# Applications and Limitations of High-Strength Concrete in Prestressed Bridge Girders

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High-strength concrete provides a higher compressive strength, a higher modulus of elasticity, a higher tensile strength, reduced creep, and greater durability than normal-strength concrete. For the same cross section and span length, a high-strength concrete girder will have less initial deflection, a higher permissible tensile stress, less prestress loss, less camber change, and longer life than a similar girder made with normal-strength concrete. Structurally, the benefits of using high-strength concrete are fewer girders for the same width bridge, longer span lengths or reduced dead load. The limitations of existing prestressed concrete girders relative to the use of high-strength concrete and several options to more effectively utilize high-strength concrete are described. Analytical results indicate that the use of existing girder cross sections with concrete compressive strengths up to 69 MPa (10,000 psi) allow longer span lengths and more economical structures. However, to effectively utilize concrete with compressive strengths greater than 69 MPa (10,000 psi), additional prestressing force must be applied to the cross section through the use of smaller strand spacings, larger strand sizes, higher-strength strands or post-tensioning.

For over 25 years, concretes with compressive strengths in excess of 41 MPa (6000 psi) have been used in the construction of columns of high-rise buildings (*1*). Initially, the availability of high-strength concretes was limited to a few geographic locations. However, over the years, opportunities have developed to utilize these concretes at more locations across the United States. As opportunities have developed, material producers have accepted the challenge to produce concretes with higher compressive strengths.

In the precast prestressed concrete bridge field, a specified compressive strength of 41 MPa (6,000 psi) has been used for many years. However, strengths at release frequently control the concrete mix design so that actual strengths at 28 days are often in excess of 41 MPa (6,000 psi). It is only in recent years that a strong interest in the utilization of concrete with higher compressive strengths has emerged. This interest has developed at a few geographic locations in a manner similar to that in the building industry. Several research studies (*2–9*) have addressed the application of high-strength concrete in bridge girders. These studies have suggested that there may be a limit at which the higher-strength concretes can no longer be effectively utilized.

This paper examines the use of high-strength concrete in precast prestressed solid-section girders. The ob-

The girder depths were selected on the basis that they are suitable for similar span lengths. Dimensions of all sections are shown in Figure 1.

## Method of Analysis

The majority of the cost-effectiveness analyses were performed using computer program BRIDGE. BRIDGE was written as part of the previous investigation for the Optimized Sections for Precast, Prestressed Bridge Girders (2). The required input of BRIDGE consists of girder span, spacing, and cross section; concrete and strand characteristics; and relative costs of materials. The program determines deck thickness and deck reinforcement, required number of prestressing strands, and cost index per unit surface area of bridge deck. The program also provides section properties, moments, stress levels, and deflections. Comparisons were made on the basis of relative costs.

For purposes of making the cost comparisons, the relative unit cost for in-place materials was assumed to be the same as that used in the previous report (2).

- Concrete (girders and deck): 1 unit/unit weight of concrete;

