The New Texas U-Beam Bridges: An Aesthetic and Economical Design Solution

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A new precast, prestressed concrete beam was recently developed by the Texas Department of Transportation. Aesthetics and economy were primary design considerations for this open-top trapezoidal beam. Two U-beam bridge projects are currently under contract, with production of the U-beams due to begin in the fall of 1993. This paper discusses the development of the U-beam, including design, production and construction aspects. Cost comparisons with other bridge systems are also given together with anticipated usage of the U-beam.

During the 1920s and 1930s, aesthetics was a major design consideration in the construction of bridges in Texas. This was expressed primarily through railing treatments and substructure shapes. Many of the ornate and/or unusual bridges constructed during that period have been given historical status during recent years.

After World War II, the more basic concerns of economy and durability, however, took the forefront with the introduction of prestressed concrete in North America. In 1950, the Walnut Lane Memorial Bridge in Philadelphia, Pennsylvania, was the first major prestressed concrete bridge built in the United States. The entry of Texas into prestressed concrete bridge construction occurred in 1952, when two 30 ft (9.1 m) standard slab-and-girder spans were post-tensioned together to make a 60 ft (18.3 m) prestressed span.

The Federal Aid Highway Act began the interstate highway network in 1956, escalating highway construction and, concomitantly, the need for economical and durable prestressed concrete bridges and other structures. That same year, the first significant prestressed concrete beam bridge in Texas was constructed over the Corpus Christi Harbor; the 2000 ft (610 m) bridge was composed of 40 and 60 ft (12.2 and 18.3 m) specially shaped beams that were precast at the jobsite and post-tensioned in place. During this same period, Texas was developing standard beam shapes that were suitable for pretensioning or post-tensioning applications.

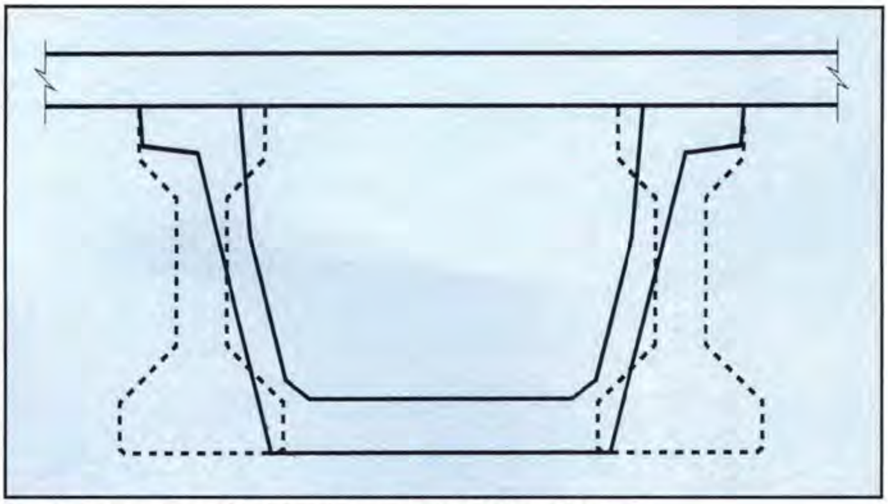

Fig. 1. Comparison of I-shaped beams with U-shaped beams.

THE CHALLENGE

Although the driving forces behind innovation in bridge design at the Texas Department of Transportation (TxDOT) have remained economy, durability, function and safety, today aesthetics is again being considered, albeit with caution since aesthetic designs are typically more costly. The renewed emphasis toward aesthetics in bridge design has come from within the department and from the public. The basic philosophy at the TxDOT now is to develop aesthetically pleasing alternatives for the more visible bridges, but to do so at costs that are competitive with standard designs.

The state system has 33,300 bridges, and the city and county system has 14,500 bridges, for a total of 47,800 bridges in Texas. Of these, almost 14,400 are "structurally deficient" or "functionally obsolete," and require rehabilitation or replacement at an estimated cost of $5.3 billion. Such enormous needs, within limited budgets, require increasingly innovative thinking and state-of-the-art engineering practice in the planning, design and construction of bridges.

Through the years, the TxDOT has used various types of bridge construction: simple pan-form and slab-span structures, complex post-tensioned gull wing railroad structures, post-tensioned slabs, segmental, simple and continuous trusses, steel curved girders, strutted girders and box girders. Over the past couple of years, an average of 500 structures per year have been let to contract. The serviceability and long-term maintenance advantages of precast, prestressed (pretensioned) concrete beams, in combination with their substantial economy, moved this type of construction to the forefront in the early 1960s.

Extremely good performance has been obtained from prestressed concrete beams produced in Texas precasting plants. The most common and cost-effective bridge span continues to consist of simply supported prestressed (pretensioned) concrete I-shaped beams, such as the AASHTO Type IV beam [spans to about 120 ft (36.6 m)] and the Texas Type C beam [spans to about 90 ft (27.4 m)]. The current average total cost of cast-in-place slab and prestressed concrete I-shaped beam bridges in Texas is $31.67 per sq ft, including substructure. This compares to an average cost of $41.21 per sq ft for steel bridges.

Although the prestressed concrete I-shaped beam bridge is both durable and economical, the beams are spaced relatively close together with numerous visual breaklines along the side face of the bridge. To some observers, this is considered to be unattractive. This perception of being unattractive may be due, in part, to the large number of prestressed concrete beam bridges in Texas; something common may eventually be considered unattractive even though still functional.

DEVELOPMENT OF THE U-BEAM

To achieve the desired aesthetics, yet maintain the economy of precast, prestressed beams manufactured under controlled plant conditions, a new shape was developed. The number of beams and the number of visual breaklines have been reduced by replacing the I-shaped beams with more widely-spaced beams having smoother lines, as compared in Fig. 1. The result is the U-beam, a trapezoidal open-top section with sloping webs.

Metrication

As shown in Fig. 2, the U-beam was developed in metric dimensions, in anticipation of the FHWA mandate that all federally funded construction plans be specified in metric (SI) units after September 1996. Depths were maintained approximately the same as existing beams, primarily to facilitate widening of existing structures.

