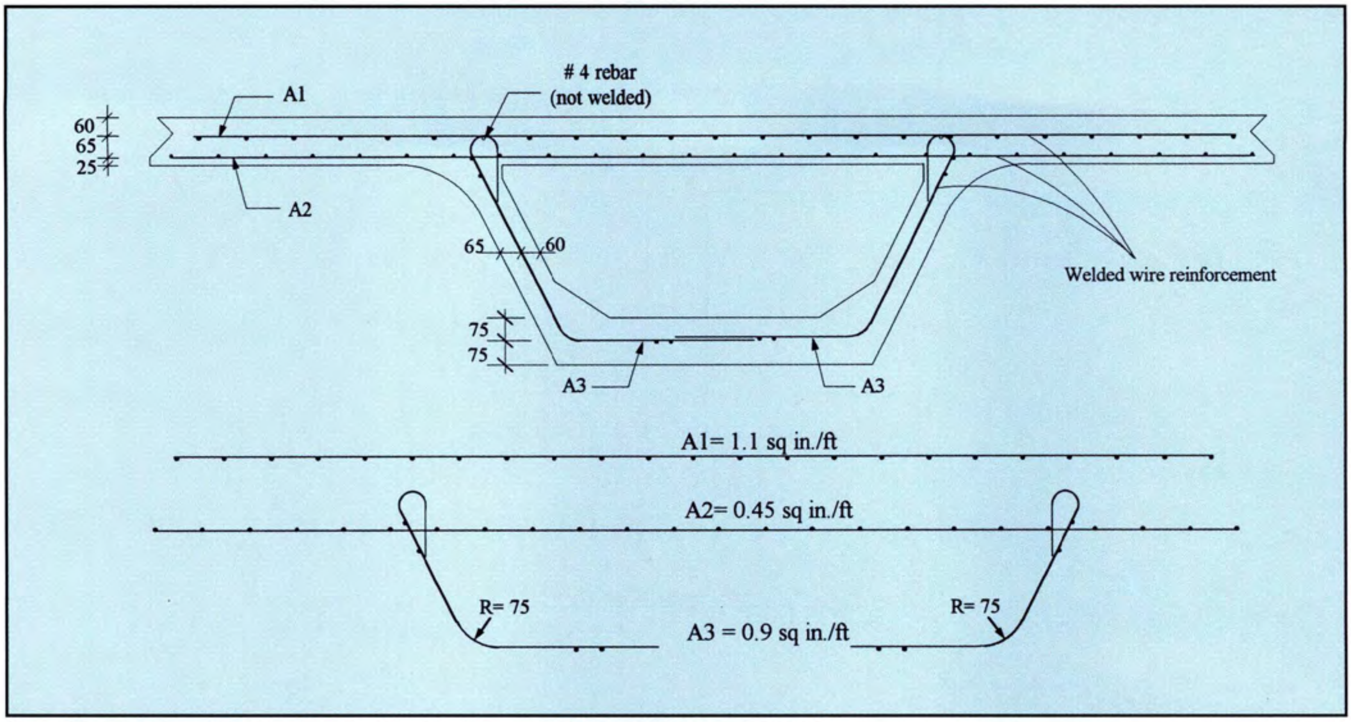


Fig. 8. Transverse reinforcement of closed box beams. **Note:** 100 mm = 3.937 in.