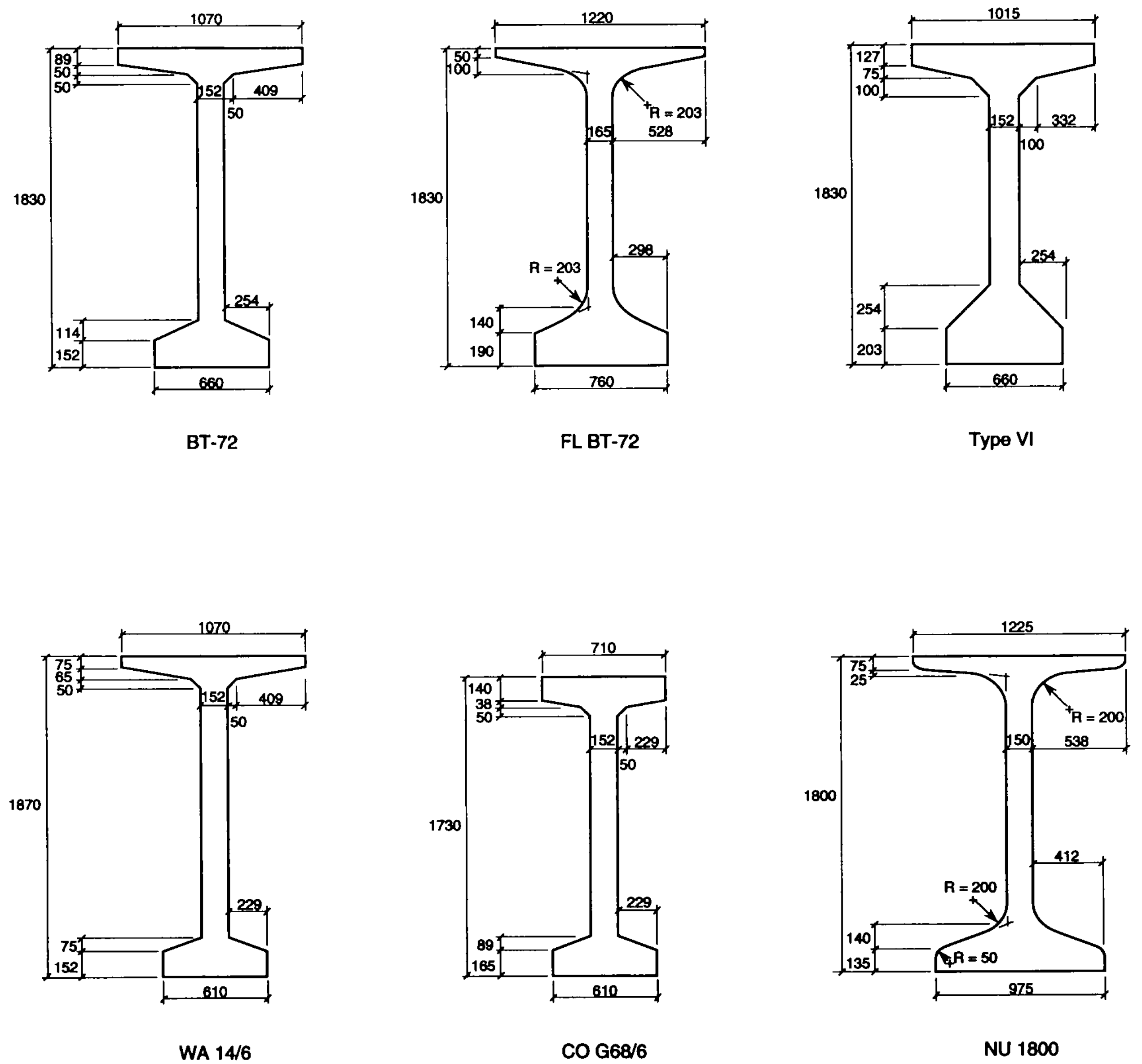


FIGURE 1 Cross sections of girders analyzed (dimensions in millimeters).

- Strands: 8 units/unit weight of strands;
- Reinforcing steel: 9 units/unit weight of reinforcing; and
- Epoxy-coated reinforcing steel: 12 units/unit weight of epoxy-coated reinforcing.

The relative costs of materials were taken as the product of material weight and the relative unit cost. The summation of relative cost of materials was then divided by deck area to give cost index per unit area.

It is recognized that shipping lengths, girder weights, lateral stability of girders, and prestressing bed capacities that exist today could limit the type of girders that can be produced. In addition, design information for use with very high-strength concretes may not be available. However, these limitations were not used as a means to restrict potential applications. The intent of the project was to look beyond current design and production capabilities.

## Cost-Effectiveness

Computer program BRIDGE was used to perform cost-efficiency analyses of the various cross sections. Full details of the analyses were given previously (*13*). As shown in Figure 2, the cost index per unit surface area of bridge deck can be plotted versus span length for a given cross section. At various girder spacings, different cost curves result, as shown by the solid lines in Figure 2.

An "optimum cost curve" is obtained if the end points of each individual cost curve are joined, as shown by the dashed line in Figure 2. This "optimum cost curve" indicates the least cost index for a particular span and varies as a function of girder spacing. As shown in Figure 2 and discussed by Rabbat and Russell (*2*), for a given span, cost index per unit area of bridge deck decreases as girder spacing increases.

Optimum cost curves are generated for a constant girder concrete strength. The cost chart in Figure 2 is for a 28-day girder concrete strength of 41 MPa (6,000 psi). Additional optimum cost curves can be generated at other girder concrete strengths for the same girder cross section. Figure 3 is a plot of the optimum cost curves for a BT-72 at 41, 55, 69, and 83 MPa (6,000, 8,000, 10,000, and 12,000 psi). The compressive strength of the concrete in the deck was assumed to be 28 MPa (4,000 psi) for all girder concrete strengths.

Figure 3 illustrates the benefits and limitations of higher-strength concrete for existing cross sections of precast, prestressed bridge girders. Although Figure 3 represents one particular cross section (BT-72), the results and relationships are consistent with those of other sections analyzed within this investigation (*13*) and will be used as a basis for discussion. To examine the benefits and limitations, the curves must be studied at three separate locations.

The first location is for spans less than 27.4 m (90 ft). For these spans, the controlling condition is initial prestress at transfer. For a given span, there is a point at which additional prestressing will cause tension in the top fibers regardless of the concrete strength. Although this tension would be offset in the service load condition, the dead load at prestress transfer is constant for a given span and cross section and independent of the final in-place girder spacing. As a result, there is no benefit realized for higher-strength concrete at these span lengths.

The second location is for spans between 27.4 and 30.5 m (90 and 100 ft) when concrete strengths are between 41 and 55 MPa (6,000 and 8,000 psi) and spans between 27.4 and 33.5 m (90 and 110 ft) for strengths of 55 MPa (8,000 psi) and greater. As previously discussed, Rabbat and Russell (*2*) found that for a given span, cost index per unit area of bridge deck decreases as girder spacing increases. With the use of higher-strength concrete, additional prestressing will allow larger girder spacings for a given cross section and span length. However, there is a point at which the increase in the unit deck costs begins to offset the savings in unit girder costs associated with larger spacings. This effect is discussed in more detail elsewhere (*13*).

The third location to examine in Figure 3 is for spans exceeding 30.5 m (100 ft) when concrete strengths are between 41 and 55 MPa (6,000 and 8,000 psi) and spans exceeding 33.5 m (110 ft) when concrete strengths exceed 55 MPa (8,000 psi). These areas represent the optimization of benefits of high-strength concrete for the cross sections analyzed. The higher-strength concrete allows larger prestressing forces and, as a result, greater girder spacings for a given span length, thus reducing unit cost. For these span lengths, the original conclusion of Rabbat and Russell (*2*) is confirmed: for a given span length, cost index per unit area of bridge deck decreases as girder spacing increases.

