In early applications of prestressed concrete in bridges, designers developed their own ideas of the "best" girder sections. Each contractor used a slightly different girder shape, thus preventing the reuse of girder forms on subsequent contracts. Producers soon found that they could not afford to keep a variety of expensive steel forms, and that it was too expensive to design custom girders for each bridge.

As a result, representatives of the Federal Highway Administration (formerly the Bureau of Public Roads), the American Association of State Highway and Transportation Officials (AASHTO), and the Prestressed Concrete Institute (PCI) began working on what has become a series of standard AASHTO-PCI sections for bridge girders (called AASHTO girders in this paper). Standard girders Types I through IV were developed in the late 1950's, and Types V and VI in the early 1960's.

Adoption of the AASHTO standard bridge girders simplified design practice and led to wider use of prestressed concrete for bridges. Standardization of girders has brought considerable savings in the construction of bridges. In recent years, there have been several indications of a need to either update the design of the standard AASHTO girders or develop entirely new designs for major prestressed concrete girders. For example, some state highway departments have developed "improved" girder shapes. A few selected girders are shown in Fig. 1. Therefore, the question was "How efficient are the standard AASHTO girders?"

RESEARCH OBJECTIVES

This investigation was undertaken to evaluate the latest prestressed concrete bridge girder designs being used in the United States and to determine which
represented optimum designs that could be promoted as national or regional standards. The investigation was limited to bridges built with pretensioned I- and T-sections, for spans in excess of 80 ft (24.4 m), and with concrete compressive strengths up to 7000 psi (48.3 MPa).

**Scope**

The objectives of the study were accomplished within the following scope:
1. Current precast, prestressed concrete girders with composite cast-in-place deck designs being employed in the United States were summarized.
2. Creative new concepts becoming available through research were reviewed.
3. Girders representing optimum designs and exhibiting strong potential for standardization were determined.
4. Recommendations for standardization of the most practical and cost-effective designs were made.

**RESEARCH APPROACH**

The project was divided into two phases. In Phase 1, information was collected throughout the United States on a regional basis from selected highway agencies and producers. Advantages and disadvantages of the concepts inventoried were assessed.

In Phase 2, structural efficiency and cost-effectiveness of the best existing designs, as well as some modified ones, were evaluated relative to the efficiency of AASHTO sections. This included evaluation of structural parameters such as girder spacing, span length, concrete strength, and deck thickness.

A computer program was developed for use in the parametric studies. A relative unit cost index was assigned to girder and deck-slab concretes, prestressing strands, and reinforcing steel. These reflected in-place relative costs

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**Synopsis**

Efficiency of the latest prestressed concrete bridge girder designs being used in the United States was evaluated. Bridges built with pretensioned I- and T-sections for spans in excess of 80 ft (24.4 m) were considered. Information on current designs was collected from selected highway agencies and producers throughout the United States.

In all states surveyed except California, the most economical bridges for spans of 70 to 130 ft (21.3 to 39.6 m) were constructed with pretensioned bridge girders. Precast, prestressed bridge girder sections inventoried were analyzed on three efficiency scales. Bulb-T’s, Colorado, and Washington girders were more structurally efficient than AASHTO-PCI girders.

Cost analyses were performed on existing Bulb-T’s, Colorado, Washington, and AASHTO girders, and on their modified counterparts with 6-in. (152 mm) thick webs. Parameters included girder span, girder spacing, deck thickness, and concrete compressive strength. Based on relative unit costs for in-place materials and labor, cost charts were prepared.

All girders were compared using optimum cost curves. Bulb-T’s were found most cost-effective with estimated cost savings of 17 percent on the in-place cost of girders and deck compared to the AASHTO girders. Next most cost-effective sections were the Washington Series girders. Modified Bulb-T’s are recommended for use as national standards.
Fig. 1. Existing girders analyzed. (AASHTO-PCI, Bulb-T, Colorado, and Washington).
for finished girder and deck. Costs of materials and labor were included. Data generated by the computer program were used to determine the most cost-effective girders.

Survey results of Phase 1, computer program documentation, and results of Phase 2 analyses are available in a detailed report. A summary of the structural efficiency and cost-effectiveness analyses is presented in this paper.

