Summary Paper

Feasibility Study of Standard Sections for Segmental Prestressed Concrete Box Girder Bridges

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Segmental prestressed concrete box girder bridges were introduced in North America in the late sixties and early seventies, following their successful entry into the European market during the post World War II reconstruction period. Several bridges of this type, both precast and cast in place, were built successfully in the United States and Canada during this time, and the approximately 70 projects which have been designed to date indicate that the segmental prestressed concrete box girder bridge is a very viable alternative for medium to long span bridge structures in North America.

At the same time, it is recognized that the design and construction of segmental bridges still largely follow practices in Europe and that a closer identification with American construction practice is in order. Standardization of certain aspects of segmental box girder bridges appears to be one way to ex-

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NOTE: This Summary Paper is a condensation of the results of an investigation commissioned by the Federal Highway Administration on the feasibility of using standard sections for segmental prestressed concrete box girder bridges. The study was initiated in 1980 and completed in July of 1982. The full length report, entitled "Feasibility of Standard Sections for Segmental Prestressed Concrete Box Girder Bridges" (FHWA/RD-82/024) by F. Kulka, S. J. Thoman, and T. Y. Lin is available from the National Technical Information Service, Springfield, Virginia 22161.

Synopsis

Presents the highlights of a study which investigated the feasibility of developing standard sections for segmental prestressed concrete box girder bridges. The report is based on an extensive survey of segmental box girder bridges in the United States and Canada. Recommendations are given for specific items that could be standardized, while also discussing areas which might not be appropriate to standardization.

pand their economical use by instilling confidence among bridge engineers and by producing a cost effectiveness through uniformity in design, thus permitting precasters and contractors to invest in forms and equipment on a broader basis than is done today.

This report deals with the feasibility of standardizing segmental prestressed concrete box girder bridges in the United States. The study relied heavily on a survey of bridge engineers in the United States and Canada, which produced valuable information on all bridges of this type. Statistical studies were conducted to determine correlations and uniformity of significant parameters, particularly with respect to geometry.

Analytical design studies, mainly to determine the economical use of materials, were made to augment the statistical analyses. The results were evaluated both qualitatively and quantitatively, and an advisory technical review committee was formed to review the content of the study and its recommendations.

The report takes the position that standardization of segmental prestressed concrete box girder bridges is possible and should be initiated. The specific areas which should be standardized are listed and discussed in the report, as are those which are not currently subject to standardization and those which are questionable.

Scope of Study

Standardization of highway construction elements is a long-standing practice in the American highway industry. Development of the AASHTO-PCI I-girders is one example; precast concrete culverts, traffic barriers, and piles are other examples. It is fairly well agreed that standardization has merits in cost savings, reduction of construction time, and improved product quality.

It was felt that for standardization of box girder sections to succeed, a uniform approach should be used in order to permit bridge engineers to design such sections with a sufficient degree of uniformity and to allow precasters and contractors to bid and build them as they would any other advanced type of structure.

The object of this study, then, was to consider all the advantages and disadvantages of standardization and make appropriate recommendations for future development. In doing so, care was taken not to let standardization limit competition; rather, standardization was approached with a view towards exploiting all the alternatives, thereby improving design and increasing competition. The scope of the study included:

1. An assessment of the state of the art of segmental bridge construction.
2. Development of design constraints as affected by construction limitations.
3. An analysis of costs and benefits of standard sections.
4. Development of specific recommendations concerning the feasibility of standard sections for segmental prestressed concrete box girder bridges.

Study Approach

It was felt essential that the recommendations concerning possible standardization be based on experiences with existing practices rather than on arbitrary judgments.

Accordingly, a questionnaire concerning prestressed concrete segmental box girder bridges was sent to bridge engineers in all states and territories plus the provinces of Canada. The survey included bridge site, state of completion, cross section, design and details, construction, costs and other pertinent information. The response was excellent, and the information collected provided a good sampling for further in-depth studies.

The data obtained were categorized and statistical studies were made to evaluate significant parameters, leading to a rational assessment of the state of the art of segmental bridge design and construction. Analytical studies were performed in cases where data were not available, permitting the establishment of qualitative and quantitative relationships.

State of the Art of Box Girder Bridges

Cast-in-place, conventionally formed box girder bridges had been used in North America for many years when, in the late sixties, segmental box girder construction was introduced to the continent. This type of structure was a European development of the post-World War II era, when the reconstruction of war-torn European countries demanded methods of construction which would overcome the scarcity of labor and which would produce many structures in the shortest possible time. The development of cast-in-place segmental construction is generally attributed to Germany, while precast segmental construction is primarily a French innovation.

Since the volume of construction was large and there was sufficient investment available, the box girder became popular even though it is not necessarily the most economical section for all conditions. The box girder can, however, safely accommodate spans up to 800 ft (244 m) and resist a wide range of stresses. Furthermore, its resistance to torsion made the box girder particularly suitable for cantilever construction, which proved to be a good method for rapid construction and for achieving long spans without the use of falsework or shoring.

The Lievre River Bridge in Quebec (completed in 1967) was the first precast prestressed segmental bridge built in North America. This was followed shortly by the Bear River Bridge near Digby, Nova Scotia. The first major segmental box girder bridge in the United States was the JFK Memorial Causeway in Corpus Christi, Texas (completed in 1973).

As a result of a fairly active program of promotion, more than 50 segmental bridges have been constructed in North America since that time. Their record with respect to economy and successful

