Use of High-Strength Concrete in Prestressed Concrete Box Beams for Highway Bridges

JOHN J. SCHEMMEL AND PAUL ZIA

A study was conducted to determine the structural and economic benefits of using high-strength (6,000 to 12,000 psi) concrete in box beams for highway bridges. The goal was to establish a range of application of various beam designs in terms of span capacity. The study focused on long-span, simply supported, prestressed concrete box beams. The application of high-strength concrete was investigated in two ways. First, high-strength concrete was substituted for normal-strength concrete in the design of standard beam sections. Second, to improve structural performance, modifications were made to the geometry of the standard beams in conjunction with use of the high-strength material. In both cases a parametric study was performed to identify the most structurally efficient designs. Results indicate that the maximum attainable span of the box beam can be significantly increased by using high-strength concrete in conjunction with a modified internal void shape. In addition, attainable span lengths were generally longer and had ½-in. rather than 0.6-in. strands for the beam sections studied. Those designs found to provide the greatest structural benefit were subsequently examined for their relative cost-effectiveness. Comparisons were made on the basis of a total superstructure cost per square foot of bridge deck. For shorter span lengths, spread box beams 3 ft wide were found to be the most cost-effective. For longer spans, the 4-ft-wide adjacent box sections were less costly. Strand size does not appear to significantly influence the cost of a box beam.

A recently concluded study (1) conducted for the North Carolina Department of Transportation (NCDOT) examined the use of high-strength concrete in highway bridge applications. Interest in such research stemmed from the need for long-span bridges in the coastal regions of the state, as well as a recognition of the potential structural and economic advantages of high-strength concrete.

Long-span bridges are often necessary in coastal areas in order to ensure that navigational requirements are met. Generally, steel bridges are used for most long-span installations along the coast of North Carolina, because reinforced and prestressed concrete bridges have not been found to be as economical. However, steel superstructures are particularly susceptible to corrosion in this environment; thus they require frequent maintenance.

The use of high-strength concrete in a highway bridge structure offers many benefits and advantages. From a structural viewpoint, span lengths can be increased and dead loads reduced with the use of lighter and more slender cross sections. In terms of serviceability, durability is improved and deflections may be reduced because of the increase in stiffness. From the standpoint of overall economy, total project costs may be reduced because fewer elements are required.

Realizing that the advantages of high-strength concrete could be directly applied to design situations in the state, NCDOT initiated a research project to assess the extent to which this material might prove beneficial in highway bridge construction. This project examined both standard and modified girder, beam, and pier elements. Results (1) for the girder and pier elements considered were similar to the findings of others (2,3). Because of space limitations, only the findings relative to the box beams are presented.

OBJECTIVE

The primary focus of this investigation was the use of high-strength concrete in the girder and pier systems of a simple stringer-type bridge. The main objectives were to identify the structural and economic benefits of utilizing concrete with a compressive strength between 6,000 and 12,000 psi in these types of structural elements. This was to be accomplished by first establishing the range of application for various girder and pier designs in terms of their span length and axial load capacity, respectively. Then the cost-effectiveness of selected designs was evaluated by comparing their cost of construction.

APPROACH

Parametric studies were conducted to identify those box beam designs that provided the greatest structural benefits. The study was confined to simply supported, precast, pretensioned members. In addition to the standard AASHTO box beams, a number of modified sections were investigated. The box beams were evaluated for their maximum span length and the number of prestressing strands required for any given span. High-strength normal-weight concretes of 6,000, 8,000, 10,000, and 12,000 psi at 28 days were considered.

In order to identify the most cost-effective box beams, an economic study was made for those designs that had demonstrated superior structural benefits. The beams were evaluated on the basis of a total cost per square foot of deck over a range of spans. Unit costs for materials and labor were estimated using data from a number of sources.

J. J. Schemmel, 4190 Bell Engineering Center, Department of Civil Engineering, University of Arkansas, Fayetteville, Ark. 72701. P. Zia, Box 7908, Department of Civil Engineering, North Carolina State University, Raleigh, N.C. 27695.

On the basis of the results of the parametric and economic studies, recommendations were made regarding the most beneficial beam designs.

PARAMETRIC STUDY

The goal of this study was to determine the effect of various structural parameters, such as concrete strength and cross-sectional shape, on the span capacity of a box beam. To accomplish this, a detailed flexural analysis was performed on each of the beam designs considered. To facilitate this effort, computer programs were developed to handle the input, analysis, and output.