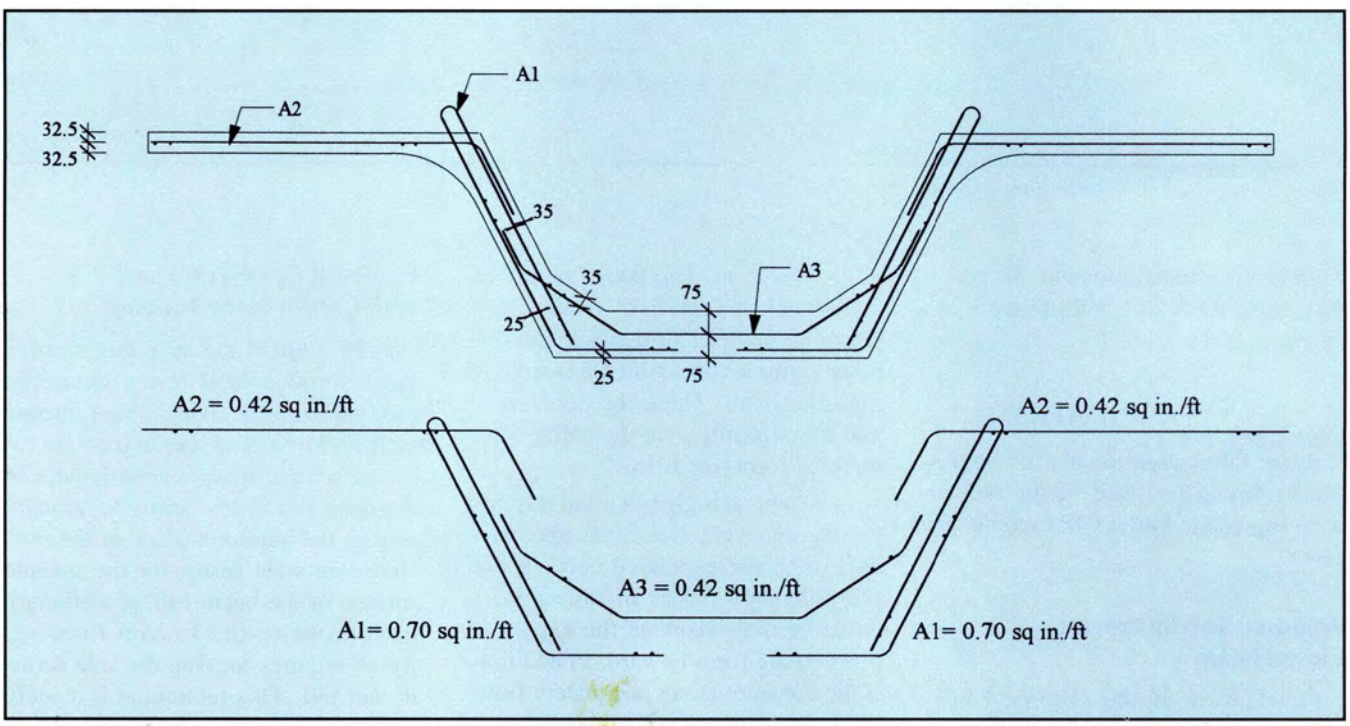


Fig. 9. Transverse reinforcement of open box beams. **Note:** 100 mm = 3.937 in.

would require extension panels to increase beam depth.

COMPARISON WITH AASHTO BOX SECTIONS

The proposed box beams were compared with AASHTO box beams to illustrate their structural efficiency. The proposed closed and open 600-box beams were compared with the AASHTO BI-48 box beam, which has a structural depth of 27 in. (685 mm). The proposed closed and open 800-box beams were compared with the AASHTO BII-48 box beam, which has a structural depth of 33 in. (838 mm). Fig. 10 shows the cross section of the bridge used in comparison between the AASHTO box beams and the proposed beams.

Structural Efficiency Factors

Five different structural efficiency factors were used in the comparison. These factors are: (1) width-to-depth ratio; (2) span-to-depth ratio; (3)