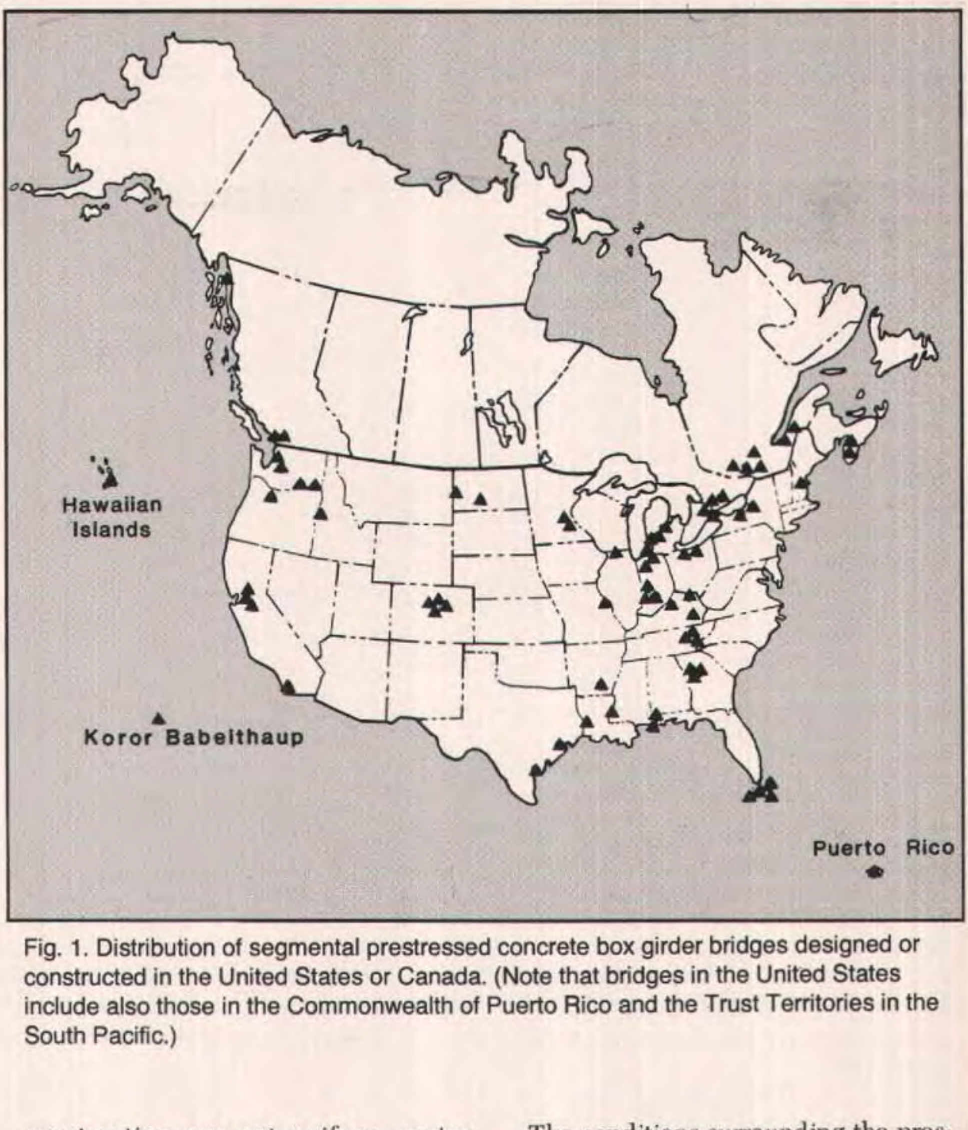

Fig. 1. Distribution of segmental prestressed concrete box girder bridges designed or constructed in the United States or Canada. (Note that bridges in the United States include also those in the Commonwealth of Puerto Rico and the Trust Territories in the South Pacific.)

construction was not uniform, owing mostly to a wide variety of site conditions, design practices, specifications and bidding requirements. The 1980 dollar cost per square foot of bridge deck of some 37 segmentally constructed box girder bridges appears to vary widely from \$30 to \$150 (\$323 to \$1615/m²). Nevertheless, sufficient cases of successful and economical construction exist to make the segmental box girder a very viable choice in the concrete bridge market.

The conditions surrounding the present state of segmental box girder construction raise the obvious question of standardizing at least some aspects of its design and detailing. Ideally, standardization could bring about cost benefits by permitting contractors to invest in forms, installations and equipment which could be reused more often, thus reducing the cost of mobilization. Details and joinery could be simplified in the process of standardization, and overall safety and integrity could be

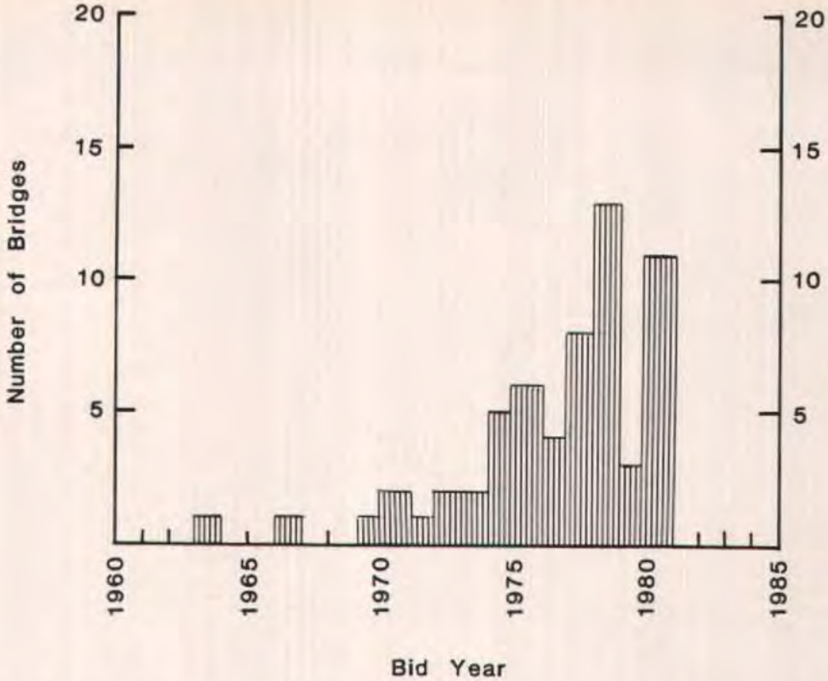

Fig. 2. Number of bridges bid in successive years.

added to the structure by making available past experience and knowledge to those new in the industry.

The map in Fig. 1 shows the distribution of existing segmental bridges in North America (which also includes the Commonwealth of Puerto Rico and the Trust Territories in the South Pacific) in 1981. It can be seen that the vast majority of these bridges lie in the eastern part of the United States, which is consistent with the distribution of other bridges as well. Bridges shown on this map are located in Canada and 18 U.S. states and territories.

The histograph in Fig. 2 shows the bridges as they were bid. It can be seen that there is a steady increase in the number of bridges from 1970 to the eighties. The peaks and valleys are not too important, since the time at which the bridge incidence was plotted can vary with respect to the completion of design or start of construction. The three bridges before 1970 were built in Canada, which preceded the United States in segmental bridge construction. Nevertheless, Fig. 2 shows a steady increase in the use of segmental bridges and dramatically so in the late seventies. Indeed, it may be concluded that this method of bridge construction is here to stay.

The five major types of construction which have been employed are the balanced cantilever type (precast and cast in place), span-by-span construction, progressive placing, and incremental launching.

In the balanced cantilever construction method the segments are cantilevered out from each side of their support, so as to balance the moment which is induced in the pier. The segments can either be precast or cast in place.

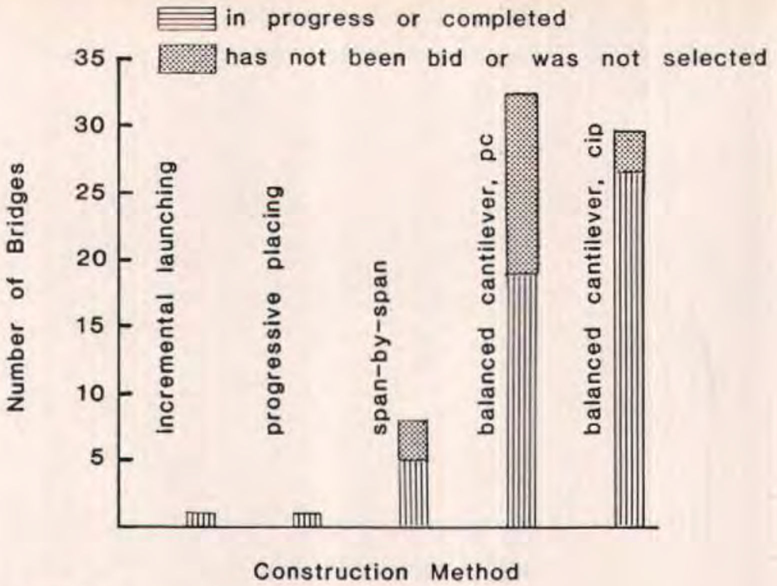

Fig. 3. Frequency of various construction methods.