Program Development

The following is a brief overview of the analysis process used in this study. A more detailed description of the computer programs can be found elsewhere (*1*).

In the parametric study each analysis began by using the preprocessing routine to define the geometric and material properties of the structure to be analyzed. This included data relative to the bridge cross section, beam cross section, concrete and steel material properties, prestressing strands, loadings, and deflection limits. An important feature of this routine is the option to select a standard box beam shape or directly define a cross section for analysis.

The flexural analysis itself begins with the computation of the cross-sectional properties, loads, and moments. A general strand pattern, which is used in the placement of the prestressing strands, is also established at this point. Then an incremental or iterative process is invoked to determine the maximum span length of the beam, along with the relationship between span length and the required number of prestressing strands. With each increment in span, strands are added to the cross section as necessary until the extreme fiber stresses, ultimate strength, minimum reinforcement, and deflection requirements (when specified) are satisfied. Checks are made at both mid-span and span ends. The initial camber and live load deflection were computed for all beam designs. Although no limits were specified in either case, the deflections were not found to be excessive. The span length is continually increased in small increments until at least one design criterion can no longer be satisfied, regardless of the number of prestressing strands added to the section. The analysis is then terminated. Data generated by the flexural analysis are sent to the postprocessing routine to be formatted and printed. Pertinent data are also stored for use in the subsequent cost analysis.

In general, the flexural analysis routine conforms to the latest AASHTO (*4*) and NCDOT (*5*) design specifications. Before this routine was written, it was necessary to determine which parts of these specifications, if any, required modification to account for the use of higher-strength concretes. It was concluded, after an extensive review of the literature, that the majority of the AASHTO and NCDOT specifications still applied to the design of a prestressed box beam when high-strength concrete was used. The most notable differences between normal and high-strength concrete related to the

modulus of elasticity, modulus of rupture, and in some cases the creep of concrete. The equations recommended by ACI Committee 363 (*6*) for the modulus of elasticity (E_c) and modulus of rupture (f_r) were used in this study. These equations are

$$E_c = 40,000(f_c')^{1/2} + 1,000,000 \text{ psi} \qquad (1)$$

$$f_r = 11.7(f_c')^{1/2} \text{ psi} \qquad (2)$$

Some uncertainty remains regarding the creep of high-strength concrete. Although many studies report less creep with high-strength concrete, the effect of this on the loss of prestress has not been fully established. For this study it was assumed that the specific creep (creep strain/psi) would remain nearly the same as that for normal-strength concrete, because large prestressing forces would be required in some cases. Therefore, the prestress loss due to creep was based on the current AASHTO (*4*) equation. The AASHTO (*4*) equations for losses due to elastic shortening, shrinkage, and stress relaxation were also used. For shrinkage, the relative humidity was taken as 75 percent.

Scope

A typical 36-ft-wide bridge with two 12-ft traffic lanes, a cast-in-place deck, and standard New Jersey barriers was used in this study. The primary variables examined were the beam cross section, beam spacing, strand diameter, and concrete compressive strength.

The eight standard AASHTO box beams were investigated. A typical beam cross section is shown in Figure 1. These sections are either 3 or 4 ft wide with a depth that varies between 27 and 42 in. The shape, size, and location of the internal voids are such that thickness of the walls remains unchanged for all members. In addition to the standard shapes, two sections with modified internal voids were considered. The modified cross sections are shown in Figures 2 and 3. Type A has a bottom flange that is larger than the standard beam, as well as a thinner web. This cross section permits two rows of prestressing strand across the bottom. Type B has a wider web, which permits two columns of strand, and a slightly thicker bottom flange.

Both adjacent and spread box beam designs were investigated. For the spread box beams, only an 8-ft spacing was considered. This was in part because of the limits on spacing
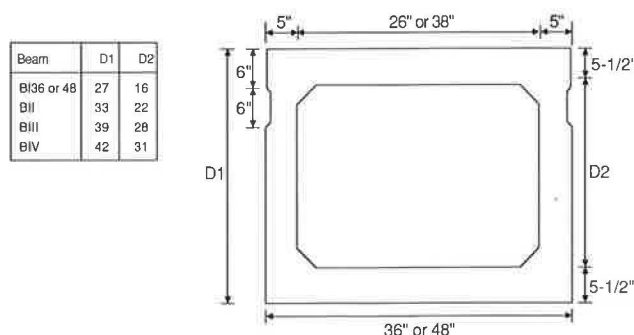

Beam	D1	D2
BI36 or 48	27	16
BII	33	22
BIII	39	28
BIV	42	31

FIGURE 1 Standard AASHTO bridge box beams.