Cooperative Development Process

The development of the U-beam involved many people. The original concept of a Texas open-top trapezoidal shape was conceived in the late 1980s by Robert L. Reed, who retired as head of bridge design at the Division of Bridges and Structures in 1985. He was instrumental in the early developmental stage, and gave the beam its name, the "U-beam." The Division of Bridges and Structures also has a highly motivated and innovative group of engineers and engineering technicians in-house, and several persons have contributed significantly to the development of the U-beam.

In addition, the TxDOT is fortunate to have an excellent working rela-

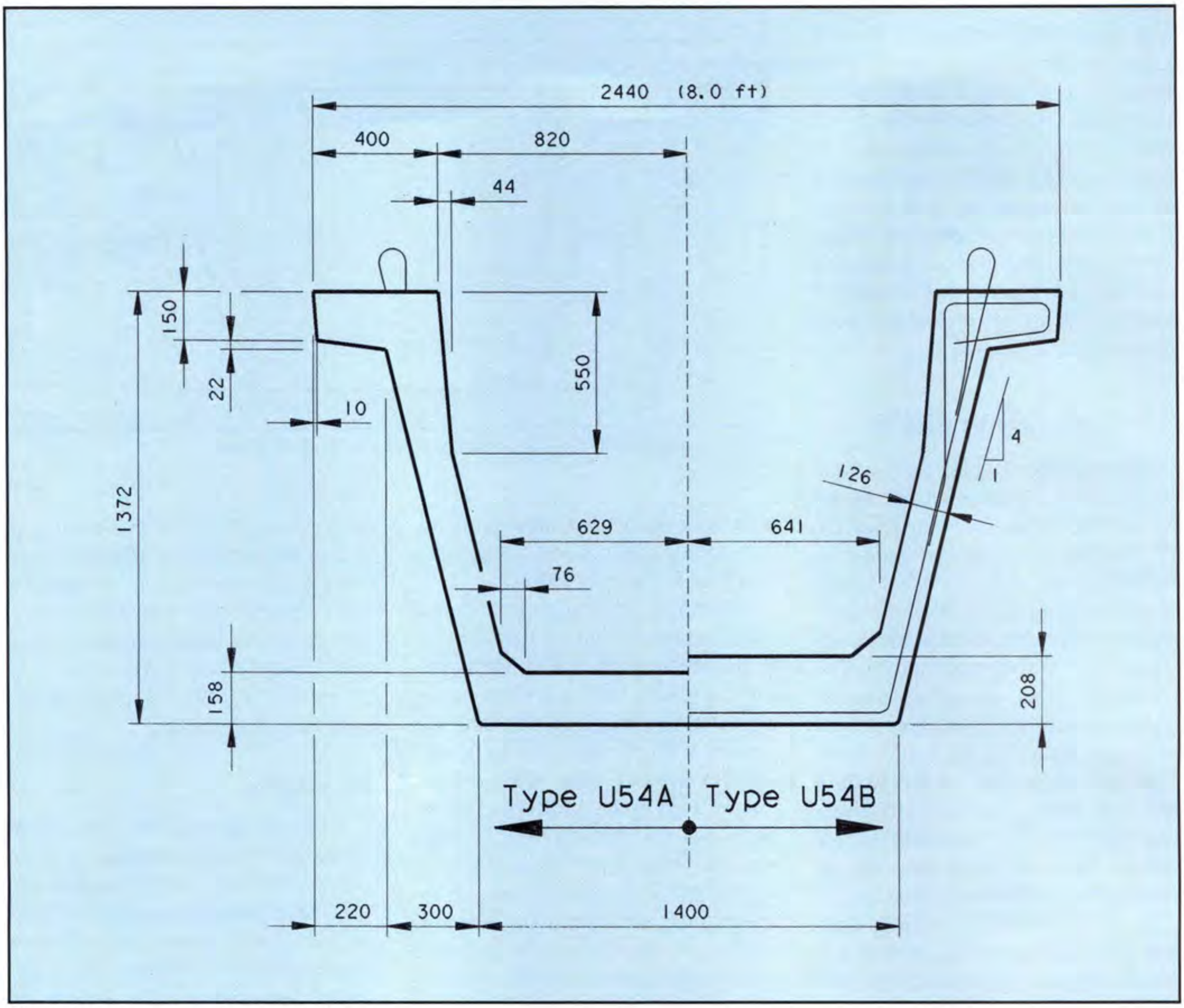

Fig. 2. Cross section of Type U54 beam.

tionship with the Precast Concrete Manufacturers Association of Texas (PCMAT), which has members from most of the precasting plants in the state. Meetings between the TxDOT and the PCMAT are usually held twice a year, with the agenda consisting of many topics of mutual concern, all related to getting the best and most trouble-free and constructable bridge at a fair price to both precast producers and the TxDOT.

Shortly after preliminary details of the U-beam were distributed to the precast producers at one PCMAT meeting, one of the participating plants took the initiative, at their cost, to construct a full-scale mock-up of the end region reinforcement prior to any contract being advertised. This enabled the engineers and the precaster to actually see the details and modify them as needed, within design constraints, to simplify the production process.

In addition to the major contributions provided by the PCMAT, good input was also received from other states, precasters and consultants, and from engineers at the TxDOT district offices. The Louisiana Department of Transportation contributed its own open-top trapezoidal beam experience, and this information was invaluable during the developmental stage.

Cross Section

The Type U54 beam shown in Fig. 2 is 1372 mm (54.02 in.) deep and is an aesthetic alternative to the 54 in. (1372 mm) AASHTO Type IV beam. Likewise, the Type U40 beam is 1016 mm (40.00 in.) deep and is an aesthetically pleasing alternative to the 40 in. (1016 mm) Texas Type C beam. The AASHTO Type IV beam and, to a lesser degree, the Texas Type C beam constitute most of the prestressed concrete beams used in Texas.

The U-beam is larger than any precast, prestressed concrete beam produced in Texas, having a bottom flange width of 1400 mm (4.59 ft), two top flange widths of 400 mm (15.75 in.) each, and web widths of 126 mm (4.96 in.). Sections with two standard depths have been developed, the U54 beam at 1372 mm (54.02 in.) and the U40 beam at 1016 mm (40.00 in.).