In precast construction the segments are manufactured at a factory or at the project site. The segments are then transported to the bridge superstructure and lifted into their final position where they are post-tensioned against the previously erected segments.

In cast-in-place construction a form traveler is employed to carry the forms into which the segments are cast in their final position. After the concrete has reached sufficient strength, the segment is post-tensioned against the already completed superstructure.

The span-by-span method features a superstructure constructed in one direction, one span at a time, incorporating either precast or cast-in-place segments.

The progressive cantilever method is similar to the balanced cantilever cast-in-place construction method, except that the segments cantilever outward from only one side of the pier, while the sidespan is cast on falsework.

In the incremental launching method the segments are cast near the bridge abutment. Once a segment has reached sufficient strength, it is post-tensioned, then vertical and horizontal hydraulic jacks are engaged to lift the segments and push them out longitudinally from the abutments.

Fig. 3 shows the number of segmental bridges classified according to construction method. Balanced cantilever, both cast in place and precast, comprises by far the largest percentage of bridges. It is interesting to note that in reviewing bidding history, more contractors favored cast in place rather than precast segments when they had a choice in the method of construction. One reason for this is that contractors are in general more experienced with cast-in-place construction methods.

Of the 33 bridges designed in precast segments, 15 were constructed; the others were not built or changed to a different type. Of the 27 balanced cantilever bridges 24 were constructed as designed; the others were either not built or changed to a different type. Incremental launching and progressive

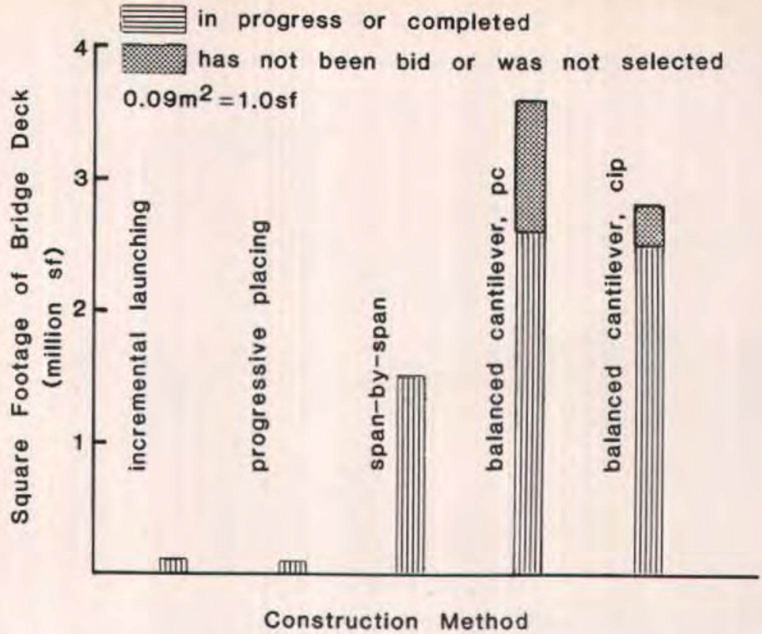

Fig. 4. Total square footage of bridge deck for various construction methods.

placing represent only one bridge each, hence, cannot necessarily be considered representative.

The bridge deck area for the various methods of construction is shown in Fig. 4. It may be seen that span-by-span construction encompasses about 30 percent of the total bridge deck area, but as shown in Fig. 3, represents only about 10 percent of the total number of bridges. That indicates that this method obviously was applied to very large projects. In balanced cantilever construction the total bridge deck area is about equally divided between cast-in-place and precast structures as designed, but the proportion of bridges actually constructed to the total designed is higher for the cast-in-place structure.

The project size greatly influences the method of construction to be used. Table 1 shows the average length of segmental bridges surveyed. Here the total deck area of bridges for each type of construction was normalized to an equivalent 40-ft (12 m) width, and the resulting total bridge length was then divided by the number of particular bridges, thus obtaining an average length of bridge for each construction type. The numbers show that the average length for span-by-span construction is about 40 percent larger than for balanced cantilever. In other words, it

Table 1. Average bridge lengths for various construction methods.

Construction method	Average length for a 40-ft (12 m) roadway
Incremental launching	1087 ft (331 m)
Progressive placing	1165 ft (355 m)
Span-by-span	5347 ft (1630 m)
Balanced cantilever	
(precast)	3133 ft (955 m)
(cast in place)	2818 ft (850 m)

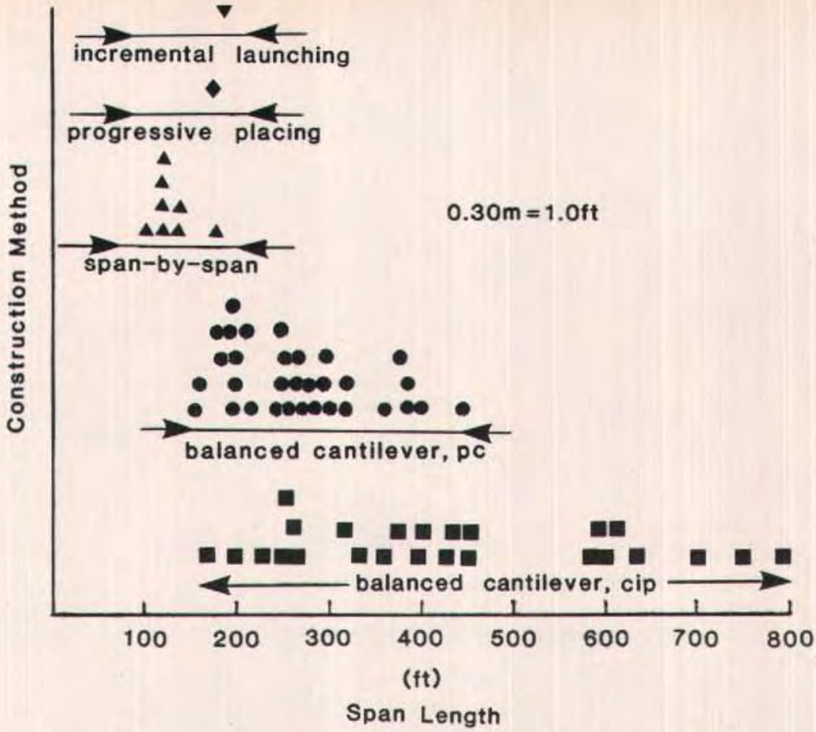

Fig. 5. Span ranges of box girder bridges for various construction methods.

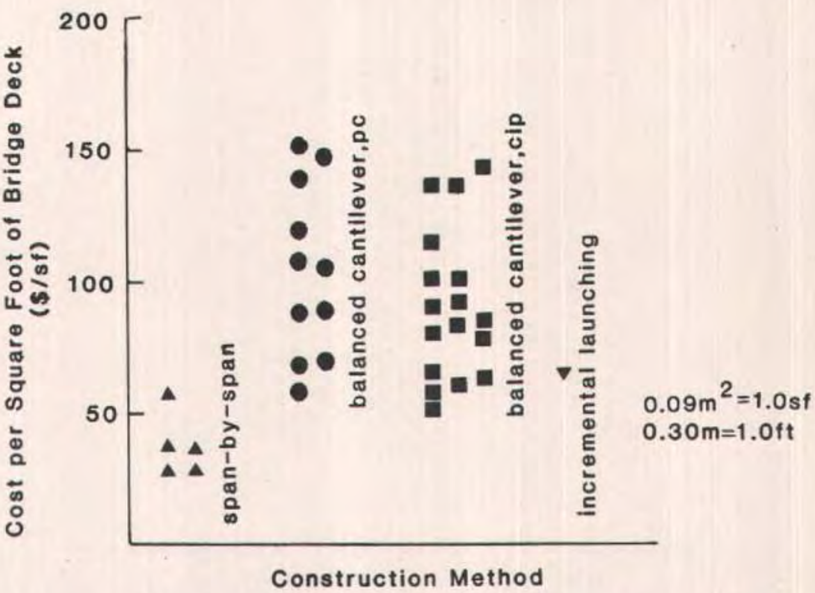

Fig. 6. Cost of segmental prestressed concrete box girder bridges for different construction methods.