At these longer span lengths, the optimum girder spacings that result in lowest possible cost for a given cross section are not reached. In other words, the cost index as a function of girder spacing is still decreasing when the girder capacity is reached. For example, at a span length of 42.7 m (140 ft) with a 41-MPa (6,000-psi) girder, the maximum spacing is 1.8 m (5.9 ft), whereas a 55 MPa (8,000 psi) girder can be spaced at 2.5 m (8.3 ft). Although the deck costs will be greater for the 55-MPa (8,000-psi) girder, the savings in girder costs far outweigh increased deck costs and result in a more cost-effective superstructure.

Figure 3 also indicates that cost benefits vary as a function of span length and girder concrete strength.

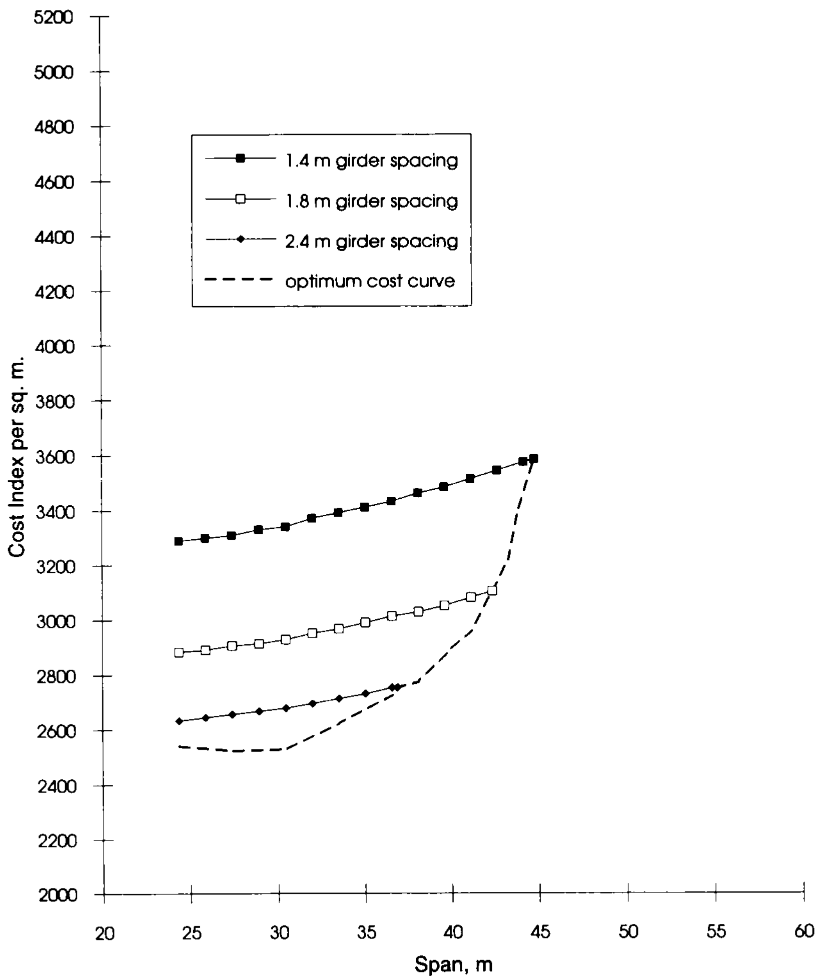


**FIGURE 2** **Cost chart for a BT-72, 41 MPa (6,000 psi).**

For example, a 55-MPa (8,000-psi) girder has a 3 percent lower cost index than a corresponding 41-MPa (6,000-psi) girder at a span length of 33.5 m (110 ft), but a 10 percent lower unit cost at a span length of 42.7 m (140 ft). These cost benefits continue to increase as the span length increases, reaching a maximum of 18 percent at a span length of 44.8 m (147 ft). At this point, the lower-strength girder has reached its maximum span length, whereas the higher-strength girder still has additional capacity. In other words, another benefit of high-strength concrete is the ability to achieve greater span lengths.

Figure 3 also indicates another important point: the diminishing returns realized with the use of high-strength concrete for existing cross sections. The shift in the optimum cost curve decreases for each succeeding 13-MPa (2,000-psi) increase in girder compressive strength. For example, at a girder spacing of 1.5 m (5 ft), the maximum span length increases by 4.6 m (15 ft) when girder compressive strength is increased from 41 to 55 MPa (6,000 to 8,000 psi); however, the maximum span length increases by only 2.7 m (9 ft) when girder compressive strength is increased from 55 to 69 MPa (8,000 to 10,000 psi). Furthermore, the span length increases fall off dramatically at girder compressive strengths exceeding 69 MPa (10,000 psi).

The primary cause of these diminishing returns is the decreasing strand eccentricity. Once strands are placed within the web, the efficiency of a particular section begins to decrease rapidly. The incremental benefit of each succeeding strand decreases when sufficient room within the flange does not exist. Once additional prestressing force cannot be induced in the girder, the beneficial effects are limited to the increase in concrete tensile strength, which only increases as the square root of compressive strength (*1*).