Note that the suffix A refers to a section with a maximum of two layers of prestressed strands in a 158 mm

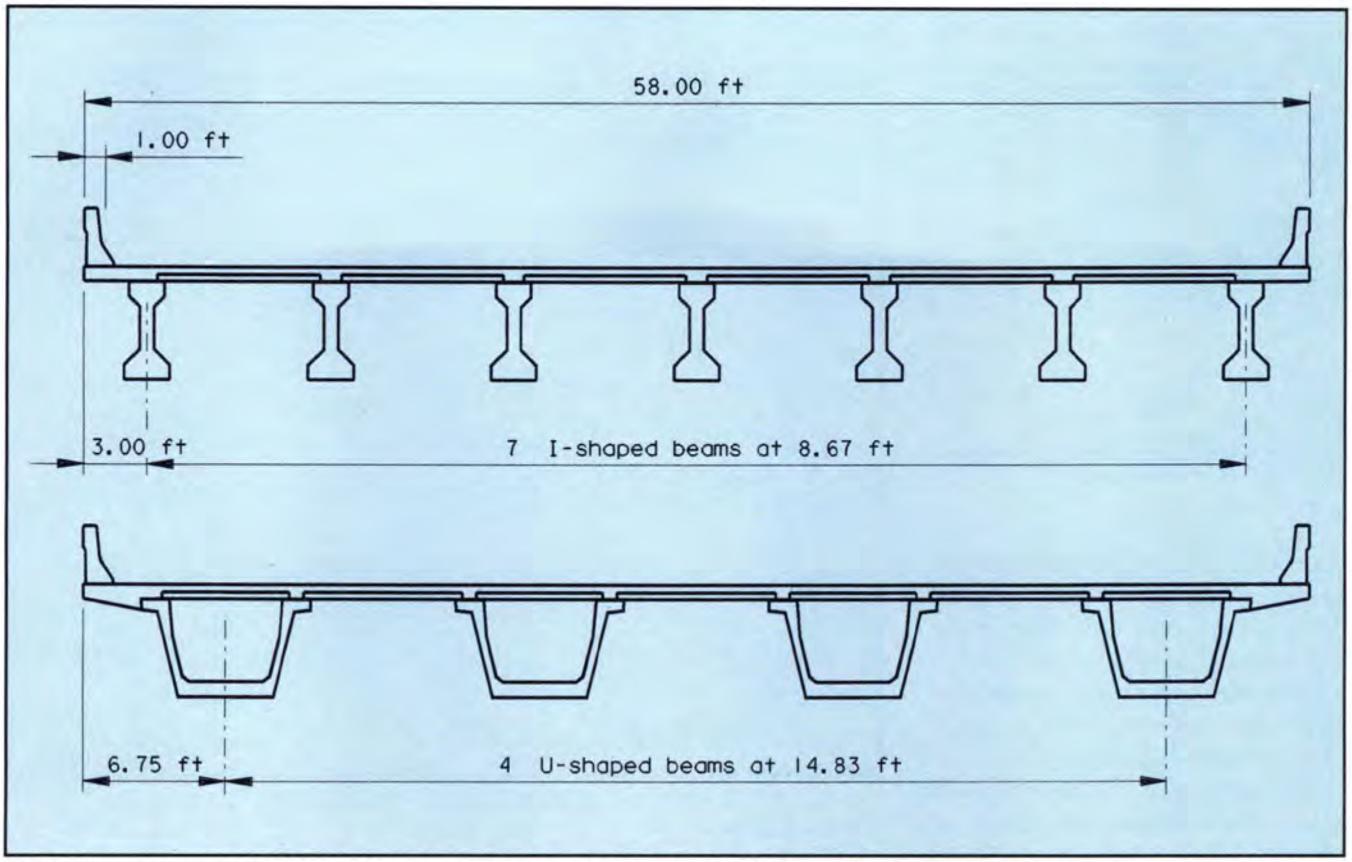

Fig. 3. Comparison of 56 ft (16.6 m) roadway cross section with AASHTO Type IV beams and U54 beams. Note: 1 ft = 0.3048 m.

(6.22 in.) bottom flange, and the suffix B refers to a section with three layers of prestressed strands in a 208 mm (8.19 in.) bottom flange.

The overall top flange width of the U54 beam is 2440 mm (8.01 ft). The 1372 mm (54.02 in.) depth was selected to allow the use of the U54 beam on widenings and retrofits of existing bridges with 54 in. (1372 mm) beams. A comparison of two structures can be seen in Fig. 3, which shows AASHTO Type IV beams and U54 beams for a 56 ft (17.1 m) wide roadway.

With an emphasis on economics in the development of the U-beam, every phase of beam design, beam production and bridge construction was examined to develop processes that are simple, yet as similar as possible to existing methods.

Design

Although the 54 in. (1372 mm) simple-span prestressed (pretensioned) concrete U-beam has been designed to a maximum span length approaching 130 ft (39.6 m), lengths greater than approximately 115 ft (35.1 m) may require 28-day concrete strengths higher than the maximum of 8000 psi (55 MPa) typically used in Texas. Longer span lengths may also require closer beam spacings, and this could result in a loss in the aesthetic quality of the overall structure.

Beam spacings in the 13 to 16 ft (3.96 to 4.88 m) range are preferred. The maximum span length for the 54 in. (1372 mm) U-beam is, therefore, comparable to the 120 ft (36.6 m) preferred maximum length of the 54 in. (1372 mm) AASHTO Type IV beam, and the maximum span length of the 40 in. (1016 m) U-beam is comparable to the 90 ft (27.4 m) preferred maximum length of the 40 in. (1016 m) Texas Type C beam. These span lengths are based on designs using HS20 loading.

A prime consideration in the development of the U-beam was the structural efficiency of the section. Several methods can be used to evaluate the section efficiency. The TxDOT decided to use the method developed by Guyon,[1] which has been discussed by Podolny and Muller[2] and Rabbat and Russell.[3] In essence, the efficiency factor can be expressed as the ratio of the moment of inertia of the section divided by the product of the area and the distances from the centroid of the section to the top and bottom fibers. Mathematically, the equation takes the form:

$$\rho = \frac{I}{A y_b y_t} = \frac{r^2}{y_b y_t}$$

where

ρ = efficiency factor of section
I = moment of inertia of section
A = area of cross section
y_b = distance from centroid of section to bottom fiber
y_t = distance from centroid of section to top fiber
r = radius of gyration of section $= \sqrt{I / A}$

The higher the efficiency factor, the more efficient the section becomes. A theoretical maximum efficiency factor of one results with thin top and bottom flanges and webs of negligible thickness. As indicated in Table 1, both the U54A and the U54B are more effi-

Table 1. Comparison of efficiency and weight of I-shaped and U-shaped beams (see text and Refs. 1, 2 and 3).