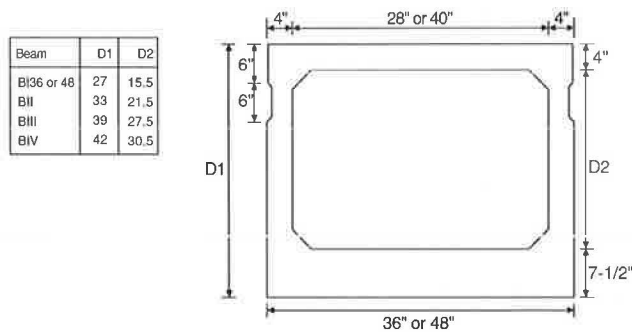| Beam	D1	D2
BI36 or 48	27	15.5
BII	33	21.5
BIII	39	27.5
BIV	42	30.5

FIGURE 2   Modified Type A bridge box beams.

indirectly imposed by the AASHTO equations for the live load distribution factor. A 4-in. deck with No. 5 bars spaced at 8 in. on center was used with the adjacent beam designs. For the 8-ft beam spacing, a 7.5-in. deck with No. 5 bars spaced at 6 in. on center was specified.

Both ½- and 0.6-in. diameter seven-wire prestressing strands were used in the designs. (The authors recognize that currently there is a lack of sufficient information on the development length of the 0.6-in. strand.) Only low-relaxation Grade 270 strands were considered. A standard 2-in. grid was used in positioning the ½-in. strand, and a 2.5-in. grid was used for the 0.6-in. strand. An outside cover of 2 in. was used in all cases. To ensure that stresses did not become excessive, strands were assumed to be sheathed, as necessary, to prevent bonding and force transfer near the ends. In addition, two strands were located near the top fiber of each section, in order to control transportation and erection stresses.

Four combinations of release and 28-day concrete strengths were considered in this study. Release strengths varied from 4,000 to 7,000 psi in 1,000-psi increments. The corresponding 28-day strengths ranged from 6,000 to 12,000 psi in 2,000-psi increments. A study conducted at North Carolina State University (7) indicated that these strengths could be achieved by using locally available materials.

Other pertinent design assumptions included the following:

1. Flexure was assumed to govern the design of the beams. Shear was not examined. Erection camber and live load deflections were computed.

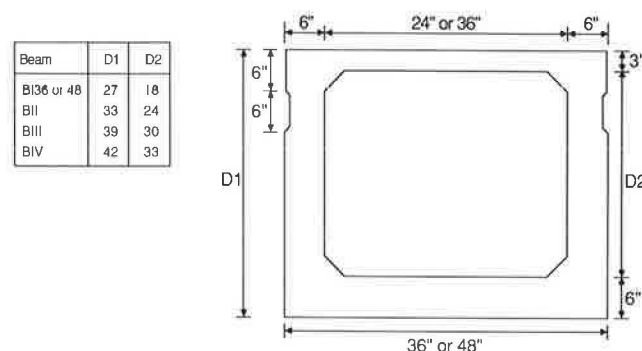2. The bridge deck was assumed to develop full composite action with the beams in resisting any superimposed loads. In computing the section properties of the composite beam, the deck thickness was reduced by ¼ in. to allow for wearing of the deck.

3. A typical interior beam was used to determine the effective flange width and the magnitude of the superimposed loads.

4. The live load was the HS20 truck or lane load, whichever governed. (It is recognized that HS25 loading has replaced HS20 in some states. However, this is not the case in North Carolina.) The weight of the future wearing surface was taken as 20 psf. The dead weight of the barriers was distributed equally to all beams.

5. Prestress losses were computed according to NCDOT specifications. The loss due to concrete shrinkage was taken as 5,750 psi, which corresponds to 75 percent relative humidity.

6. The allowable tensile stress in the precompressed tensile zone was taken as 0 psi because of exposure to a corrosive marine environment.