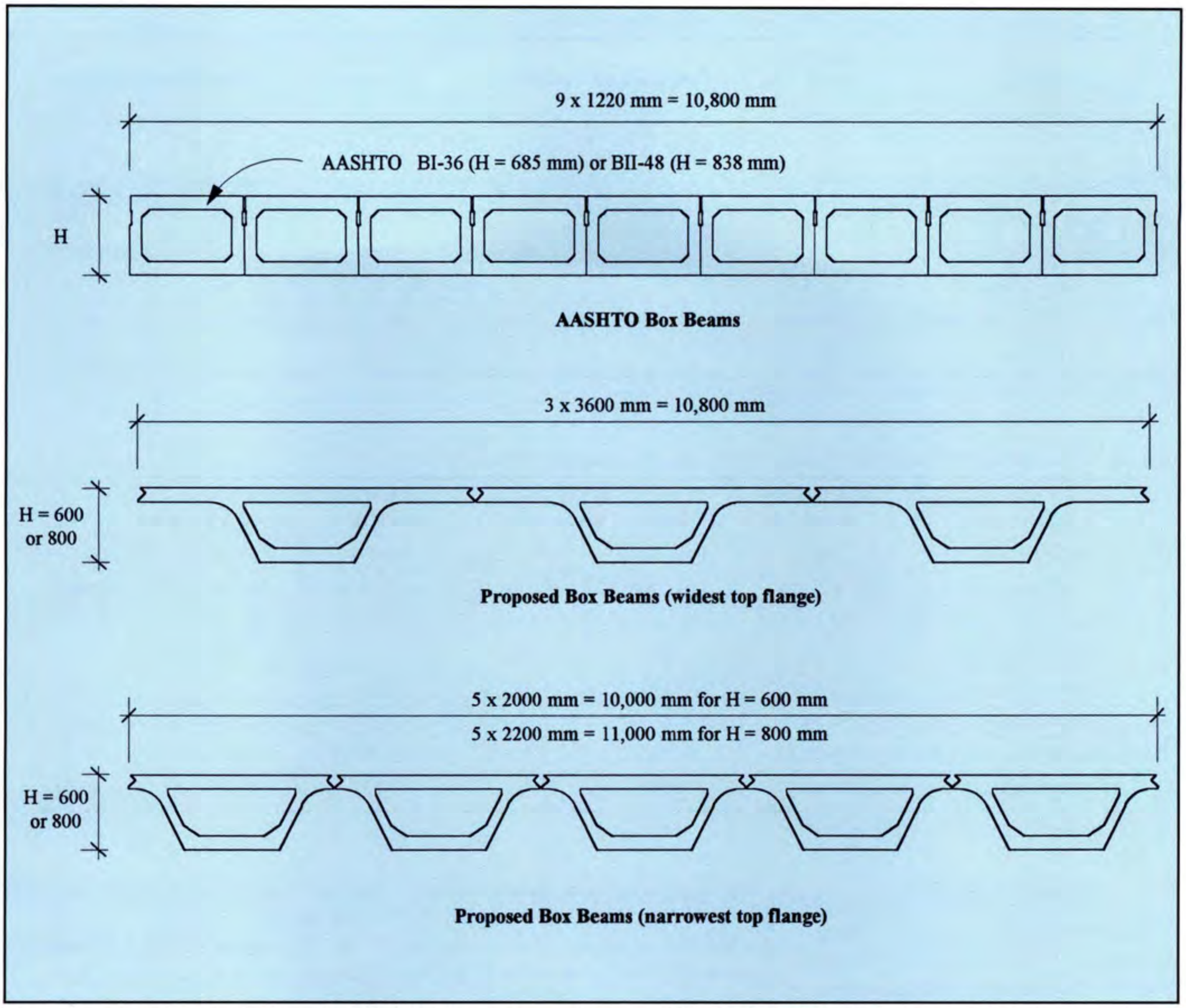


Fig. 10. Cross section of a bridge using AASHTO box beams and proposed box beams. **Note:** 100 mm = 3.937 in.

equivalent slab thickness; and (4) an efficiency factor ρ.

The efficiency factor ρ was developed by Guyon[15] and discussed by Podonly and Muller[16] and Rabbat and Russell.[9] It is based on maximizing section moduli for top and bottom fibers for a given cross-sectional area. It is given by:

$$\rho = \frac{I}{A y_b y_t} \tag{1}$$

where

I = moment of inertia of section

A = cross-sectional area

y_b = distance from center of gravity to bottom fiber of section

y_t = distance from center of gravity to top fiber of section

Tables 3 and 4 give the comparison between the AASHTO box beams and the proposed closed and open beams. Note that the equivalent slab thickness and ρ coefficient for the open box beams are calculated based on composite section properties. From these tables, it can be concluded that:

1. The proposed box beams cover more area than the AASHTO box beams. The number of beams that need to be produced and installed is significantly reduced compared to the AASHTO box beams. Reduction ranges between 45 percent for the narrowest proposed beam and 67 percent for the widest proposed beams. This should result in higher construction speed and lower cost of the superstructure.

2. The proposed box beams have an average equivalent slab thickness of 60 percent of the AASHTO box beams, which results in reduction of superstructure weight and possible additional savings in the substructure and foundation.

3. The proposed box beams can span up to 95 ft (29 m), which is comparable to the AASHTO box beams.

4. The efficiency factor, ρ, of the proposed box beams is comparable to that of the AASHTO beams. It ranges between 80 and 99 percent of that of the AASHTO box beams. This efficiency factor, however, only relates to allowable flexural stress design. It does not reflect the many other factors that represent total bridge cost.

5. No transverse post-tensioning is needed for the proposed box beam compared to the adjacent boxes, which reduces the cost and time of erection.