Beam type	Efficiency factor	Weight (kips per linear ft)
AASHTO Type IV	0.456	0.82
U54A	0.516	1.07
U54B	0.509	1.17
Texas Type C	0.426	0.52
U40A	0.505	0.92
U40B	0.485	1.02

Note: 1 kip per ft = 0.00148 kg/m.

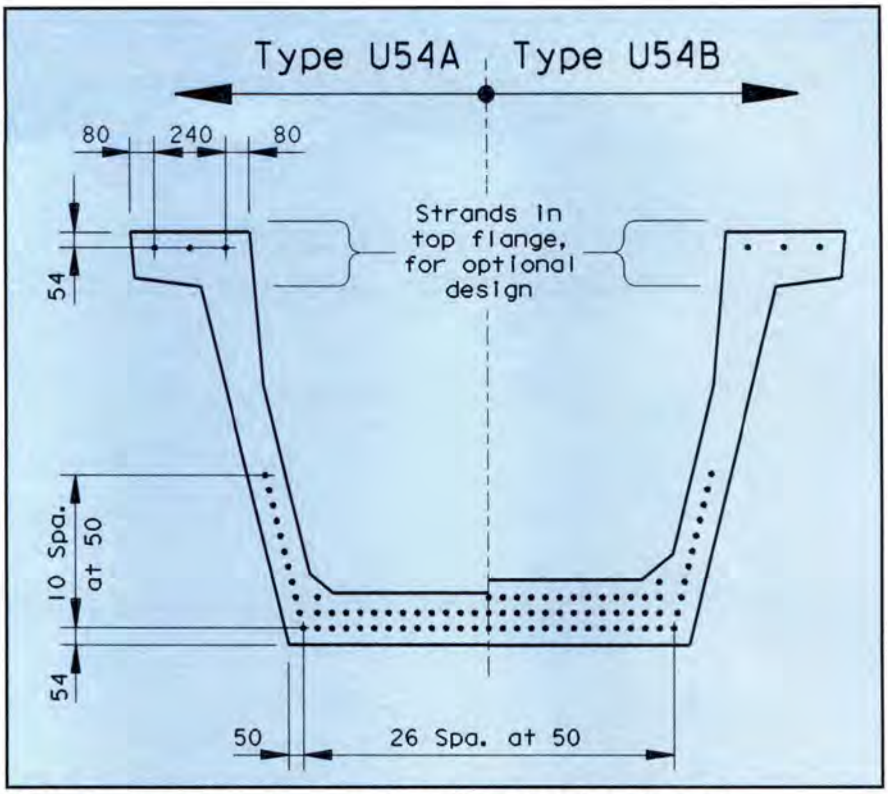

Fig. 4. Prestressed strand patterns. Note: Dimensions in millimeters; 1 mm = 0.0394 in.

cient than the AASHTO Type IV beam. Likewise, both the U40A and the U40B are more efficient than the Texas Type C beam.

Beam weight was also a consideration. As shown in Table 1, the I-shaped beams have lighter sections, but because they are more closely spaced than U-beams, 1.7 to 2.0 times as many I-shaped beams are typically required per span. Therefore, the total weight of a U-beam span is usually less because the reduced number of U-beams more than offsets the additional beam weight, particularly with the 54 in. (1372 mm) beams.

A secondary benefit of the reduced superstructure dead weight is a reduction in substructure, with fewer and/or smaller columns required. The foundation requirements for the total structure are likewise reduced. In addition to these economic advantages, the cleaner visual lines enhance the appearance of the total structure.

Maximum concrete strengths in U-beam designs are usually the same as those for I-shaped beams and box beams. These strengths are approximately 6000 psi (41 MPa) at release and 8000 psi (55 MPa) at 28 days. The U-beam is stressed with standard 0.5 in. (12.7 mm) diameter 270 ksi (1862 MPa) low-relaxation strands on a 50 mm (1.97 in.) grid, as shown in Fig. 4.

A maximum of 74 strands in the U54A and U40A beams and 99 strands in the U54B and U40B beams may be placed in the lower flange and webs. Strands are straight and are debonded in the end regions as required. Depressed strand arrangements for the web strands are not anticipated until possibly later in production development.

As indicated in Fig. 4, an optional strand pattern with four or six strands in the top flanges may be used. Use of this option allows debonding in the end region to be minimized and required only in the top layer of bottom-flange strands. Strands in the top flanges may be debonded in the middle quarter to a third of the span and then cut at midspan so that no force is applied in the debonded midspan region.

The U-beams are typically designed to the same debonding criteria as used in standard Texas box-beam designs. The criteria are a minimum of six bonded strands in the bottom row, a maximum of 75 percent debonded strands per row and per section, and a maximum debonding length of 20 percent of the span, not to exceed 15 ft (4.57 m). These values are currently being evaluated based on recently completed research on debonding that was conducted at The University of Texas at Austin by Ned H. Burns, Ph.D., and others.

Live Load Distribution

Highway bridges in Texas are currently designed for HS20 live loads. A significant design concern with the U-beam was appropriate lateral distribution of these loads. Spread box beams are governed by Article 3.28, "Distribution of Loads for Bending Moment in Spread Box Girders," in the 1992 AASHTO *Standard Specifications for Highway Bridges*.[4] Several of the specification limits were exceeded in the designs for interior U-beams. Many designs required fewer than four beams or more than 10 beams, a beam spacing of greater than 11 ft (3.35 m) and/or roadway widths of less than 32 ft (9.75 m) or greater than 66 ft (20.1 m).

To resolve the concern about adequacy of existing specification guidelines, a procedure was developed for the determination of the live load distribution that included evaluation of five cases:

- Case 1 used the current AASHTO distribution for interior beams.
- Case 2 was the same as Case 1 except that the assumed roadway width was limited to 66 ft (20.1 m),

with a corresponding decrease in number of beams.