In general, increases in the girder concrete strength result in the following:

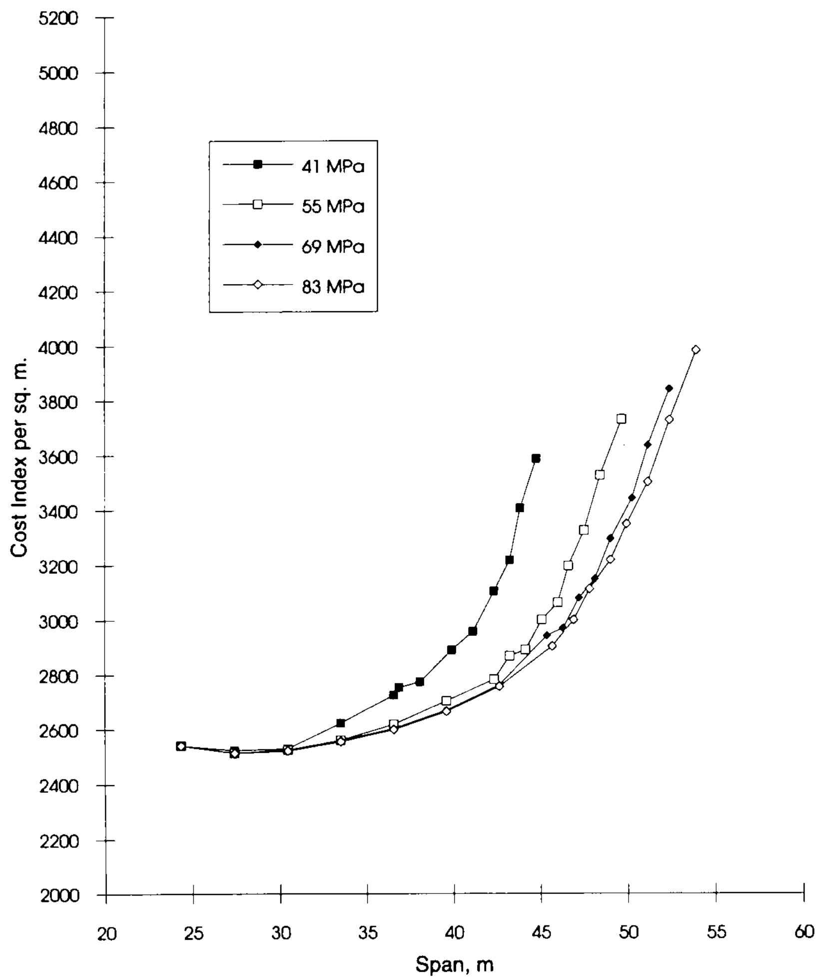


**FIGURE 3 Optimum cost curves for a BT-72.**

1. A shift in the optimum cost curve to the right for each succeeding increase in girder concrete strength. This is beneficial because longer span lengths can be achieved without an increase in the unit cost.
2. Decreasing incremental benefits for each incremental increase in concrete strength.
3. Minimal benefits beyond a girder concrete strength of about 69 MPa (10,000 psi).
4. No benefit from higher concrete strength for the horizontal portion (shorter span lengths) of the optimum cost curve.

Cost comparisons for the other analyzed sections of similar depths are shown in Figure 4 for concrete strengths of 41 and 83 MPa (6,000 and 12,000 psi). Optimum cost curves for the BT-72, WA 14/6 and CO G68/6 are shown in Figure 4*a*. Important observations from this figure consist of the following:

1. The curves are essentially identical for the shorter span lengths.
2. The curves vary at the longer span lengths. However, this variation is greatest for the CO G68/6 and is attributable to the shallower depth and thinner top flange. The BT-72 and WA 14/6 are similar within the vertical portions.
3. Incremental shifts in the optimum cost curve for increasing girder strength vary for each section. The BT-72 undergoes the largest shifts, whereas the WA 14/6 undergoes the smallest. This fact is due primarily to the number of prestressing strands that can be placed within the flange. The BT-72, WA 14/6 and CO G68/6 can accommodate 39, 30, and 35 strands, respectively, within the bottom flange. Strand placement within the flange is more efficient than that in the web and allows the CO G68/6 to gradually gain on the WA 14/6 as girder strength is incrementally increased.

Optimum cost curves for the NU 1800 and FL BT-72 are shown in Figure 4*b*. No cost advantage existed for one section over the other as the curves are almost identical.