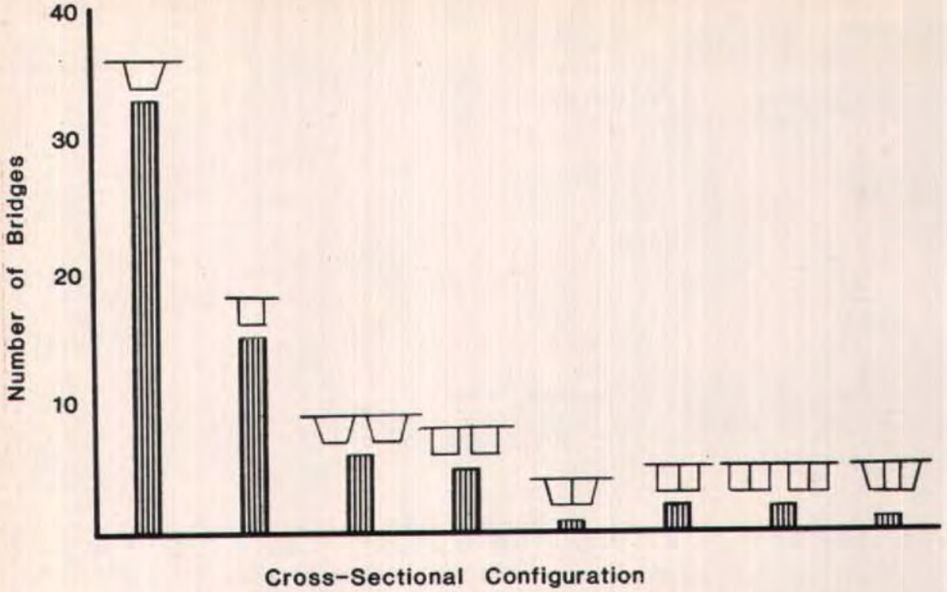

Fig. 7. Frequency of various cross-sectional configurations of box girder bridges.

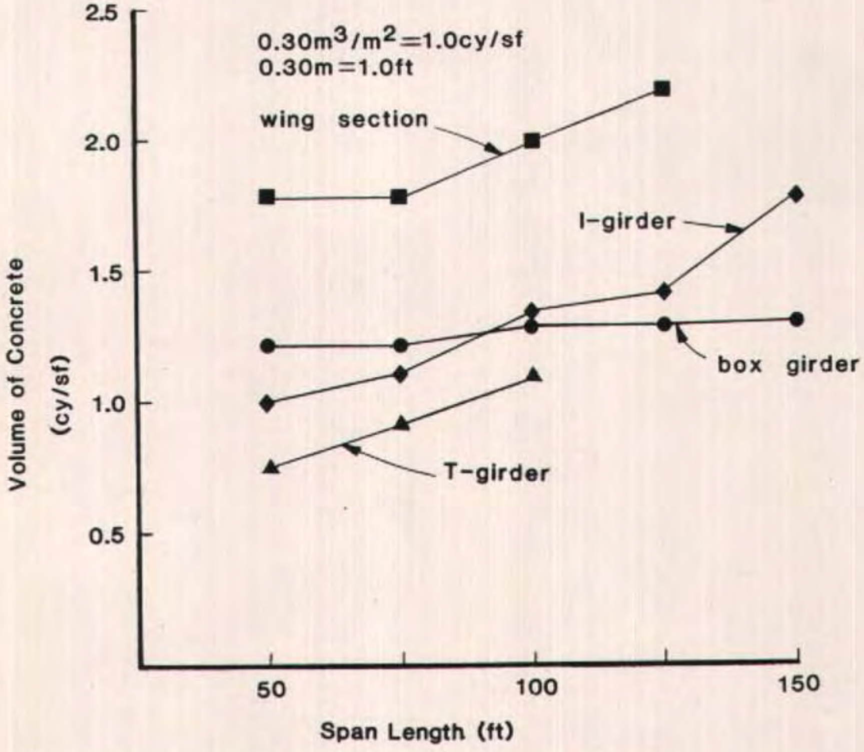

Fig. 8. Weight of mild steel reinforcement for various girder types.

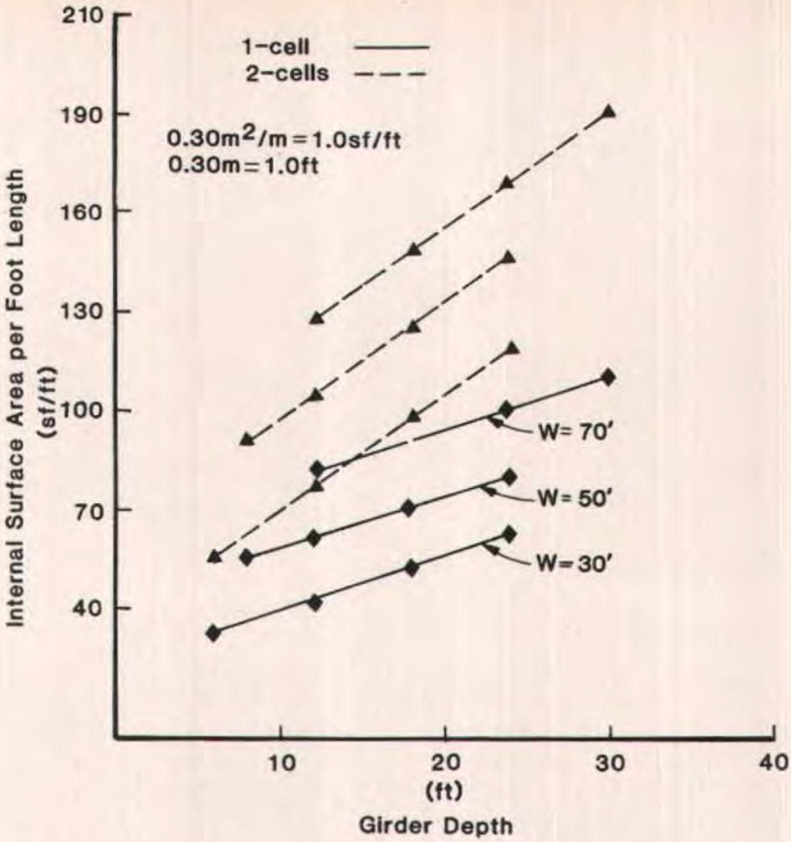

Fig. 9. Internal surface forming area for various deck widths and girder depths.

takes a larger project with many short spans, as for example a causeway, for this method to be economical as compared to other structural sections.