**STRUCTURAL EFFICIENCY**

In a pretensioned bridge member, the predominant stresses are flexural. Therefore, the designer's goal should be to use a section that has the highest section modulus with the least area. Conversely, for a given sectional area, the highest section modulus is desirable. The final decision is based on economy. Usually, efficiency and economy go hand in hand.

One way of measuring the relative performance of bridge girder sections has been proposed by Anderson. He suggested that the relationship between cross-sectional area and section modulus for the bottom fibers be compared. Such a relationship is shown in Fig. 2.

Although the AASHTO Type VI section has the highest modulus, it also has the biggest area, that is, it is the heaviest. Colorado G68 section, the Washington Series 120 and 14, Bulb-T BT72, and AASHTO Type VI girders have about the same span capabilities. However, G68, BT72, and Series 120 and 14 are about 40 percent lighter than Type VI.

An efficiency factor for prestressed sections has been derived by Guyon. The method is based on maximizing section moduli for top and bottom fibers for a given cross-sectional area.

This efficiency factor, \( \rho \), is defined as:

\[
\rho = \frac{r^2}{y_t y_b}
\]

where

- \( r \) = radius of gyration of section = \( \sqrt{I/A} \)
- \( y_t, y_b \) = distance from center of gravity to top and bottom fibers, respectively
- \( I \) = moment of inertia
- \( A \) = cross-sectional area

Variation of the efficiency factor, \( \rho \), with respect to depth of section is plotted in Fig. 3.

For spans in excess of 75 ft (22.9 m), the stress in bottom fibers governs design of bridge girders. For this reason, Aswad proposed an efficiency ratio, \( \alpha \), that accounts for the section modulus for bottom fibers. This ratio is defined as:

\[
\alpha = \frac{3.46 S_b}{Ah}
\]

where

- \( S_b \) = section modulus for bottom fibers
- \( A \) = cross-sectional area
- \( h \) = depth of section

Fig. 4 shows variation of efficiency ratio for different sections. Through analysis based on Colorado regional costs, Aswad determined that girders with the highest efficiency ratio had the lowest cost per square foot of superstructure.

According to Figs. 2 through 4, Bulb-T's, Washington, and Colorado girders are the most structurally efficient sections. Detailed structural and cost analyses to determine most cost-effective girders are described in the following section.

**COST-EFFECTIVENESS**

In this section, the girder cross sections selected for cost-effectiveness analyses are described, and the assumptions for the structural and cost analyses are stated. The number of parameters involved in the analysis necessitated development of a computer program. Data generated by this
program were used to make cost-effectiveness comparisons.

**Cross Sections Analyzed**

Comparisons of the structural efficiency of girder cross sections indicated that the most efficient sections were Bulb-T's, Washington series, and Colorado G54 and G68 sections. Bulb-T's have been used successfully in the Pacific Northwest.

According to Figs. 2 through 4, they are the most structurally efficient. A set of Bulb-T sections was developed in 1959 by Anderson. These sections, as well as the Washington series and Colorado G68, have 5-in. (127 mm) thick webs. Strands deflected within the webs of these sections are bundled. End blocks are used in these girders.

Several survey participants expressed concern about possible difficulties in manufacturing and transporting girders with 5-in. (127 mm) thick webs. The main concerns were consolidation of the concrete in thin and deep members.
Fig. 3. Variation of efficiency factor with depth of section.

Fig. 4. Variation of efficiency ratio with depth of section.
and stability of such slender members during transportation. On the other hand, some survey participants felt that present AASHTO girders can be improved by reducing their web thickness.

At a meeting held in April 1980,8 members of the PCI Bridge Committee were asked about the minimum practical web width to place and consolidate the concrete in precast, prestressed I-sections. All committee members were in favor of a minimum web width of 6 in. (152 mm).

AASHTO standard bridge girders Types I and II have 6-in. (152 mm) thick webs. In all regions of the United States, concrete has been placed and consolidated in these sections without difficulty. Therefore, in Phase 2, sections with 5-in. (127 mm) thick webs were evaluated and compared with similar sections with 6-in. (152 mm) thick webs. Sections with 6-in. (152 mm) thick webs should be easier to manufacture and transport than sections with 5-in. (127 mm) thick webs.