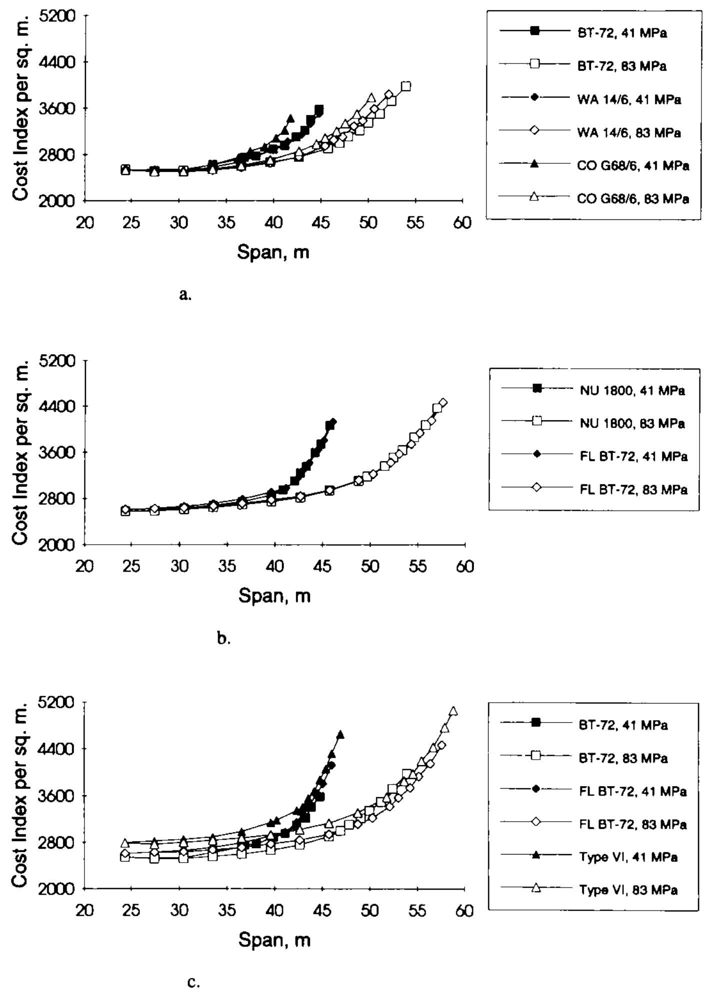


**FIGURE 4 Comparison of different cross sections: (*a*) BT-72, WA 14/6, CO8/6; (*b*) NU 1800, FL BT-72; (*c*) BT-72, FL BT-72, Type VI.**

Figure 4*c* contains plots of the optimum cost curves for the BT-72, FL BT-72, and Type VI at concrete strengths of 41 and 83 MPa (6,000 and 12,000 psi), respectively. Important observations from this figure consist of the following:

1. At a girder strength of 41 MPa (6,000 psi), the BT-72 is the most cost-effective cross section, with savings of 1 to 6 percent over the FL BT-72 and 5 to 13 percent over the Type VI.
2. At all girder strengths, the BT-72 is the most cost-effective cross section for span lengths up to about 45.7 m (150 ft), with savings of 3 to 6 percent over the FL BT-72 and 8 to 13 percent over the Type VI.
3. Incremental shifts in the optimum cost curve for increasing girder strength vary for each section. The FL BT-72 undergoes the largest shift, whereas the BT-72 undergoes the smallest. This fact is primarily because of the number of prestressing strands that can be placed within the bottom flange. However, it is also a function of the efficiency in which the strands are placed in the bottom flange. For instance, the FL BT-72 and BT-72 have wide rectangular bottom flanges, whereas the Type VI has a more squarish bottom flange. Although the Type VI can accommodate significantly more strands than the FL BT-72 (81 versus 59), their placement is not as efficient (less eccentricity) and, as a result, shifts in the FL BT-72 curve are greater than those for the Type VI.
4. As a result of the incremental shifts in the optimum cost curve as discussed in Item 3, the FL BT-72 becomes the most cost-effective cross section for span lengths exceeding about 45.7 m (150 ft) and girder strengths of 55 MPa (8,000 psi) and greater.
5. Although the FL BT-72 and Type VI enjoy greater horizontal shifts in their optimum cost curve than the

BT-72 as a result of larger bottom flanges, they pay a price at smaller span lengths. For these spans, the BT-72 is the more cost-effective cross section at all girder concrete strengths.

Comparisons were also made to determine the effect of the premium cost for higher-strength concretes on the cost index per unit area. The following ratios were assumed for the premium costs of higher-strength concrete (1 MPa = 145 psi):

| *Strength (MPa)* | *Minimum Ratio* | *Intermediate Ratio* | *Maximum Ratio* |
|---|---|---|---|
| 41 | 1.00 | 1.00 | 1.00 |
| 55 | 1.00 | 1.05 | 1.10 |
| 69 | 1.00 | 1.13 | 1.25 |
| 83 | 1.00 | 1.25 | 1.50 |

The comparisons of optimum cost curves were made for the BT-72 for compressive strengths from 41 to 83 MPa (6,000 to 12,000 psi). Data from the three sets of cost index curves are shown in Figure 5. The effect of the premium costs is to displace the relative positions of the curves for the various concrete strengths. These data indicate that as the premium for the higher-strength concretes increases, it becomes more economical to utilize a lower-strength concrete for longer span lengths. For example, with no premium concrete costs, the 55-MPa (8,000-psi) compressive strength concrete is the most economical up to a span length of approximately 36 m (120 ft). However, with the maximum premium costs, it is more economical to use 41 MPa (6,000 psi) up to a span length of approximately 36 m (120 ft) and then to utilize 55 MPa (8,000 psi) up to a span length of 46 m (150 ft). However, on a relative basis, when comparing different cross sections, the effect of the premium concrete costs is to displace cost index curves by a similar amount. Consequently, although the premium costs are important when comparing concrete strengths for the same girder cross section, they are less significant when comparing different cross sections with the same concrete strength.

Limited analyses were made to investigate the sensitivity of the cost index per unit area to the assumed relative unit costs of the different materials. On the basis of an industry survey, a range of relative unit costs was obtained. Comparisons of optimum cost curves for BT-72 were made for this range. It was concluded (*13*) that the cost index per unit area on a comparative basis is relatively insensitive to the assumed relative costs of the in-place materials.