- Case 3 was a lower bound limit of 90 percent of the distribution for conventional beams at the same spacing.
- Case 4 was taken from the Load and Resistance Factor Design (LRFD) specifications for prestressed concrete spread box beams, which is based on NCHRP Report 12-26/1, "Distribution of Wheel Loads on Highway Bridges."[5]
- Case 5 results from assuming hinges at interior flanges, and is calculated for exterior beams in accordance with AASHTO, and for interior beams with beam spacings greater than 11.5 ft (3.5 m), in accordance with the NCHRP report cited.

The largest live load distribution from these five cases is used in the design of the U-beams. For interior beams, Case 4 (LRFD, spread box) controls most frequently, followed by Case 1 (AASHTO, spread box). For exterior beams, Case 4 again typically controls, followed by Case 5. Case 2 occasionally controls interior beams, whereas Case 3 does not typically control. In general, the new LRFD distribution will give the most conservative distribution for the subject types of beams.

The procedure for calculating distribution using the previously described five cases may appear cumbersome. The method is believed to be appropriate, however, until more specific spread-box studies are performed with higher-level computer models for various parameters, including span lengths, roadway widths, number of beams and beam spacings.

Production

The closed-top box beam, while quite efficient, has historically been more costly and difficult to consistently manufacture than I-shaped prestressed concrete beams, mainly due to problems in placing concrete around internal void forms. In the one-stage monolithic casting method, the void form is tied into position prior to concrete placement, and is typically of polystyrene at a cost similar to an equivalent volume of concrete. Precast producers in Texas generally prefer this method, in which the concrete is initially poured down one web and vibrated across the bottom flange; the concrete is then poured down the other web and across the top flange.

Problems occur because buoyancy forces resulting from the concrete under vibration often displace the void form upward and sometimes laterally. In addition, if the mix is not well designed, or if casting procedures are not followed exactly, consolidation problems may occur in the bottom flange concrete below the void form. This is of particular concern since the bottom flange cannot be visually inspected, and, therefore, no reliable means is available for determining whether unintentional voids have formed at locations along the length of the beam.

Although one precast producer uses the two-stage monolithic casting method for box beams, precasters in Texas typically prefer the one-stage method for beams with internal voids. The two-stage method requires casting the bottom flange, securing the void form, placing the top flange reinforcement, then vibrating the web concrete into the already-cast bottom flange while the bottom flange concrete is still plastic. In Texas, especially in the hot summer months, this can be a real challenge!

The inherent problems associated with the internal voids in closed-top box beams were largely responsible for the decision to develop a trapezoidal beam with an open top, thus eliminating the possibility of such problems. Significant effort was made in the development of the U-beam to streamline the anticipated production process. Chamfers at the top of the bottom flange, as shown in Fig. 2, are used to allow a more efficient flow of concrete, which is especially important for the one-stage monolithic casting method.

Drafts are provided on all form surfaces except the bottom to facilitate form removal. This allows the interior form to be lifted up and the side forms moved out, similar to all I-shaped sections. The interior form can be one unit or split, as shown in Fig. 5. The split form allows direct vibration of the concrete in the bottom flange, with relatively equal web pouring. Proper consolidation of concrete can thus be assured.

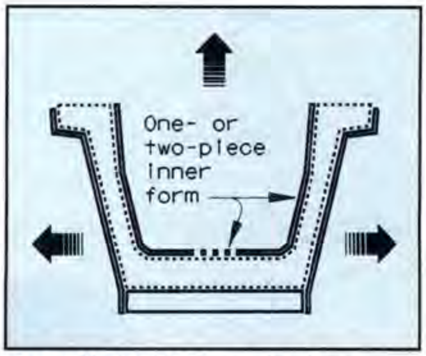

Fig. 5. Method for removing form.

THE U-BEAM BRIDGE

As shown in Fig. 6, the outside edge of the exterior U-beam top flange is embedded in the deck overhang, creating a smooth line from edge of deck to web of beam. Also note that, for the 26 ft (7.92 m) roadway, the number of U-beams per span is reduced to half the number of I-shaped beams required.

Precast Concrete Panels

Precast, prestressed concrete panels were introduced in 1963 as part of the composite deck for Texas bridge construction. The panel provides approximately half the deck thickness. Texas has invested significant time and money in research on this highly successful deck construction method.

In 1976, the bid item "Reinforced Concrete Slab" was introduced, which changed the traditional measurement from cubic yards of concrete to square feet of bridge deck. The contractor has the option of using conventional forms, stay-in-place metal deck forms, or precast, prestressed concrete panels. Precast, prestressed concrete panels are the preferred method in Texas for constructing decks on most prestressed concrete beam bridges and some steel beam bridges, with the panels quickly providing a convenient and safe working surface for the remaining cast-in-place deck construction.

Although no exact data on precast concrete panel usage exist, a check with the largest precast beam produc-