The following sections were evaluated in Phase 2 of the project:

1. Colorado G54 and G68 girders. Girder G68 has a 5-in. (127 mm) thick web.
2. Washington Series 80, 100, 120, and 14 girders. These girders have 5-in. (127 mm) thick webs.
3. Anderson’s Bulb-T’s³ BT48, BT60, and BT72. These girders have 5-in. (127 mm) thick webs. The tips of the top flanges are 1 in. (25.4 mm) thick.
4. A girder similar to Colorado G68 but with a 6-in. (152 mm) thick web. This section is designated Modified Colorado G68/6 in this report.
5. Girders similar to the Washington series but with 6-in. (152 mm) thick webs. These sections are designated Modified Washington Series 80/6, 100/6, 120/6, and 14/6.
6. Girders similar to Anderson’s Bulb-T’s, but with 6-in. (152 mm) thick webs and 2-in. (50.8 mm) thick top flange tips. These sections are designated Modified Bulb-T’s BT48/6, BT60/6 and BT72/6.
7. AASHTO standard bridge girders Types IV, V, and VI.
8. Modified AASHTO girders where web thicknesses, and top and bottom flange widths are reduced by 2 in. (50.8 mm). These were considered with the idea that existing forms could be used with reduced space between them. These sections are designated Modified Types IV, V, and VI.

Dimensions of the existing and modified sections are shown in Figs. 1 and 5.

Structural Parameters

The sections were evaluated through a detailed structural analysis. The following parameters were considered:

1. Girder spacing
2. Span length
3. Deck thickness
4. Concrete strength

Girder spacing was varied between 4.5 and 10 ft (1.37 and 3.05 m). Spans in excess of 80 ft (24.4 m) were considered. Deck thickness varied with girder spacing. Concrete strength for girders was varied between 5000 and 7000 psi (34.5 and 48.3 MPa).

Development of Computer Program

To evaluate the effect of each variable, a parametric study was carried out. The number of variables necessitated preparing a computer program to analyze each case and generate cost data.

This program, called Program BRIDGE, required input of girder span, spacing, and cross section; concrete and strand characteristics; and relative costs of materials. The program determined deck thickness and reinforcement, required number of strands, and cost index per unit surface area of bridge deck.
Modified AASHTO

Modified Bulb-T

Modified Colorado G68/6

Modified Washington Series

Fig. 5. Modified girders analyzed. (AASHTO, Bulb-T, Colorado, and Washington).
The following assumptions were made in Program BRIDGE:

1. Design conforms to AASHTO Specifications.
2. Live load consists of HS 20-44 loading.
3. Girders are simply supported.
4. A typical interior girder is considered.
5. Concrete deck is cast in place and acts compositely with the girder. Deck formwork is supported on the girder. In calculations of the composite section properties, the transformed area of strands is neglected.
6. Concrete compressive strength of the deck is constant and equal to 5000 psi (27.6 MPa) at 28 days.
7. Strands are Grade 270 (1862 MPa) stress relieved with \( \frac{1}{2} \)-in. (12.7 mm) diameter and have an idealized trilinear stress-strain curve.
8. Total prestress losses are constant and equal 45,000 psi (310 MPa).
9. Initial or long-term camber or sag do not govern design as the AASHTO specifications do not specify deflection limits for concrete bridges.
10. Cost of materials, labor, transportation, and erection of girders with concrete compressive strengths between 5000 and 7000 psi (34.5 and 48.3 MPa) is assumed constant. The effect of increasing the girder concrete strength from 5000 to 7000 psi (34.5 to 48.3 MPa) on the in-place cost of the girder is negligible.
11. Relative unit costs of materials and labor are constant for the cost analysis. All girders are compared on a common basis.
12. Cost analysis comparisons are for precast girders and a cast-in-place deck. Cost of substructure and approach fills are not considered.

Relative Unit Cost Indexes

Several factors affect the cost of the superstructure. Costs of material and labor vary from region to region, between states of a region, between districts of a state, and within a district according to bridge location. An assessment of local and regional factors was not possible within the scope of this investigation. However, a cost analysis was possible by comparing the cost of the recommended sections on a common basis.