## Analyses of Modified Cross Sections

The analysis of existing sections indicated that the utilization of high-strength concrete was limited by the amount of prestressing force that can be applied to a girder cross section and the eccentricity of the force. Consequently several alternatives were investigated to increase the amount of prestressing force that can be applied at maximum distance from the neutral axis. The alternatives included decreasing strand spacing, increasing strand size, increasing strand strength, and increasing bottom flange size.

### Strand Spacing and Size

Previous analyses in this investigation were based on a strand diameter of 12.7 mm (0.5 in.) at a spacing of 51 mm (2 in.). The effect of decreasing the strand spacing to 38 mm (1.5 in.) and providing strands 15.2 mm (0.6 in.) in diameter spaced at 51 mm (2 in.) and 64 mm (2.5 in.) was investigated. The results are shown in Figure 6 for a BT-72. The most cost-efficient solution occurs with the largest amount of prestressing force that can be accommodated within the section. The benefits are more pronounced at the longer span lengths and illustrate one way to increase the effectiveness of high-strength concrete.

### Strand Strength

The possibility of using a higher grade prestressing strand was also investigated. A limited benefit was obtained by using a 2,070-MPa (300-ksi) strand compared with a 1,860-MPa (270-ksi) strand.

### Section Geometry

Two modifications of the bottom flange were studied. Modification 1 consisted of increasing the bottom flange edge thickness from 152 mm (6 in.) to 203 mm (8 in.) while maintaining the overall 1830-mm (72-in.) section depth. Modification 2 consisted of increasing the bottom flange thickness from 152 mm (6 in.) to 203 mm (8 in.) by increasing the section's overall depth from 1830 to 1880 mm (72 to 74 in.).

Figure 7 compares optimum cost curves at concrete strengths of 41 and 83 MPa (6,000 and 12,000 psi), respectively. As can be seen from this figure, the modifications have a larger impact on the 83 MPa (12,000 psi) girders than on the 41 MPa (6,000 psi) girders.

The behavior of the optimum cost curve for the modifications is consistent with the previous conclusion that the bottom flange limited the effectiveness of higher concrete strengths; however, the behavior is slightly different from that which was experienced with modifications to strand size, spacing, and strength. A penalty

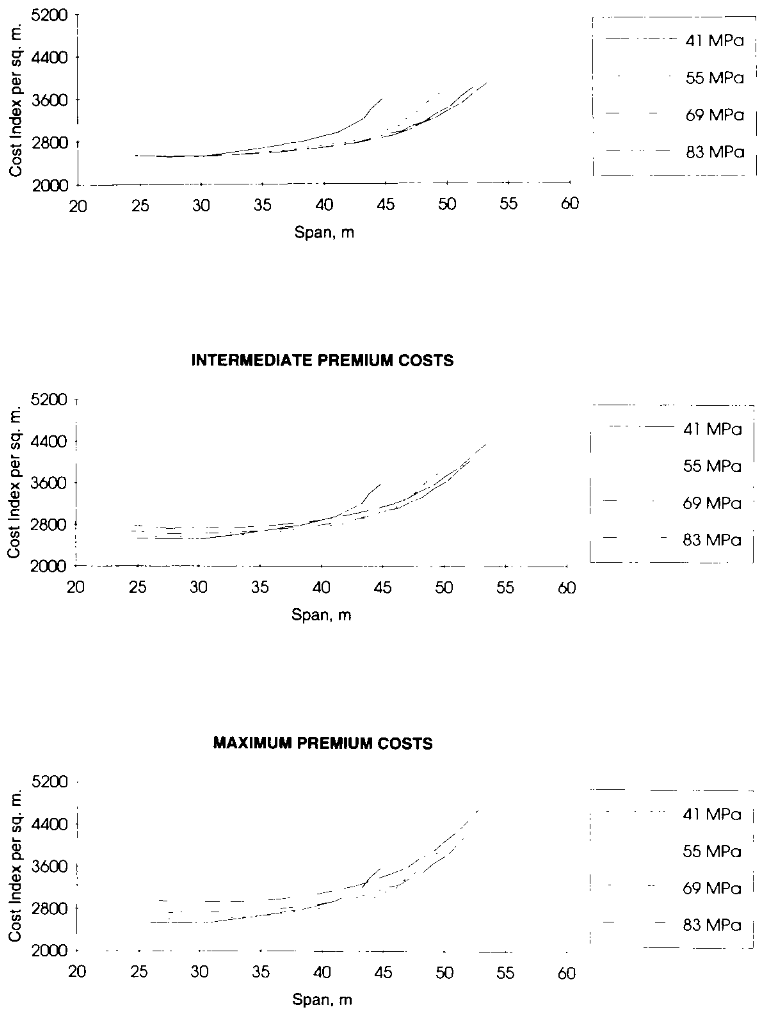


**FIGURE 5** Effect of premium concrete costs for a BT-72.

is paid in the form of increased volume of concrete and corresponding weight when the bottom flange size is increased to incorporate more prestressing, as opposed to reducing strand spacing to obtain the same result. This penalty offsets some of the potential benefits of more prestressing with the bottom flange, and, consequently, cost benefits are not realized until concrete strengths exceed 55 MPa (8,000 psi). In addition, this penalty results in the original BT-72 being more cost-effective at all concrete strengths for span lengths of 42.7 m (140 ft) and less.