The distribution of construction methods for segmental bridges with respect to span length is shown in Fig. 5. It can be noted that the balanced cantilever method was used primarily for spans greater than 200 ft (61 m). The span-by-span method was used for spans between 80 and 180 ft (24 and 55 m) as were the incremental launching and progressive placing methods. For spans longer than 450 ft (137 m), only cast-in-place segments were employed, most likely because of the increased weight of precast segments needed for long spans.

Fig. 6 shows the costs of these bridges. It may be seen that there is no obvious uniformity to be discerned from these cost figures. Partially, the reason for this is the fact that accurate costs are very difficult to establish. First of all, cost figures are not readily available; secondly, when they are available it is not totally clear what the costs cover. However, costs do vary widely principally as the result of lack in uniformity of design and construction practices. In any event, the figures might demonstrate qualitatively the fact that costs of the bridges varied considerably within the construction method itself, in addition to differences between the various construction methods.

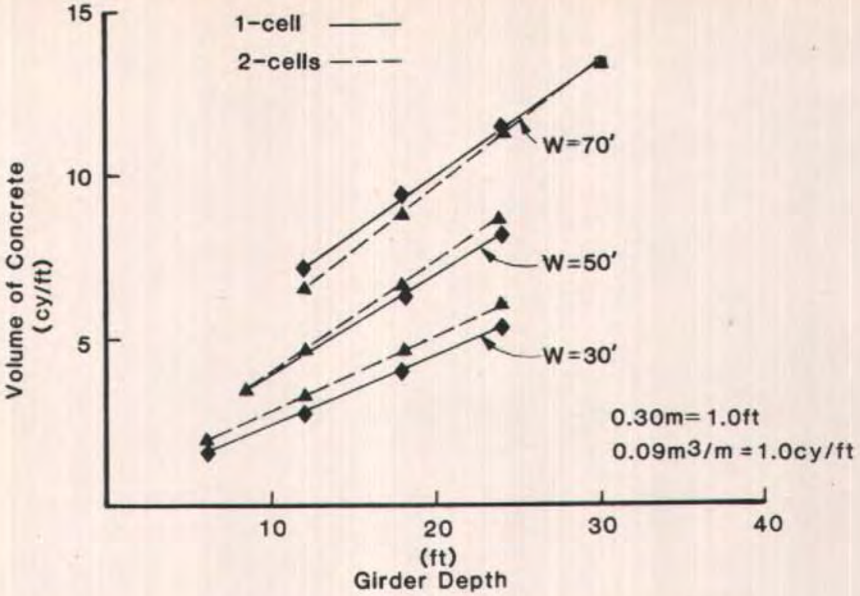

Fig. 10. Volume of concrete for various deck widths and girder depths.

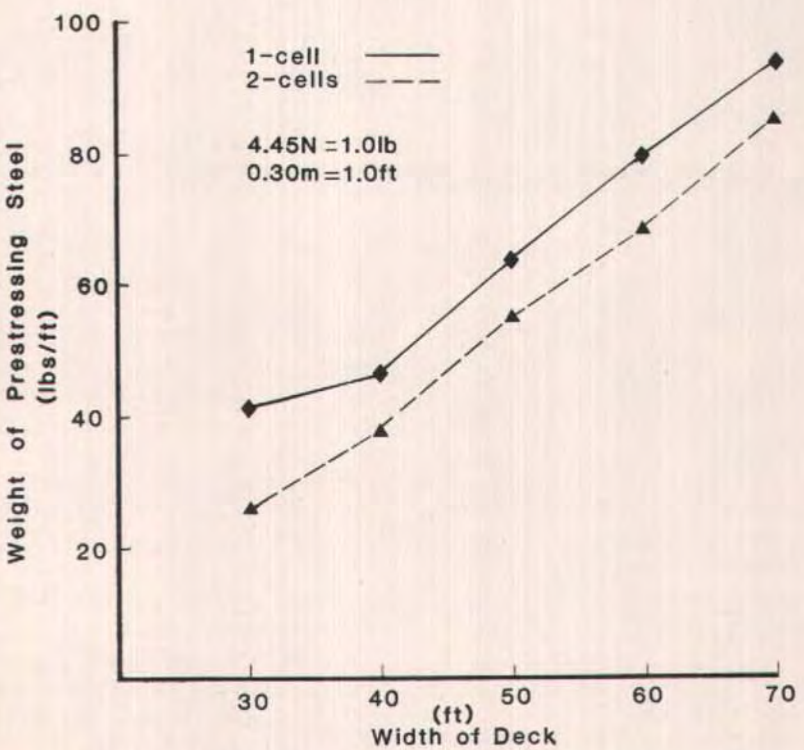

Fig. 11. Weight of transverse prestressing steel for various deck widths.

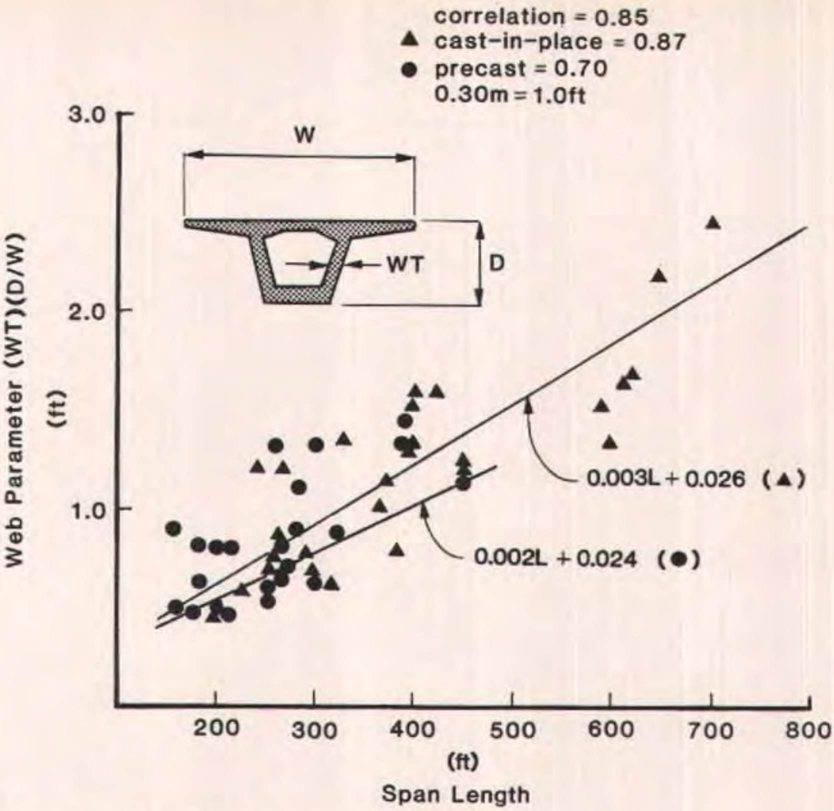

Fig. 12. Variation of web parameter with span length.

Bridge Cross Sections

The cross sections of bridges used in the United States and Canada contained single cells, double cells, triple cells, and twin single cells. The histogram in Fig. 7 shows the number and shape of cells incorporated into the cross section of the box girders used to date. It is evident that the single cell or a combination of single cells is the most widely used section, representing about 90 percent of all bridges surveyed.