7. Two intermediate diaphragms placed at the one-third points were used for all sections and span lengths.

Results

In most cases, the maximum span capacity of a beam increased as the concrete strength was increased. Relative to that for 6,000-psi concrete, the increase in maximum span ranged from 0 to 25.8 percent for the individual beam designs investigated. Table 1 gives the average percent increase in maximum span for all standard 3- and 4-ft-wide beams and both strand diameters. It is clear from these data that when 0.6-in. strands are used, there is no advantage to using a compressive strength greater than 8,000 psi. However, with ½-in. strands, the maximum span length increased with the concrete strength, up to 10,000 psi. If the compressive strength is increased further to 12,000 psi, there is only a slight additional benefit.

In addition, the form of the relationship between span length and number of strands remains essentially the same as the concrete strength is increased. This can be seen in Figure 4

Beam	D1	D2
BI36 or 48	27	18
BII	33	24
BIII	39	30
BIV	42	33

FIGURE 3   Modified Type B bridge box beams.

TABLE 1   PERCENT INCREASE IN SPAN LENGTH FOR STANDARD SECTIONS

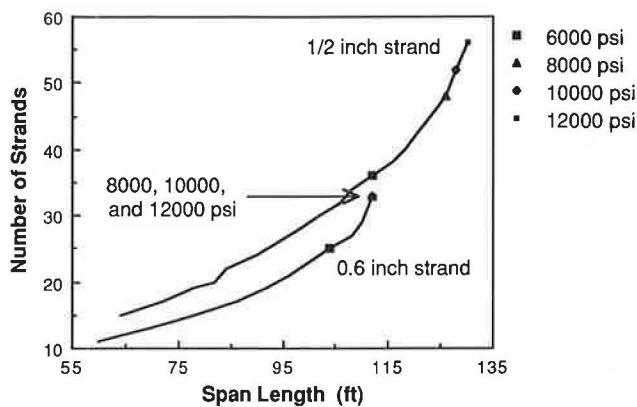|	Average Increase in Maximum Span Over that for 6,000 psi Concrete		
Concrete Strength (psi)	1/2" Strand (%)	0.6" Strand (%)	
3 Foot Beams			
8,000	12.4	4.6	
10,000	17.8	4.6	
12,000	18.3	4.6	
4 Foot Beams			
8,000	12.2	3.5	
10,000	16.9	3.5	
12,000	17.3	3.5	

FIGURE 4   Span capacity curves for both ½- and 0.6-in. strands: AASHTO BIV36 adjacent box beams.

where, for an AASHTO BIV36 box beam, span-versus-strand curves are plotted for each concrete strength and both strand diameters. The maximum span length associated with each level of strength is identified on these curves. The plots show that a compressive strength is most beneficial within the range between its own maximum span and that of the next lowest strength.

Figure 4 also displays the main advantage of using 0.6-in. strands in box beams: Fewer 0.6-in. than ½-in. strands are required for the same span length. The difference in the number of strands required varies quite a bit with the span length and the cross section of the beam. However, for an otherwise similar design, maximum span lengths tend to be shorter with 0.6-in. strands.

In Figure 5, span-versus-strand curves are plotted for all of the standard box beams for the case of adjacent beam spacing, ½-in.-diameter strand, and 12,000-psi concrete. These plots show that the 4-ft-wide sections require more strands per beam than do their 3-ft-wide counterparts for the same span. Nonetheless, the total number of strands required for the bridge will be less with the 4-ft sections because fewer members are needed when adjacent box beams are used. Also, the total volume of concrete is less with the 4-ft beams in this
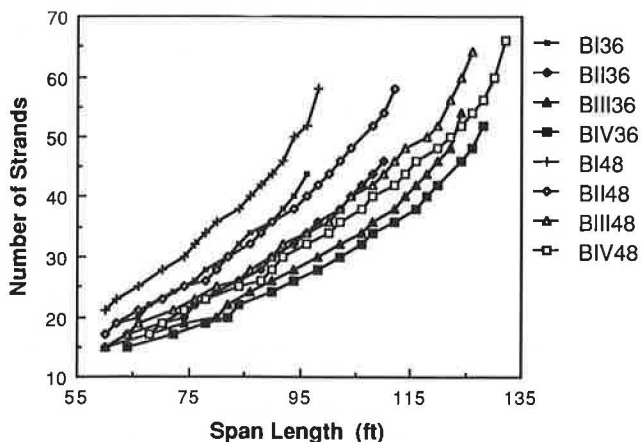
case. When an 8-ft beam spacing is used, the 3-ft-wide sections require fewer strands per beam, fewer total strands for the bridge, and less concrete.