Modification 2 is a slightly more cost-effective alternative then Modification 1. However, it is interesting to note that the shift in the optimum cost curve between Modification 1 and Modification 2 is virtually identical at both concrete strengths. This fact occurs because the benefit of Modification 2 over Modification 1 is only a slightly deeper section. Both revised sections accommodate the same maximum number of prestressing strands within their larger bottom flange.

## Conclusions

On the basis of the cost analyses described in this paper, the following conclusions are made:

1. For existing cross sections designed using Grade 270 strand 12.7 mm (0.5 in.) in diameter at 51-mm (2-in.) centers with 51 mm (2 in.) of cover, the BT-72 was the most cost-effective cross section for span lengths up to 45.7 m (150 ft) at all concrete compressive strengths. However, the WA 14/6 and CO G68/6 were equally cost-effective for span lengths up to about 36.6 m (120 ft). For span lengths greater than 45.7 m (150 ft) and all concrete compressive strengths, the FL BT-72 and NU 1800 were the most cost-effective.

2. For all existing sections designed using Grade 270 strand 12.7 mm (0.5 in.) in diameter at 51-mm (2-in.) centers with 51 mm (2 in.) of cover, the maximum useful concrete compressive strength was in the range of 62 to 69 MPa (9,000 to 10,000 psi). Above this

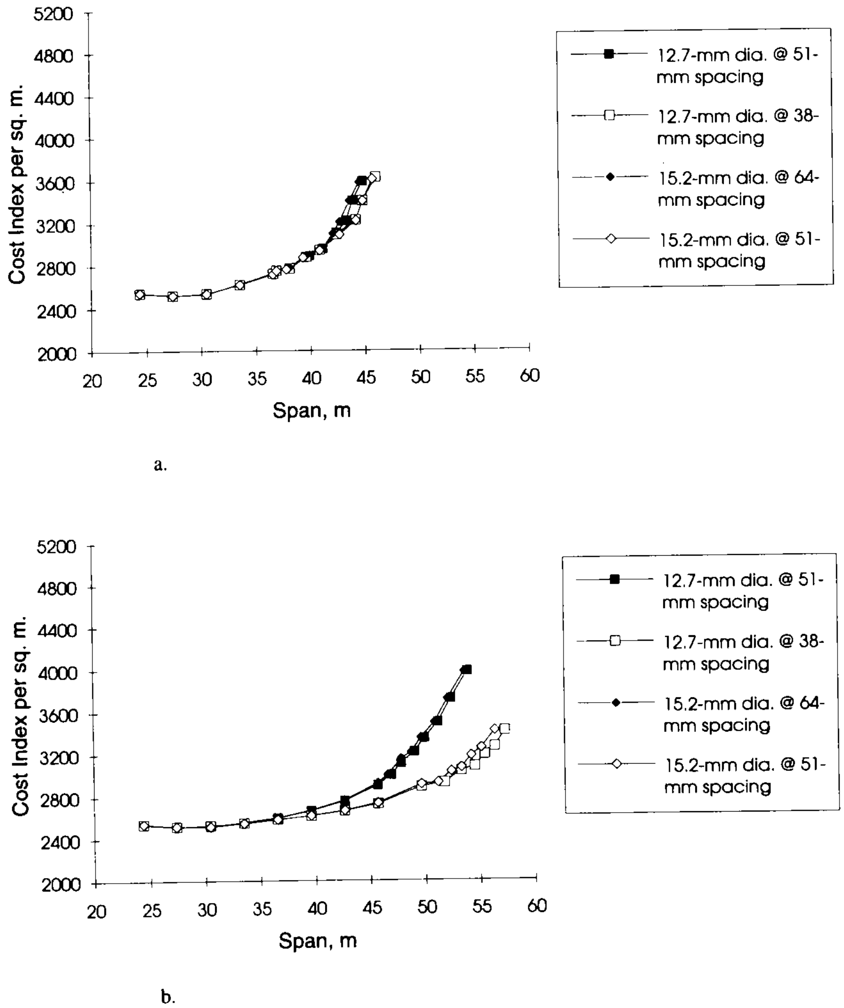


**FIGURE 6 Effect of strand spacing and size for a BT-72: (*a*) BT-72 with 41 MPa of specified girder concrete strength; (*b*) BT-72 with 83 MPa of specified girder concrete strength.**

strength level, sufficient prestressing force cannot be introduced into the cross section to take advantage of any higher concrete compressive strengths.

3. For all the cross sections analyzed, the use of a higher-strength concrete enabled a given section to be designed for a longer span length. The increase in span length with compressive strength is greater when additional prestress force can be applied to the cross section. However, if additional prestressing force cannot be included, the beneficial effects are limited to the increase in allowable tensile stress at midspan. Because this increase is limited to the increase in the square root of the compressive strength, the incremental benefits decrease with each incremental increase in compressive strength.

4. A shallower section with a higher-strength concrete can be more cost-effective than utilizing a deeper section with a lower-strength concrete. Depending on the premium for the higher-strength concrete, the unit cost of the superstructure may be lower with the shallower section than with the deeper section. In addition, there will be other savings from the reduced substructure height. This concept is worthy of further study with regard to replacement of existing bridges.

5. As the premium for high-strength concrete increases, it becomes more economical to use lower-strength concretes for longer span lengths. The unit cost of the superstructure is relatively insensitive to changes in the premium costs as the cost of the girder concrete is only one component of the total cost.