From survey data, an average cost was determined for girder concrete, deck concrete, reinforcing steel, and prestressing strands. These average costs included cost of materials and labor. For girder concrete, the cost also included transportation and erection. Average costs were then reduced to relative costs per pound of in-place material.

The following relative unit costs for in-place materials (including labor) were used for the cost analyses:

- Concrete (girders and deck) ............ 1 unit/per pound
- Strands ................ 8 units/per pound
- Reinforcing steel .......... 9 units/per pound
- Epoxy coated reinforcing steel .......... 12 units/per pound

Girders were compared based on the same unit costs. The relative costs of materials were taken as the product of material weight and relative unit costs. The summation of relative costs of materials was then divided by deck area to give cost index per square foot.

Optimum Cost Index Charts

Using Program BRIDGE, a cost chart was prepared for each of the sections shown in Figs. 1 and 5. The same relative unit costs for in-place materials (material and labor) as well as material properties were assumed for all girders and decks. A representative chart is given in Fig. 6. It depicts cost index per square foot of deck versus span length for an AASHTO Type VI girder. The solid lines are for selected girder spacings. Maximum girder spacing was set
at 10 ft (3.05 m). The dashed line is an optimum cost curve.

Fig. 6 illustrates the effect of girder spacing on cost. For a given span, as girder spacing increases, unit cost per square foot of bridge deck decreases. For an AASHTO Type VI section, if girders are spaced 10 ft (3.05 m) apart, the cost per unit area of bridge deck is 30 percent less than if girders are spaced 4.5 ft (1.37 m) apart. Therefore, it is most economical to place girders at the largest practical girder spacing. This fact has already been suggested by Scott\textsuperscript{10} and Jacques.\textsuperscript{11}

**Cost-Effectiveness Comparisons**

Optimum cost curves were used to compare the cost effectiveness of selected girders. Spans in excess of 80 ft (24.4 m) were investigated. Girder spacings considered ranged between 4.5 and 10 ft (1.37 and 3.05 m). A few selected cases are compared here.

**Overall Comparisons**

Optimum cost curves for AASHTO Type VI, Colorado G68, Washington Series 14, and Bulb-T BT72 girders are compared in Fig. 7. These girders are
intended to be used for spans in excess of 100 ft (30.5 m). Fig. 7 indicates that Bulb-T BT72 is the most economical for spans up to 135 ft (41.2 m), and that AASHTO Type VI girder is the most expensive.

Modified girders G68/6, Series 14/6, and BT72/6 are compared with an AASHTO Type VI girder in Fig. 8. For spans up to 140 ft (42.7 m), Modified Bulb-T BT72/6 is the most economical and is on the average about 3 percent cheaper than a Modified Washington Series 14/6 girder.

Optimum cost curves for Modified Bulb-T's and Modified Washington Series girders are plotted in Fig. 9. Up to spans of 140 ft (42.7 m), Modified Bulb-T's are most economical. Modified Bulb-T's are compared with AASHTO sections in Fig. 10. For spans from 80 to 120 ft (24.4 to 36.6 m), Modified Bulb-T's yield savings of about 17 percent when compared with the AASHTO girders. For spans of 120 to 140 ft (36.6 to 42.7 m), cost savings vary from 17 down to 2 percent.

These comparisons show that consid-
erable savings can be achieved by using Modified Bulb-T’s rather than AASHTO girders for spans up to 140 ft (42.7 m). Modified Washington Series 14/6 girders lead to savings over AASHTO Type VI girders for spans up to about 150 ft (45.7 m).

Web Thickness

Comparisons of Bulb-T’s, Washington Series, and Colorado G68 sections with 5-in. (127 mm) thick webs and similar sections with 6-in. (152 mm) thick webs show that girders with 6-in. (152 mm) thick webs cost 3 to 5 percent more than similar girders with 5-in. (127 mm) thick webs. However, sections with 6-in. (152 mm) thick webs are easier to manufacture throughout the United States, according to the survey results of Phase 1.