In order to establish the cost effectiveness of the single cell and double cell cross-sectional configurations, preliminary designs were made to study required material quantities. The weight of prestressing steel, weight of mild steel, the volume of concrete, and the area of internal forming for various girder depths and roadway widths were compared. Figs. 8 through 11 show relationships between material quantities and girder depths for the various top flange widths of the box sections.

In Fig. 10 it may be seen that the volume of concrete in a single cell section is less than that of a double box for a 30-ft (9 m) width, but as the width increases the difference diminishes. In a 70-ft (21 m) width the volume of concrete is greater for a single cell than for a double cell. This conclusion may also be reached by realizing that a longer span requires the top flange width to be increased in thickness in order to carry the heavier traffic loading.

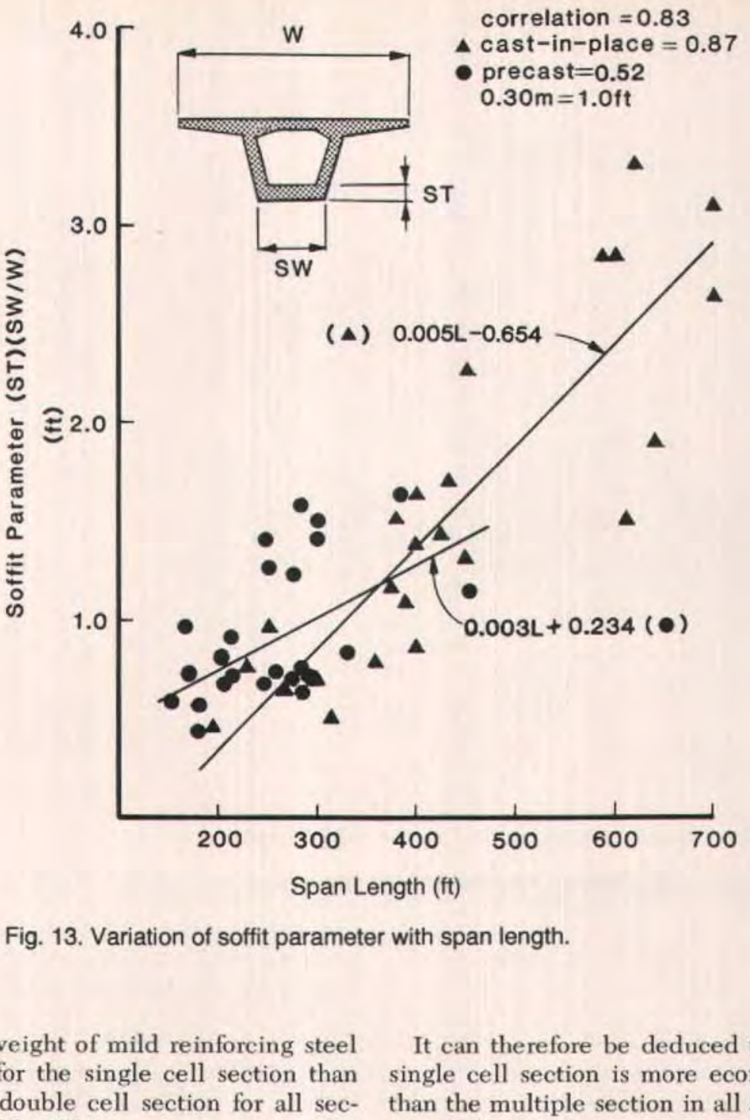

Fig. 13. Variation of soffit parameter with span length.

The weight of mild reinforcing steel is less for the single cell section than for the double cell section for all section widths. This, again, is reasonable, since much of the mild steel is nominal reinforcing and the loads are carried largely by the post-tensioning tendons. The internal surface forming area is considerably less in the single cell section, which translates into great economy for formwork. The elimination of interior webs also produces a more constructable section. The required amount of transverse post-tensioning is, of course, higher for the single-cell section than for the double-cell section.

It can therefore be deduced that the single cell section is more economical than the multiple section in all aspects, except for the transverse prestressing steel. This is true up to a width of approximately 70 ft (21 m), at which point twin single cells should be considered.

Statistical Studies of Dimension Parameters

In order to determine the degree of uniformity in dimensions, parameters in the transverse and longitudinal direction were studied statistically for the

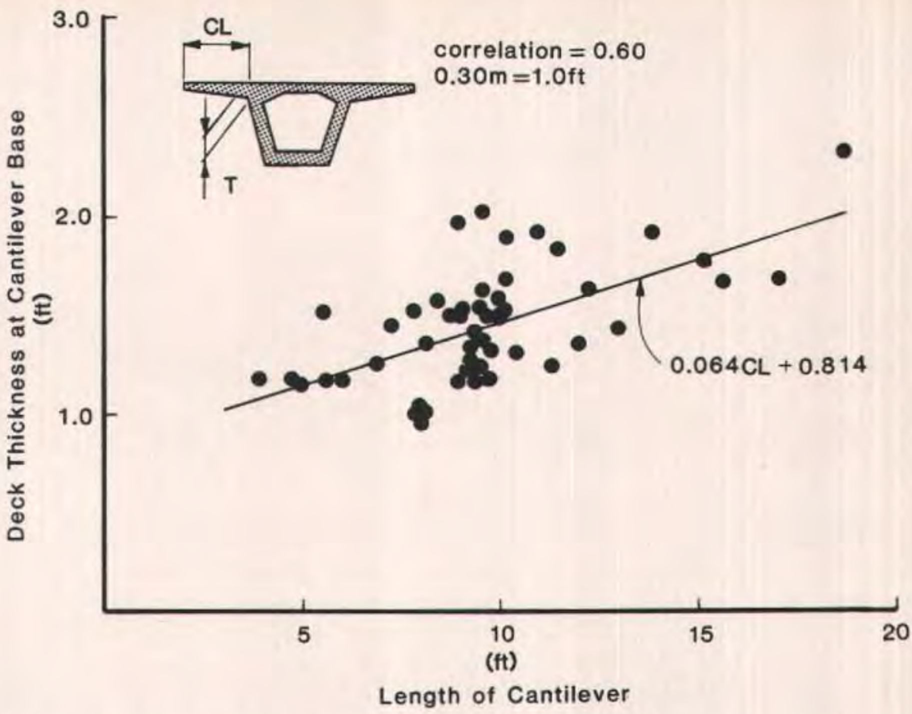

Fig. 14. Variation of cantilever deck thickness with cantilever length.

bridges surveyed. Linear regression curves were fitted through the data points using a least square criterion.

Correlation coefficients were calculated to determine the uniformity between the parameters. The parameters with correlation coefficients greater than approximately 0.80 were considered to be related, indicating uniformity. Such uniformity would suggest that the parameters lend themselves to standardization. Note that precast and cast-in-place bridges were considered together and also independently.

To study the web dimensions for a particular span length, the web area for those bridges surveyed was normalized by the bridge width. This accounted for the varied number of traffic lanes and loading conditions. The web parameter was defined as the total area of the web divided by the bridge width. The relationship between web parameter and span length is shown in Fig. 12. The correlation coefficient was 0.85 when combined and 0.87 and 0.70 when studied independently for cast-in-place and precast bridges, respectively. These values indicate uniformity, which suggests the feasibility of standardization.