6. The use of smaller-strand spacing, larger-diameter strand, or higher-strength strand in the BT-72 was beneficial at the higher concrete strength levels where additional prestressing force was needed to take advantage of the higher compressive strength of the concrete. Ad-

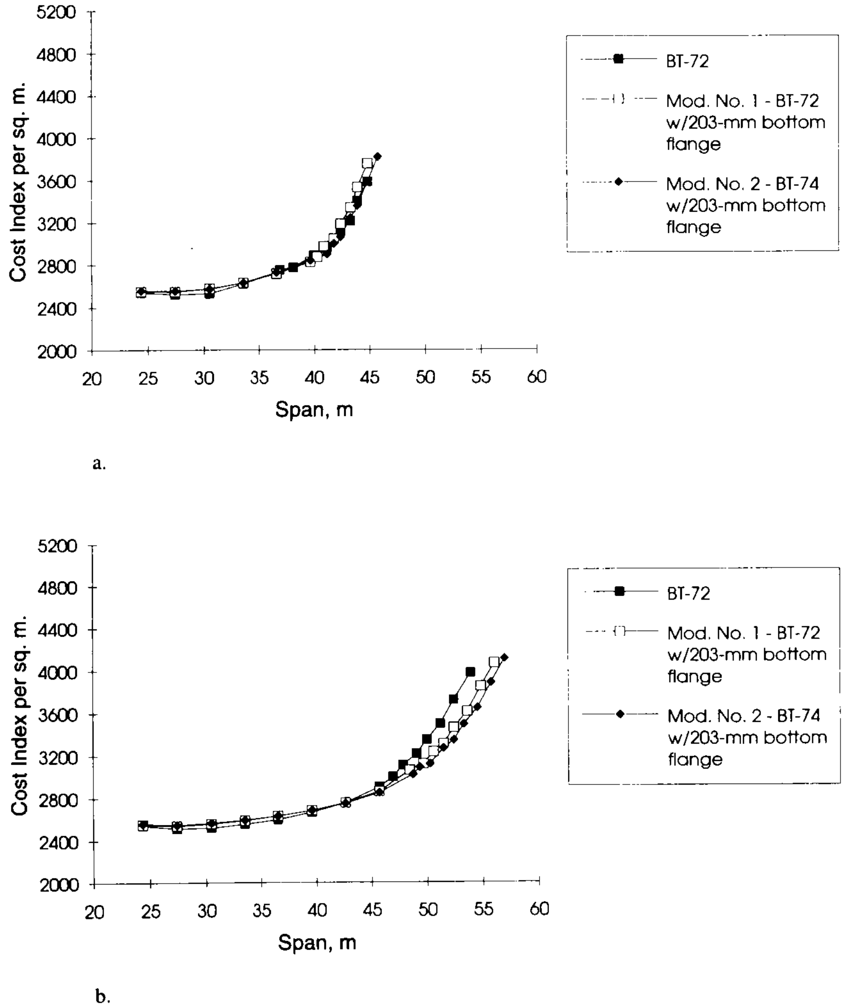


**FIGURE 7 Effect of section geometry for a BT-72: (*a*) BT-72 modifications with 41 MPa of specified girder concrete strength; (*b*) BT-72 modifications with 83 MPa of specified girder concrete strength.**

ditional research is needed on transfer and development lengths in high-strength concrete before the beneficial effects can be implemented.

7. The effect of increasing the bottom flange thickness of the BT-72 so that an additional row of prestressing strands can be added had little benefit when the girder concrete compressive strength was 41 MPa (6,000 psi) and a benefit of less than 5 percent when the concrete strength was 83 MPa (12,000 psi).

## Recommendations

1. In the near future, the industry should concentrate on the usage of concrete with specified compressive strengths up to 69 MPa (10,000 psi). For existing girder cross sections designed with Grade 270 strands 12.7 mm (0.5 in.) in diameter at 51-mm (2-in.) centers and 51 mm (2 in.) of cover, the use of concrete with compressive strengths up to 69 MPa (10,000 psi) will allow longer span girders and, depending on the premium cost for the higher-strength concrete, more economical structures. As a minimum, all highway departments should adopt 53-MPa (8,000 psi) compressive strength concrete as the normal design strength for longer span girders. It should be recognized that many precasters are already producing girders at this strength level.

2. To effectively utilize concretes with compressive strengths in excess of 69 MPa (10,000 psi), the industry must develop methods to apply additional prestressing force to the cross section. This can be achieved either by the utilization of strands 12.7 mm (0.5 in.) in diameter at 38-mm (1.5-in.) centers or strands 15.2 mm (0.6 in.) in diameter at 51-mm (2.0 in.) centers. The use

of the closer spacing for the strand 12.7 mm (0.5 in.) in diameter may be feasible with the higher-strength concretes.

3. The PCI Bulb-Tee (BT-72) should continue to be considered as a national standard for span lengths from 24.4 to 61.0 m (80 to 200 ft). However, the WA 14/6 and CO G68/6 are equivalent at span lengths up to 36.6 m (120 ft). For span lengths greater than 45.7 m (150 ft), the FL BT-72 and NU 1800 are slightly more economical.

4. Before concrete with compressive strengths in excess of 69 MPa (10,000 psi) can be successfully used, additional research is needed on transfer and development lengths; deflection, lateral stability, and dynamic characteristics of girders; prestress losses; shear strength of girders; design age strength; and alternative deck systems.

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