Comparisons between AASHTO sections and Modified AASHTO sections with 6-in. (152 mm) thick webs showed that Modified AASHTO sections yield cost savings of about 6 percent when compared with AASHTO sections.

Fig. 8. Comparison of optimum cost curves for AASHTO Type VI and Modified G68/6, Series 14/6 and BT 72/6 Girders.
Effect of Concrete Strength

In all these comparisons, the girder’s concrete compressive strength was assumed to be 6000 psi (41.4 MPa). Comparisons showed that by increasing the girder’s concrete compressive strength, from 5000 to 7000 psi (34.5 and 48.3 MPa), maximum span capability of a section was increased by about 15 percent.

Effect of Bundling Strands

In the above comparisons, strands were assumed spaced 2 in. (50.8 mm) on center at midspan. Strands were positioned as low as practical in the section to obtain maximum eccentricity of the prestressing force. Some girders were analyzed assuming that strands were bundled at midspan. Comparisons showed that overall cost savings and increase in span capability due to bundling of strands were negligible.

SI CONVERSION

Recently, new International System of Units (SI), metric sections were adopted in Canada under an arrangement agreed to by the prestressed concrete producers.

For an unspecified period of time, bridges in Canada will be designed using the new metric sections, but alternate designs will be provided based on existing nonmetric sections.

Since the new sections are more efficient than the existing ones, it was felt that the changeover would be accelerated by the competitive need to use the new sections.
CONCLUSIONS

Based on the survey of Phase 1 and cost analyses of Phase 2, the following conclusions have been made:

1. In all states surveyed except California, the most economical bridges for spans of approximately 70 to 130 ft (21.3 to 39.6 m) are constructed with pretensioned bridge girders. In California, cast-in-place post-tensioned box-girder bridges are most economical because contractors have more experience with this type of construction.

2. When compared with other sections, AASHTO standard bridge girders are not the most structurally efficient or cost-effective for spans of 80 to 140 ft (24.4 to 42.7 m).

3. Because of transportation restrictions, maximum spans made of single units are limited to about 140 ft (42.7 m). Longer spans are possible by splicing girders.

4. Intermediate diaphragms are not needed; end diaphragms are sufficient.

5. For girders with 5-in. (127 mm)
thick webs, the most cost-effective sections are Bulb-T's. For spans from 80 to 120 ft (24.4 to 36.6 m), Bulb-T's have 20 percent less in-place cost for girder and deck compared with AASHTO girders. For spans of 120 to 135 ft (36.6 to 41.2 m), the cost reduction for Bulb-T's varies from 20 to 5 percent. The next most cost-effective sections with 5-in. (127 mm) thick webs are the Washington Series.

6. In most regions of the United States, it may not be easy to consolidate the concrete in girders with 5-in. (127 mm) thick webs. Moreover, in these girders, the strands must be bundled at midspan, and end blocks are needed to conform with minimum concrete cover requirements.

7. By using girders with 6-in. (152 mm) thick webs, it will be possible to consolidate concrete in these girders in all regions of the United States. However, the use of girders with a 5-in. (127 mm) thick web will be beneficial where practical experience has shown the thickness to be satisfactory.

8. Use of 6-in. (152 mm) thick webs instead of 5 in. (127 mm) thick webs in Bulb-T's, Washington Series, and Colorado G68 girders increases the overall in-place cost of girder and deck by only 3 to 5 percent.

9. For girders with 6-in. (152 mm) thick webs, the most cost-effective sections are Modified Bulb-T's. For spans of 80 to 120 ft (24.4 to 36.6 m), Modified Bulb-T's have 17 percent less in-place cost for girder and deck compared with AASHTO girders. For spans of 120 to 140 ft (36.6 to 42.7 m), the cost reduction varies from 17 to 2 percent.

10. Next to Modified Bulb-T's, Modified Washington Series girders with 6-in. (152 mm) thick webs are the most cost-effective sections. For spans from 80 to 120 ft (24.4 to 36.6 m), overall reduction of the in-place cost of girder and deck is 14 percent. For spans of 120 to 140 ft (36.6 to 42.7 m), cost reduction ranges from 14 to 2 percent compared with AASHTO girders.