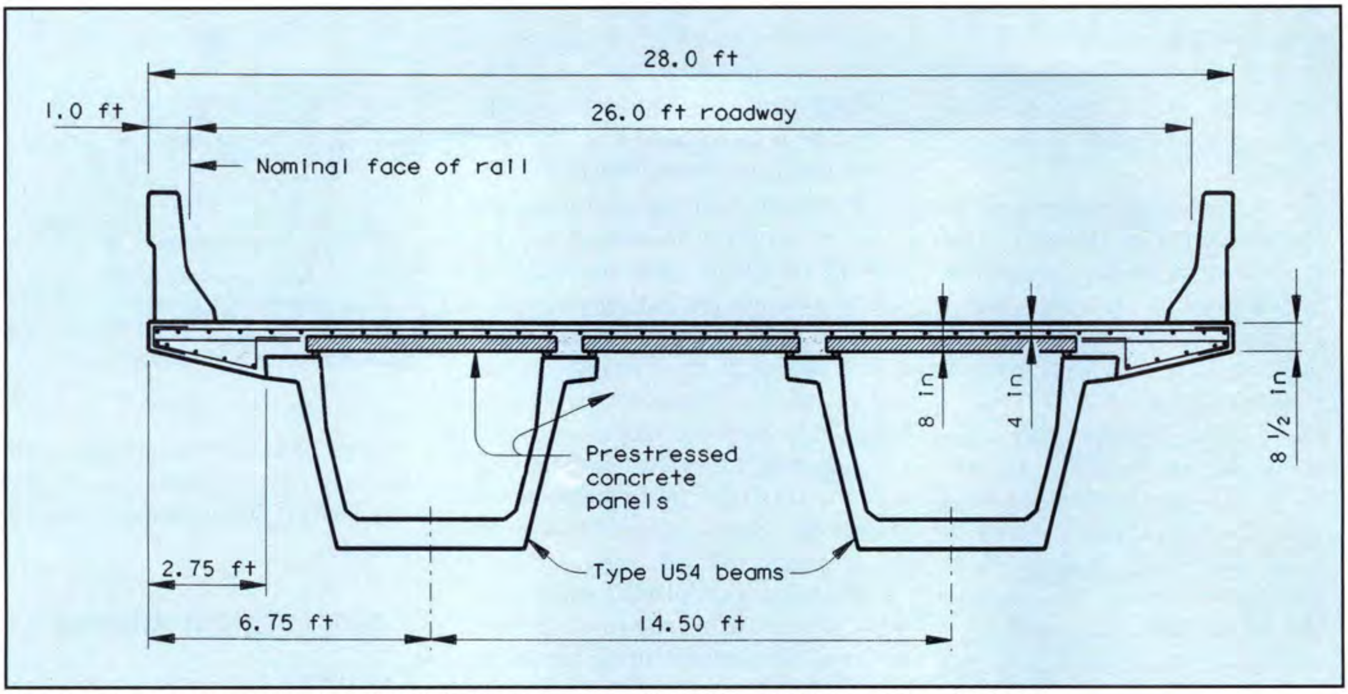

Fig. 6. Typical transverse section of 26 ft (7.92 m) roadway. Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm.

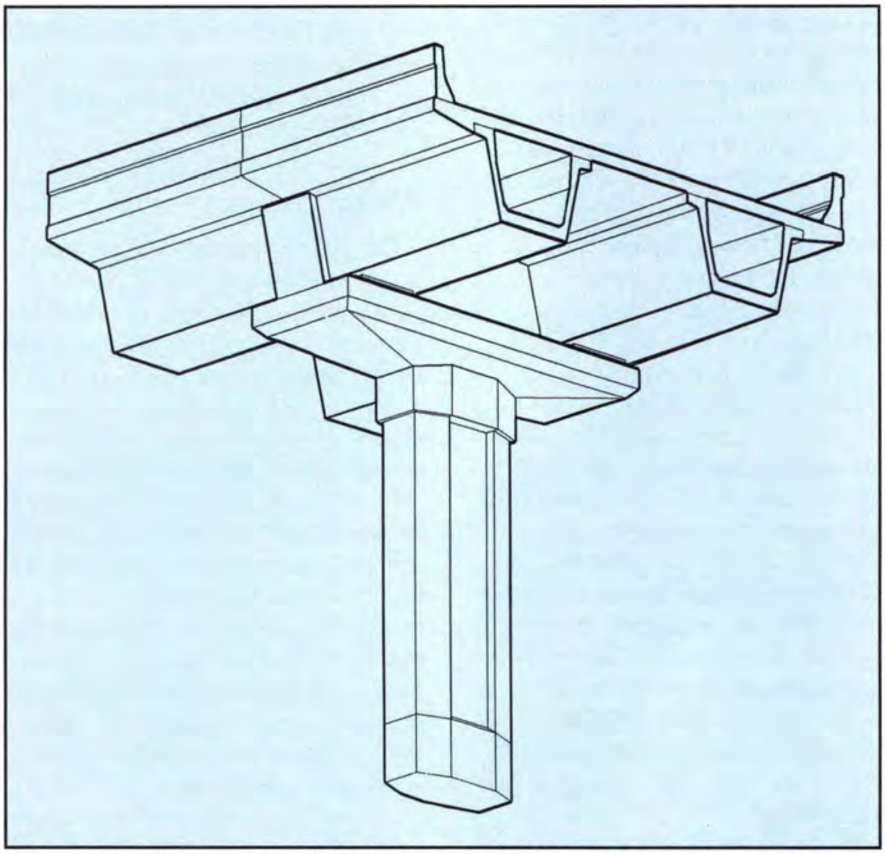

Fig. 7. Isometric of a typical 26 ft (7.92 m) roadway superstructure and preliminary single-column bent.

ers and consultants who prepare shop drawings indicate that approximately 75 percent of all prestressed concrete beam bridges in Texas are constructed with these panels. It is anticipated that precast concrete panels will continue to be preferred, and, therefore, the U-beam span details show precast concrete panels as the deck-forming method, with permanent metal deck forms allowed as an option.

Construction

One goal for U-beam construction was to minimize changes to usual construction methods. As shown in Fig. 3, precast concrete panels span between I-shaped beams, and also between and over the U-beams. The same applies to permanent metal deck forms, should the contractor select that deck-forming method. There is no difference in deck construction between a prestressed concrete I-shaped beam span and a U-beam span except for the forming of the sloping overhang. Even for the overhang detail, the brackets required are similar to those required for conventional construction.

To further simplify construction, a constant minimum composite deck thickness of 8 in. (203 mm) is used, with 60 ksi (414 MPa) reinforcing steel. The strength of the deck concrete has been changed from 3600 to 4000 psi (25 to 28 MPa) in the recently released TxDOT 1993 *Standard Specifications for Construction of Highways, Streets and Bridges.*[6]

Neoprene pads provide the bearing at supports. One large pad at one end and two smaller pads at the other end

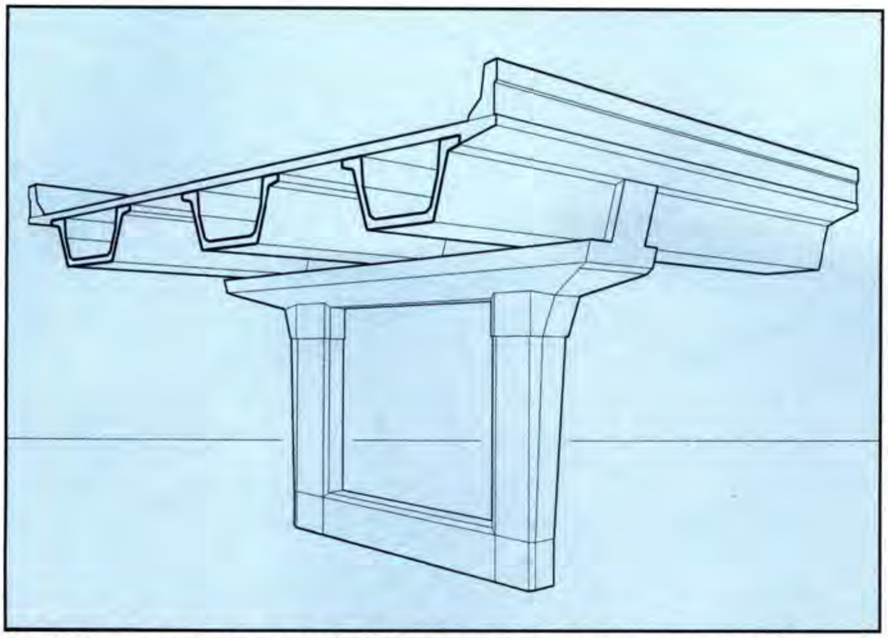

Fig. 8. Perspective of a typical 38 ft (11.58 m) roadway superstructure and preliminary two-column bent.

are used to eliminate the tendency of the beam to rock when placed on supports.