It is interesting to note that the function for these precast bridges was below and somewhat parallel to cast-in-place bridges. This indicates that for the same span length the precast segments incorporate thinner webs than their cast-in-place equivalents, which may be related to weight reduction strived for in plant production.

The study of the soffit parameter, shown in Fig. 13, was defined by dividing the soffit cross-sectional area (located near the pier) by the bridge width, which normalized the different bridges surveyed. Quantitatively, when

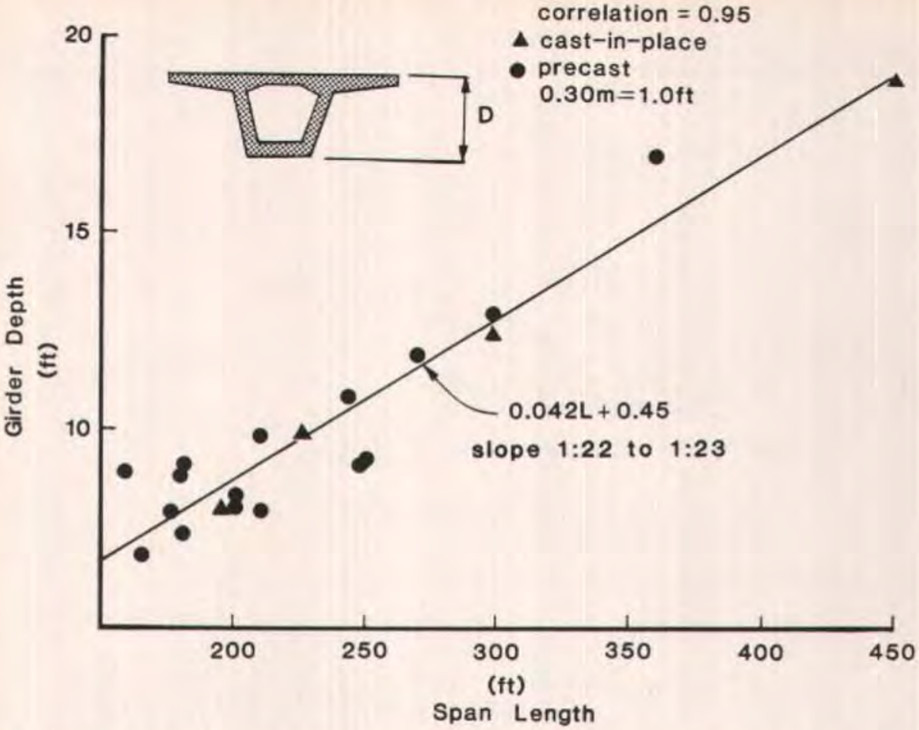

Fig. 15. Variation of girder depth with span length for balanced cantilever construction.

the structural system is continuous over a support, the bottom soffit near the support must develop a compressive force to resist the induced moment. Since this induced moment is related to the span length, the bottom soffit area must also increase with increasing span length. The correlation coefficient considering both precast and cast-in-place segments was 0.83, indicating good correlation.

In Fig. 14, the deck thickness at the cantilever base is plotted against the length of cantilever. The figure represents the results of a study of the deck thickness at the transverse cantilever support as a function of the cantilever length. Although a low correlation coefficient of 0.60 was calculated, the deck thickness could intuitively be standardized for a particular bridge width.

The low correlation may be attributed to the varying amount of transverse prestressing in the deck, which was not included in the study. Also, the deck thickness of the cantilever at its support may be controlled by dimensioning requirements to accommodate the longitudinal tendon anchorages, instead of providing the amount of resistance to induced forces.

A high correlation was found between span length and girder depth for balanced cantilevers with constant depth sections, as shown in Fig. 15. A correlation coefficient of 0.95 was calculated for the bridges considered. Results show that the average span-to-depth ratio was between 22 and 23 for span ranges between 130 and 450 ft (40 and 137 m). Also, the majority of constant depth structures are precast as opposed to cast in plaee.

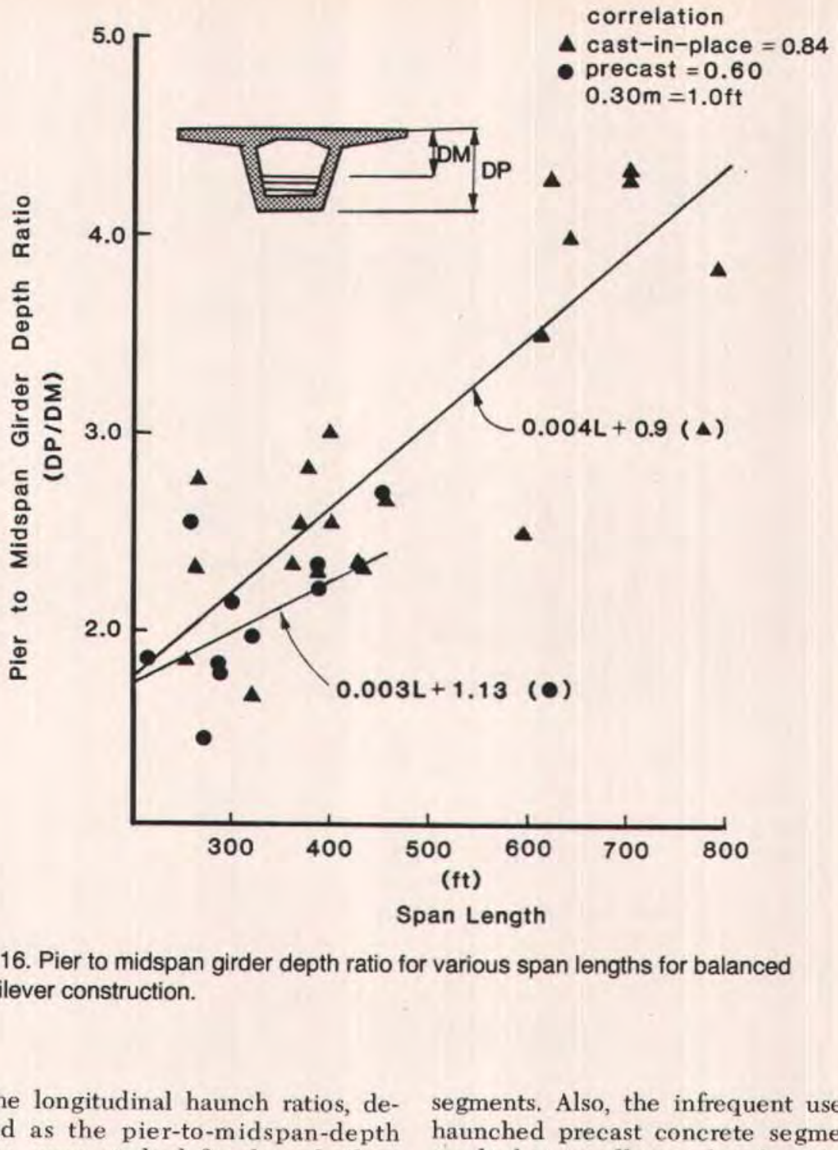

Fig. 16. Pier to midspan girder depth ratio for various span lengths for balanced cantilever construction.