Both of the modified sections considered in this study provided additional benefits over their parent box beams. The Type A sections were the most effective in almost every case. Relative to the parent beam, increases in the maximum span up to 29.7 percent were observed with the Type A section. Table 2 gives, for each level of concrete strength and both strand diameters, the average percent increase in maximum span for the Type A beam over that for the standard beams. The data indicate that the benefits of the modified sections increase with the concrete compressive strength. It is also clear that 0.6-in. strands can be used to greater advantage with the Type A sections than with the parent beams. A comparison of the span-to-strand relationships for the standard and modified sections also shows that, in general, the Type A sections reach longer span lengths and require fewer strands. Figure 6 shows the span-versus-strand curves for the standard and modified AASHTO BIII48 beams. In addition to the above, the Type A beams have a smaller cross-sectional area than does their parent section.

On the basis of the findings from this study, only the modified box beams were considered in the economic study, because they clearly provided the greatest structural benefits.

ECONOMIC STUDY

Although the constituent materials and production methods are essentially the same as those used for normal-strength concrete, high-strength concrete is generally a more costly material. This is primarily because of the increased material quantities and more stringent quality control procedures.

FIGURE 5   Span capacity curves for all standard box beams (f'_c = 12,000 psi; strand diameter = ½ in.).

TABLE 2   PERCENT INCREASE IN MAXIMUM SPAN FOR MODIFIED TYPE A SECTIONS

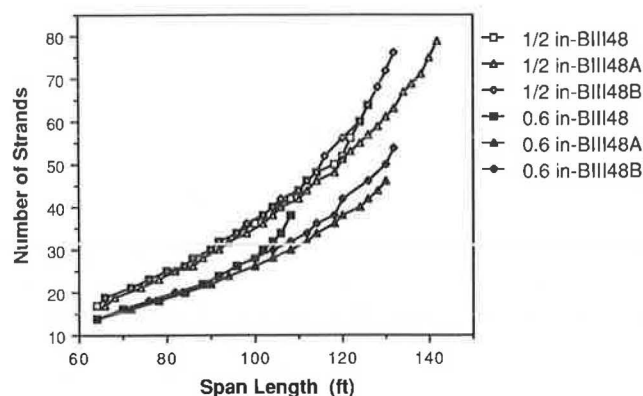|	Average Increase in Maximum Span Over that for the Standard Section		
	Concrete Strength (psi)	1/2" Strand (%)	0.6" Strand (%)
3 Foot Beams			
	6,000	2.1	4.2
	8,000	4.0	12.8
	10,000	5.1	20.0
	12,000	10.1	21.9
4 Foot Beams			
	6,000	0.0	3.1
	8,000	1.1	13.7
	10,000	4.6	20.8
	12,000	9.5	23.4

FIGURE 6 Span capacity curves for the standard and modified BIII48 box beams (f'_c = 12,000 psi).

Nonetheless, high-strength concrete can still be an economical construction material because of the structural benefits that can be realized with its use. In order to determine the cost-effectiveness of using high-strength concrete in prestressed box beams, an economic study was made of a number of selected beam designs.

Approach

When the economy of a beam design is evaluated, the overall cost of the bridge superstructure should be considered rather than the cost of a single beam element. This is important because the use of high-strength concrete in a box beam can influence other aspects of a bridge design. For this study, the superstructure was assumed to consist of only the bridge deck and the prestressed box beams. Components whose costs would be common for all bridge designs, such as the barrier rails, diaphragms, and future wearing surface, were not considered.

The cost-effectiveness of the modified box beams was evaluated by preparing a set of cost curves for each beam. These curves were created with the aid of a computer program written for this study. Using data from the parametric study as
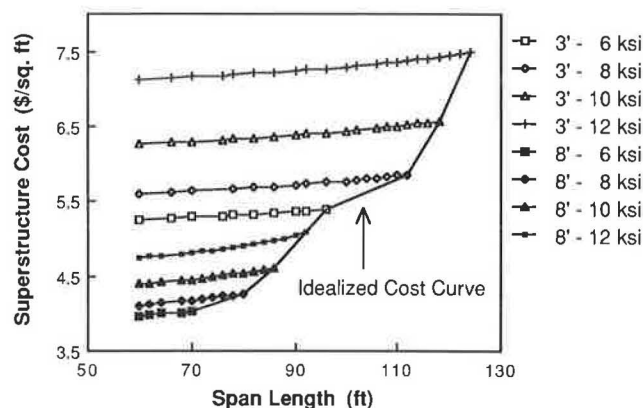