STANDARDS

To minimize the time required for design of various U-beam structures and to facilitate uniformity and, therefore, economy of bridge construction, a number of U-beam standard details have been developed. These standards are added to the contract plans, thereby also reducing the number of details required on the abutment, bent and span drawings for uniquely designed bridges.

In addition to details specific to the U-beam itself, other standard details include: (1) bearing build-ups and bearing pads, (2) deck reinforcement at interior bents and in thickened deck at ends of units, (3) precast concrete panels and (4) permanent metal deck forms.

In conjunction with the U-beam standards developed to reduce the number of details required on bridge drawings, superstructure and substructure standards are being developed for specific roadway widths and span lengths. Fig. 7 is an isometric rendering of the 26 ft (7.92 m) roadway at a single-column bent, while Fig. 8 is a perspective of the 38 ft (11.6 m) roadway at a two-column bent. The bents shown in these two figures are in the initial developmental stage.

FINITE-ELEMENT ANALYSES

During the U-beam development process, simplified finite-element models of the beam were evaluated under various loads. One typical model is shown in Fig. 9. Both a square-end model and a skewed-end model were evaluated. Also, a three-support model and a four-support model were studied to allow evaluation of the three-pad design. Hauling effects were also evaluated, although currently no specifications govern the transportation of beams; the only requirement is that the beams be erected with no visible cracking.

Results from the finite-element analyses showed no unusual behavior. Even during an assumed severe hauling twist, the analyses showed stresses to be comparable to those of typical I-shaped beams. Therefore, construction methods for U-beam bridges will follow those used for standard prestressed I-shaped beam bridges.

COST COMPARISONS

U-beam bridges are anticipated to be competitive in cost with prestressed concrete I-shaped beam bridges. Prior to the first U-beam project, which was let in March 1993, an estimate of beam cost was made. Fig. 10 presents beam cross-sectional area vs. average bid price for various prestressed concrete beams; this has been found to be a reasonable method for cost comparison.

After precast producers have amortized the U-beam formwork and precast bed modifications, it is believed that the price will approach \$60 to \$70 per linear foot. Although the price per foot of U-beams is expected to remain higher than for I-shaped beams, bridges constructed with U-beams should be competitive with bridges constructed with I-shaped beams due to the lower number of U-beams per span and the typically reduced superstructure and substructure dead weights.

The low bid on the first U-beam project was \$40.27 per sq ft, including substructure. Seven contractors bid on the project, with U-beam prices ranging from \$86.00 to \$132.60 per linear foot; the low bid went to the contractor with a U-beam price of \$120.00 per linear foot. The beams for this project are expected to be cast in the fall of 1993.

The low bid on the second U-beam project, let in June 1993, was \$30.50 per sq ft, including substructure. Six contractors bid on the project, with U-beam prices ranging from \$110.00 to \$140.00 per linear foot; the low bid went to the contractor with a weighted-average U-beam price of \$115.15. This project resulted in a second precasting plant's entry into U-beam production.

While the first two contracts have U-beam prices per linear foot higher than estimated, it is believed that, with competition and production efficiencies, the prices will eventually be within the range shown in Fig. 10. The U-beam transportation cost could be a somewhat higher percentage of the total cost per foot than for I-shaped beams because special transport equipment may be required. I-shaped beams can usually be transported with 5- to 7-axle pole-type rigs, while the heavier U-beams may require 8- to 10-axle rigs — which may possibly include additional jeep or dolly units.