11. Reduction of top and bottom flange widths and web thicknesses of AASHTO Types IV, V and VI girders by 2 in. (50.8 mm) reduces the overall in-place cost of girders and deck by about 6 percent. Span capability of the modified sections is not affected by this change in width.

12. The overall in-place cost of girders and deck is decreased substantially by placing girders at the largest practical girder spacing.

13. An increase of the girder's concrete compressive strength from 5000 to 7000 psi (34.5 to 48.3 MPa) increases the span capability of AASHTO girders by about 15 percent.

14. Bundling of strands at midspan in order to increase eccentricity of prestress does not lead to any significant overall cost reduction for the girders considered.

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Several states and producers participated in the survey. The Prestressed Concrete Institute, members of the PCI Committee on Bridges under James H. Barker, Chairman, and other individuals provided information. Their numerous contributions are gratefully acknowledged.
RECOMMENDATIONS

Based on the cost-analysis results discussed in the report and on the above conclusions, the following are recommended:

1. Modified Bulb-T girders with 6-in. (152 mm) thick webs are recommended for use as national standard precast, prestressed concrete bridge girders in the United States for spans for 80 to 140 ft (24.4 to 42.7 m).

2. If metrication is adopted in the United States, modification of the above sections to SI (metric) units should be considered as part of any standardization.

3. Girder spacing should be as large as possible.

4. A synthesis report is needed on techniques available for splicing girders for spans in excess of 135 ft (41.2 m).

5. Lightweight concrete should be given more consideration for bridges built with precast, prestressed concrete girders and cast-in-place concrete deck. Although lightweight concrete has a cost premium above that of normal-weight concrete, overall weight reduction can lead to cost savings.

6. Lateral stability of long-span girders should be investigated to determine critical lengths beyond which girders should be braced laterally during transportation and erection.

IMPLEMENTATION

Construction of the Interstate Highway System has been completed in some states. In most states, it is close to completion. Therefore, the rate of bridge construction on the Interstate System is much slower than it was from the late 1950's to the early 1970's. However, according to statistics prepared by the Bridge Division, Federal Highway Administration, considerable new bridge construction and major reconstruction is taking place.

The cost of new prestressed concrete bridge construction and major reconstruction with participation of federal funds authorized during calendar year 1980 totaled $695 million. Based on bridge inventory and inspection records, it is anticipated that "... in the next 20 to 30 years, we will have over $30 billion worth of bridge construction based on the value of the dollar today."14

As mentioned, selection of bridge type is based on economy. Safety standards for Interstate and other high-speed highways require greater clearances. Therefore, there is need for construction of bridges with spans of 110 to 130 ft (33.5 to 39.6 m). In all states surveyed except California, the most economical bridges for spans of approximately 70 to 130 ft (21.3 to 39.6 m) are constructed with pretensioned bridge girders.

The cost analysis indicate that Modified Bulb-T's can yield savings of 17 percent on the overall cost of girder and deck compared with AASHTO girders. This is in addition to the fact that the Modified Bulb-T's are about 35 percent lighter than AASHTO girders for comparable spans. A 140-ft (42.7 m) AASHTO Type VI girder is extremely heavy and therefore difficult to transport on highways. Lighter sections with 140-ft (42.7 m) spans have been transported on highways without difficulty.

Although steel forms constitute a capital investment, their life span is limited to about 10 years. Cost savings resulting from use of optimized concrete girders should be adequate to cover the cost of new forms over a period of a few years in areas where AASHTO girders are used. Where new
forms are needed, new plants built, or improved sections sought, optimized sections should be considered. The implementation of new sections should be gradual over a period of time. It will require effort on the part of both departments of transportation and producers. Preparation of design aids for the new sections will encourage and facilitate implementation of the new sections.

Highway agencies should be informed of the economic benefits that can be achieved with optimized sections. Departments of transportation will have to design with old and new sections over a transition period. The Canadian experience in switching to new metric sections sets an example of implementation of new sections under an arrangement agreeable to producers and highway agencies.

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NOTE: Discussion of this paper is invited. Please submit your discussion to PCI Headquarters by March 1, 1983.