FIGURE 7 Cost curves for the BII36A modified beam with ½-in. strand.

well as the specified unit costs for materials and labor, a total superstructure cost per square foot of bridge deck was computed for each increment in span length up to the maximum span. A total superstructure cost curve was developed for each combination of concrete strength, beam spacing, strand diameter, and beam cross section examined. Figure 7 shows the superstructure cost curves for an AASHTO BII36A beam with ½-in. strands. By connecting the points of least cost, an idealized cost curve can be created for the box beam. This approach eliminates the compressive strength and beam spacing as variables from the economic analysis. Idealized cost curves were created for each of the modified box beams and both strand diameters. A somewhat similar approach was used by Rabbat et al. (2) in their study of bridge girders.

By comparing the idealized curves, the most economical beam designs were identified as those being the least costly over a range in span length.

Unit Costs

The primary materials used in the construction of a typical superstructure include normal-strength concrete and mild steel reinforcement for the bridge deck. The box beams require high-strength concrete, internal void material, sheathing, mild steel reinforcement, and prestressing strands. Labor costs should account for the setup and removal of formwork; placement of the reinforcement and prestressing strands; tensioning of the strands; mixing, placement, finishing, and curing of the concrete; quality control testing; storage; transportation; and erection. In addition to the material and labor charges mentioned, there are the indirect costs of overhead and profit to be considered.

In order to simplify the economic analysis, only those items listed below were included in the computation of the total cost for a superstructure:

1. Normal-strength concrete and primary flexural steel for the bridge deck,

2. High-strength concrete and prestressing strands for the box beams,

3. Labor charges for the production and placement of the concrete, and

4. Labor charges for the placement of the reinforcement or prestressing strands.

It was necessary to establish a typical, or average, unit cost for each of the items listed above. This was a more difficult task than it would first appear. With high-strength concrete being a state-of-the-art material and 0.6-in. strands having had relatively limited use, little hard data are available regarding unit costs for these items. In-place unit costs for the concrete, mild steel, and prestressing strands were estimated from data found in the literature and through private conversations with local precasters. The costs used in this study are shown in Table 3. Overhead and profit were not included. Because

TABLE 3   IN-PLACE UNIT COSTS FOR MATERIALS AND
LABOR

Concrete Strength (psi)	$/cy
3,000	60
6,000	75
8,000	82
10,000	95
12,000	112

Strand Type	$/ft
1/2"-270-LR	0.30
0.6"-270-LR	0.35

Mild Steel	$/lb
#5 Bars	0.38

there were no readily available data, the unit cost for 0.6-in. strands was estimated from that for ½-in. strands.

Results

The cost curves for the AASHTO BII36A beam, shown in Figure 7, are typical of most of the modified box sections examined. These curves clearly show the economic benefit of using higher-strength concretes in conjunction with wider beam spacings. For example, the cost of a design using 12,000-psi concrete with an 8-ft spacing is, on average, 7.7 percent less than a design that uses 6,000-psi concrete and a 3-ft spacing while maintaining a similar span capacity. To reach longer span lengths, closer beam spacings and higher-strength concretes are necessary, however costly. In general, these results are similar to the findings of Rabbat (2) and Jobes (3) for the I- and T-shaped girder sections they considered.