Table 3. Comparison between AASHTO box beams and proposed closed beams.*

Parameter	AASHTO Box B I-48	Proposed 600 closed box		AASHTO Box B II-48	Proposed 800 closed box	
Width, mm (ft)	1220 (4)	2000 (6.56)	3600 (11.81)	1220 (4)	2200 (7.22)	3600 (11.81)
Depth, mm (in.)	685 (27)	600 (23.6)	600 (23.6)	838 (33)	800 (31.5)	800 (31.5)
Maximum span, m (ft)	30.5 (100)	23.8 (78)	18.3 (60)	35 (115)	29.0 (95)	23.2 (76)
Width-to-depth ratio	1.8	3.3	6.0	1.5	2.75	4.5
Span-to-depth ratio	44.4	39.0	30.0	41.8	36.3	29.0
No. of pieces	9	5	3	9	5	3
Equivalent slab thickness, mm (in.)	366 (14.4)	290 (11.4)	227 (8.9)	398 (15.7)	300 (11.8)	183 (7.2)
$\rho = I/Ay_b y_t$	0.522	0.447	0.423	0.539	0.519	0.508

* f'_{ci} = 6200 psi; f'_c = 7500 psi; HS20 AASHTO truck load.

Table 4. Comparison between AASHTO box beams and proposed open beams.*

Parameter	AASHTO Box B I-48	Proposed 600 open box		AASHTO Box B II-48	Proposed 800 open box	
Width, mm (ft)	1220 (4)	2000 (6.56)	3600 (11.81)	1220 (4)	2200 (7.22)	3600 (11.81)
Depth, mm (in.)	685 (27)	600 (23.6)	600 (23.6)	838 (33)	800 (31.5)	800 (31.5)
Maximum span, m (ft)	35.1 (115)	21.3 (70)	17.1 (56)	36.6 (120)	26.2 (86)	21.6 (71)
Width-to-depth ratio	1.8	3.3	6.0	1.5	2.75	4.5
Span-to-depth ratio	51.1	35.6	28.4	43.6	32.8	27.0
No. of pieces	9	5	3	9	5	3
Equivalent slab thickness, mm (in.)	366 (14.4)	241 (9.5)	197 (7.7)	398 (15.7)	249 (9.8)	207 (8.2)
$\rho = I/Ay_b y_t$	0.522	0.453	0.421	0.539	0.503	0.490

* f'_{ci} = 7400 psi; f'_c = 9000 psi; HS20 AASHTO truck load.

CONCLUSIONS

A precast concrete box beam system is proposed. It can span up to 95 ft (29 m), for the depths and concrete strengths considered in this study. The maximum beam weight is 53.3 tons (48.3 t). The new system can be an attractive alternative to adjacent box beam and the I-beam systems as shown below:

1. The proposed box beam family has a high span-to-depth ratio, ranging between 30 and 40, compared to I-beam bridge values of 20 to 25. This makes it more suitable for low clearance sites and bridge replacement projects.

2. Removable wood forming for the CIP topping slab is not required. This may significantly reduce the cost and time of construction, compared to I-beam bridges.

3. A large deck surface area can be covered with a few precast concrete pieces. For example, a 35.4 ft (10.8 m) wide bridge deck requires only three of the proposed 11.8 ft (3600 mm) wide box beams as compared to nine 4 ft (1219 mm) wide AASHTO box beams. This results in higher construction speed and lower erection cost.

4. The relatively flexible flanges of the proposed boxes are made continuous, thus, controlling the longitudinal joint cracks commonly encountered in AASHTO box beams. No transverse post-tensioning is required. Maintenance cost is minimized and the expected life of the bridge is increased.

5. The relatively low weight of the proposed beams makes it attractive for bridges where heavy lifting equipment is not available.

6. Fabrication of the proposed beam can be competitive with AASHTO box beams and I-beams. A significant advantage is that there is no need to move the two side forms apart to remove the beam.

7. The cast-in-place topping provided with the open beam gives a smooth riding surface and allows for simple field adjustment of the roadway surface.

8. The proposed beam is aesthetically pleasing because of its curved lines.

ACKNOWLEDGMENT

This paper is an extension of the research that was carried out by Dr. Mounir Kamel under the sponsorship of a Daniel P. Jenny Fellowship titled "Efficient Shallow Bridge Deck System Using Standard Concrete Shapes." The authors would like to thank the Precast/Prestressed Concrete Institute and the Center for Infrastructure Research at the University of Nebraska for providing funding for this project.

The authors thank Gary Krupica of HDR Engineering, Inc. for his contributions to the finite element transverse analysis.

Acknowledgment is due to Scott E. Olson, Rita Seraderian, Alvin Ericson, Sreenivas Alampalli, and George Nasser for their valuable comments and suggestions.

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