The cost per square foot of total structure, as indicated by the low bids

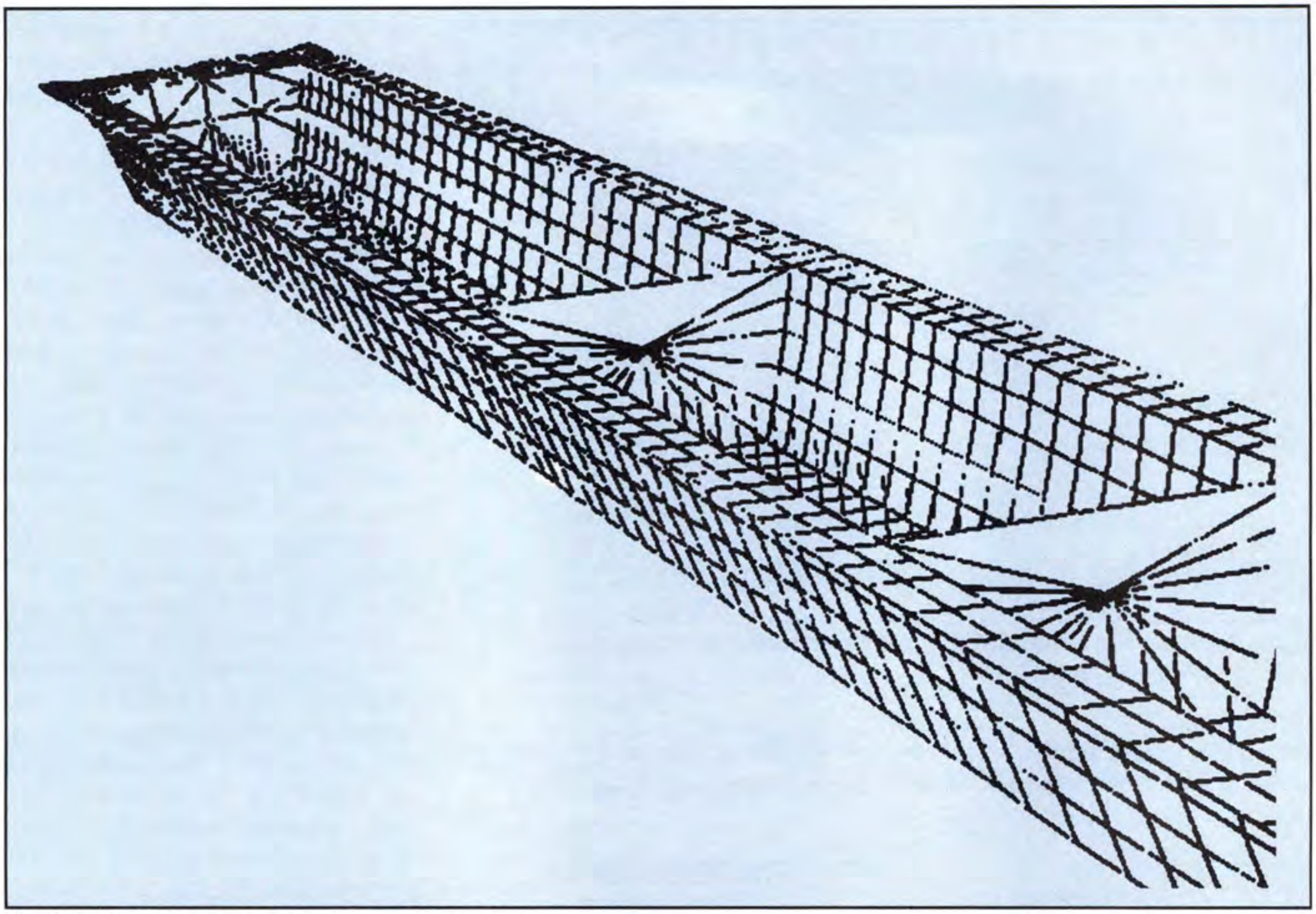

Fig. 9. Finite-element model used to analyze U-beam.

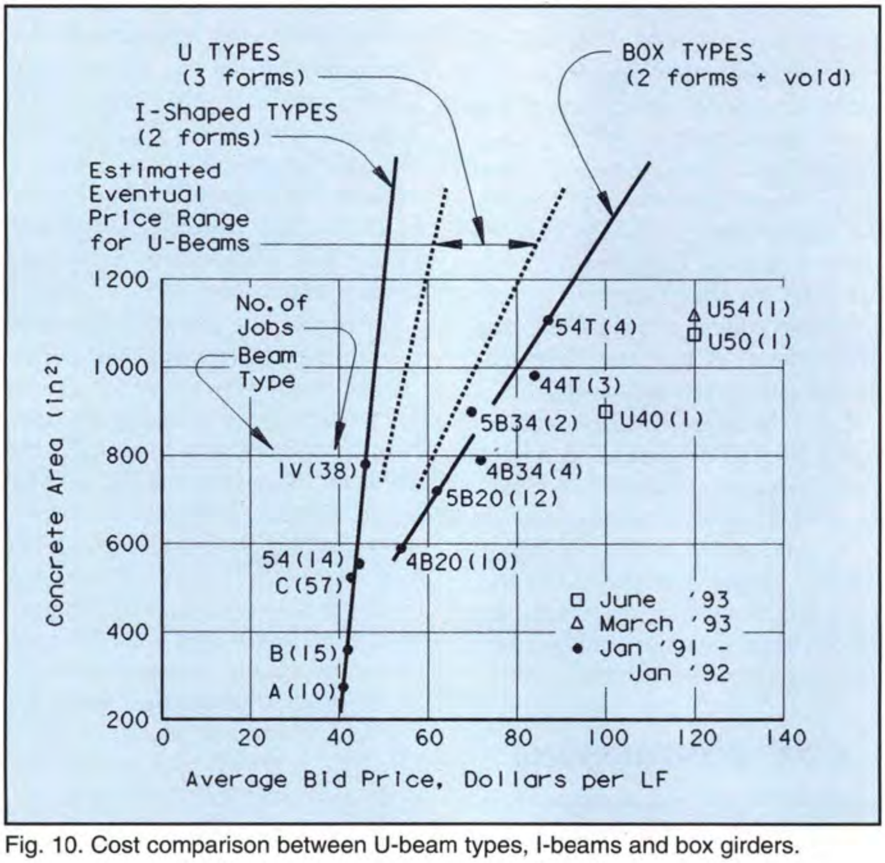

Fig. 10. Cost comparison between U-beam types, I-beams and box girders.

of \$40.27 for the first project and \$30.50 for the second project, can be favorably compared to conventional prestressed concrete I-shaped beam bridge construction costs averaging \$31.67 per sq ft of total structure. The higher cost on the first project may be the result of difficulty in allocating costs for the U-beam spans relative to the costs of the numerous steel trapezoidal box beam units on that project. The second project had no steel beams, and the cost per square foot of total structure was approximately the same as for conventional prestressed concrete I-shaped beam bridge construction.

ANTICIPATED USAGE

In the past year, construction of precast, pretensioned concrete I-shaped beam bridges totaled over 3 million sq ft (278700 m^2) of bridge deck, representing approximately 65 percent of all bridge construction in Texas. It is anticipated that the majority of Texas bridge construction will continue with this mainstay and that U-beam bridges will be constructed at the more visible and/or urban locations where aesthetic structures are appropriate. Local public input for structure type selections is emphasized.

FUTURE DIRECTIONS

When production of U-beams begins in the fall of 1993, some details may be modified due to streamlining of the manufacturing process. In addition, variations to the basic design, including the use of depressed strands, may be expected with time.

The TxDOT is now coordinating a FHWA-sponsored research project with The University of Texas at Austin; two bridges will be constructed with U-beam concrete strengths in the 12,000 psi (83 MPa) range and with 0.6 in. (15 mm) diameter strands. These parameters may become the standard, or they may be expanded in years to come. It is anticipated that the future may also see post-tensioned applications with deeper, horizontally curved U-beam segments.

The responsibility of the TxDOT is to continually strive for more durable, economical and aesthetic structures, incorporating wherever possible the use of state-of-the-art design, production, construction techniques and materials. The development and implementation of the Texas U-beam bridge is considered to be a major step toward that goal!

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