Figures 8 and 9 show the idealized cost curves for the modified BII, BIII, and BIV sections for both beam widths and strand diameters. For clarity, the curves for the BI sections are not shown; these sections were found to be the most costly in nearly all cases. The curves in Figures 8 and 9 make clear which box beam sections are the most cost-effective. For span lengths up to about 95 ft, the 3-ft-wide beams, particularly the BII36A, are the most economical. For spans longer than 95 ft, the 4-ft-wide beams, in particular the BIV48A, are more economical. Except for the longest span lengths, there is actually little difference in cost among the three section depths for either beam width. These findings are true for both strand diameters. In fact, for the unit costs used in this study, the strand diameter has very small effect on the total cost of the superstructure.
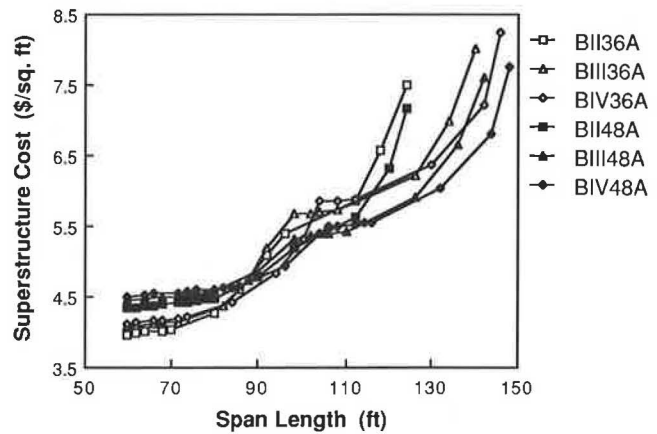

FIGURE 8   Idealized cost curves for 3- and 4-ft modified beams with ½-in. strand.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the results of this investigation, the following conclusions can be drawn with respect to the use of high-strength concrete in prestressed box beam bridges:

1. Most AASHTO design specifications still apply to high-strength concrete. The equations recommended by ACI Committee 363 for the modulus of elasticity and modulus of rupture were used in this study.

2. Span lengths longer than those previously attainable with normal-strength concrete can be reached with high-strength concrete. On average, the maximum span length of the standard box beams increased about 17 percent with an increase in the concrete strength from 6,000 to 12,000 psi. Some beams showed an increase of more than 25 percent.

3. With the modified Type A beams, maximum span lengths can be increased over the parent sections by about 10 percent with ½-in. strands and by about 22 percent with 0.6-in. strands. Some sections showed nearly a 30 percent increase in span capacity. The modified sections also required fewer strands for the same span and have a smaller cross-sectional area.
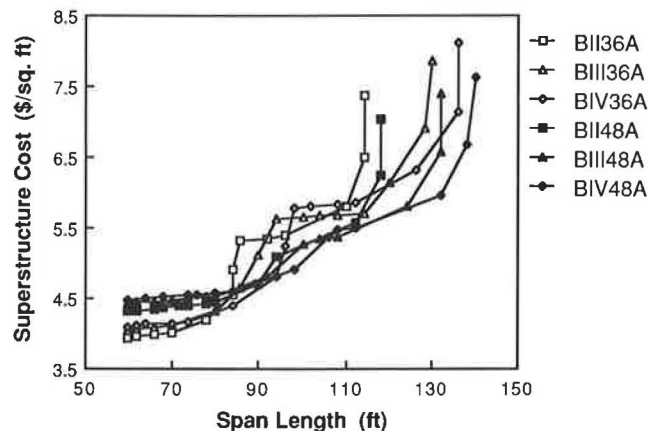

FIGURE 9   Idealized cost curves for 3- and 4-ft modified beams with 0.6-in. strand.

4. For the beams studied, longer span lengths can be reached with ½-in. strands but fewer 0.6-in. strands are required for any common span.

5. For spans up to about 95 ft, 3-ft beams at wide spacings are the most economical, but for longer spans the 4-ft beams spaced more closely are more economical.

The following recommendations are made with respect to the use of high-strength concrete in prestressed box beam bridges:

1. The modified Type A box beam sections should be used rather than the current standard. These sections allow for more strands along the bottom flange. They have a smaller cross section but larger section modulus than the parent sections. For span lengths up to 95 ft, the 3-ft-wide sections should be used. For longer spans, the 4-ft-wide sections should be used. Either ½- or 0.6-in.-diameter strands can be used.

2. Further modification of the standard box beam should be investigated. It was found that the 27-in.-deep sections were never as cost-effective as the others. The 42-in.-deep section, which is the largest, was one of the most economical for all span lengths. An even deeper section may provide further benefits.

3. Although many studies report less shrinkage and creep with high-strength concrete, the effects of this on the loss of prestress have not been fully established. Additional research is needed in this area.

4. The issue of acceptable live load deflections should be studied, because this serviceability requirement is not now addressed by the AASHTO standard specifications. The advantages of high-strength concrete could be greatly diminished if deflection criteria similar to those for steel bridges were imposed.

5. Finally, it is recommended that a few demonstration bridge projects be developed for which high-strength concrete would be specified. Either standard or modified sections could be utilized in these bridges.

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