The longitudinal haunch ratios, defined as the pier-to-midspan-depth ratios, were studied for those bridges employing balanced cantilever construction. The results are shown in Fig. 16. The cast-in-place haunch ratios varied from 1.7 for the shorter spans to 4.3 for the longer spans. A correlation coefficient of 0.84 was calculated for cast-in-place bridges, indicating high uniformity. The low correlation coefficient for precast construction may suggest difficulties or reluctance associated with using precast haunched segments. Also, the infrequent use of haunched precast concrete segments resulted in insufficient data for statistical analysis.

Preliminary Designs for Various Construction Methods

Preliminary designs were made to determine the cost effectiveness of the various construction methods. Quantities of materials rather than cost fig-

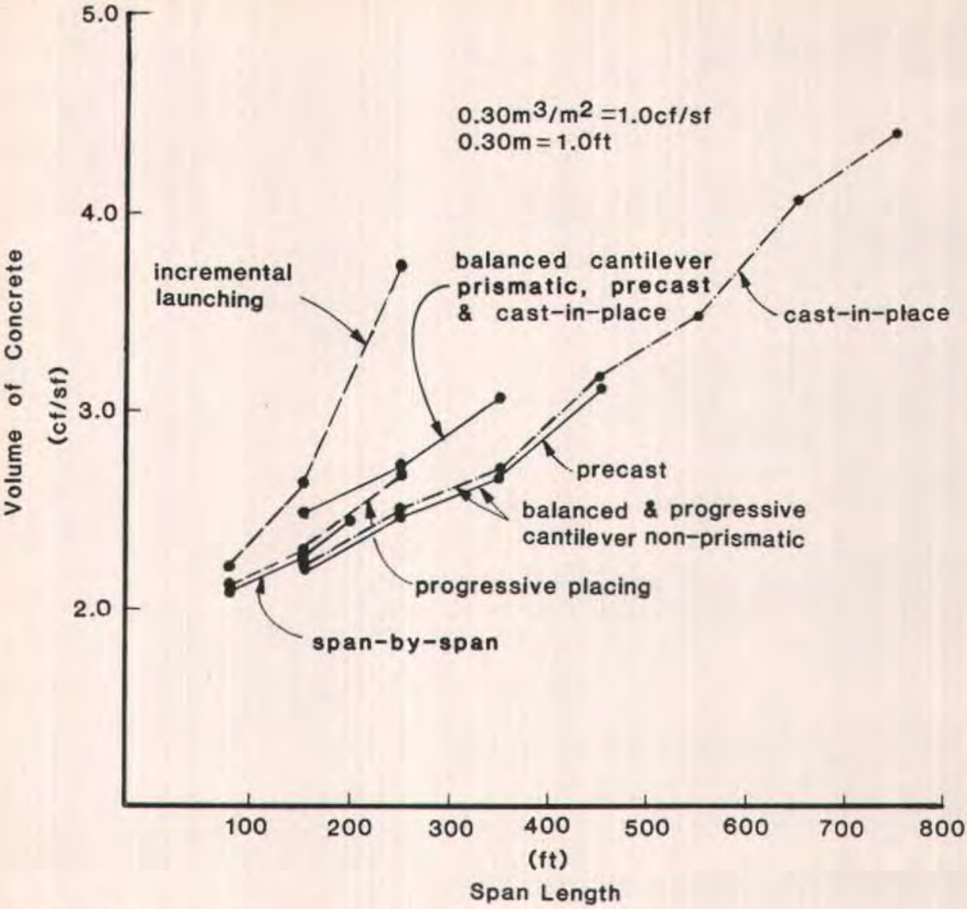

Fig. 17. Volume of concrete for various construction methods.

ures were used, since the latter are too variable.

Fig. 17 shows the volume of concrete plotted against span lengths for the various construction methods. Span-by-span construction is more efficient in the lower span ranges, with balanced cantilever being more efficient in the higher ranges. Incremental launching is cost-effective up to about 200-ft (61 m) spans, but becomes inefficient beyond that point, apparently because of the need to employ concentric prestressing. Progressive placing shows economy of concrete volume up to about 200 ft (61 m).

The weight of prestressing steel versus span lengths is shown in Fig. 18. The relationship is similar to that of volume of concrete for the various methods of construction.

From these curves and from other data presented it may be concluded that balanced cantilever is the most prevalent method of construction for spans over 150 ft (46 m). Up to 300 ft (91 m), precast construction is advantageous because such spans permit a constant depth of section. Once a parabolic haunch is necessary to accommodate the span, the cast-in-place section becomes more appropriate. It has been

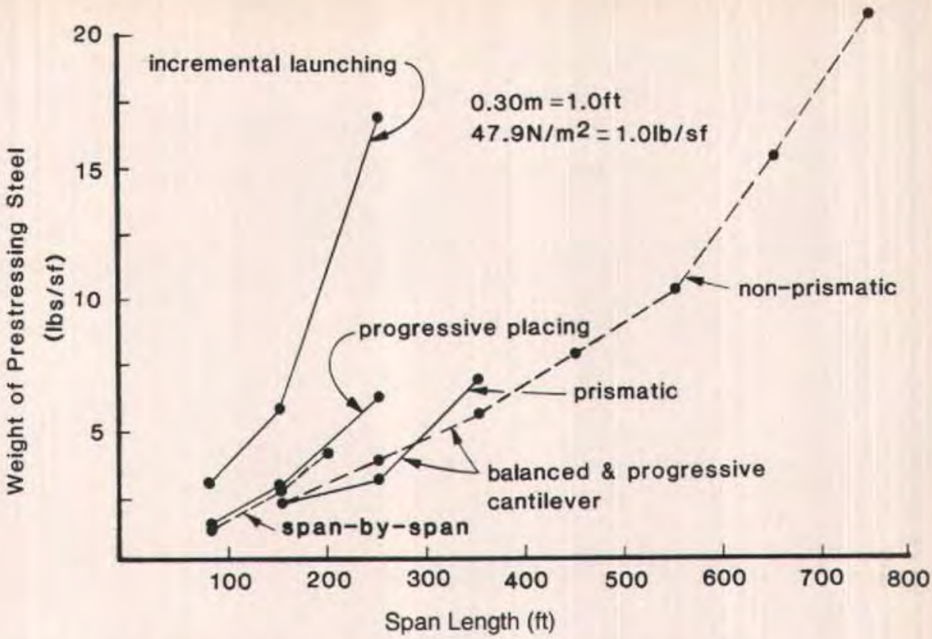

Fig. 18. Weight of prestressing steel for various construction methods.

Table 2. Parameters feasible for standardization.

Parameter	Yes	No	Maybe	Parameter	Yes	No	Maybe
Cross section dimensions	■			Span depth ratios	■		
Shape of box	■			Haunch ratios	■		
Number of cells	■			Radius of curvature		■	
Segment length			■	Construction method		■	
Joint details	■			Span limitations	■		
Post-tensioning details			■	Roadway details			■
Design guides	■			Reinforcement			■
Design criteria	■			Specifications	■		

used for spans up to about 800 ft (244 m). Span-by-span construction is restricted to the shorter spans, perhaps up to 150 ft (46 m).

Items suitable for standardization are summarized in Table 2.

Fig. 19 shows an interesting projection of use, which was based on an additional questionnaire sent to bridge engineers in the United States and Canada. It shows that the projected use, in their opinion, will feature to a great extent spans between 80 and 120 ft (24 and 37 m). This indicates that segmen-

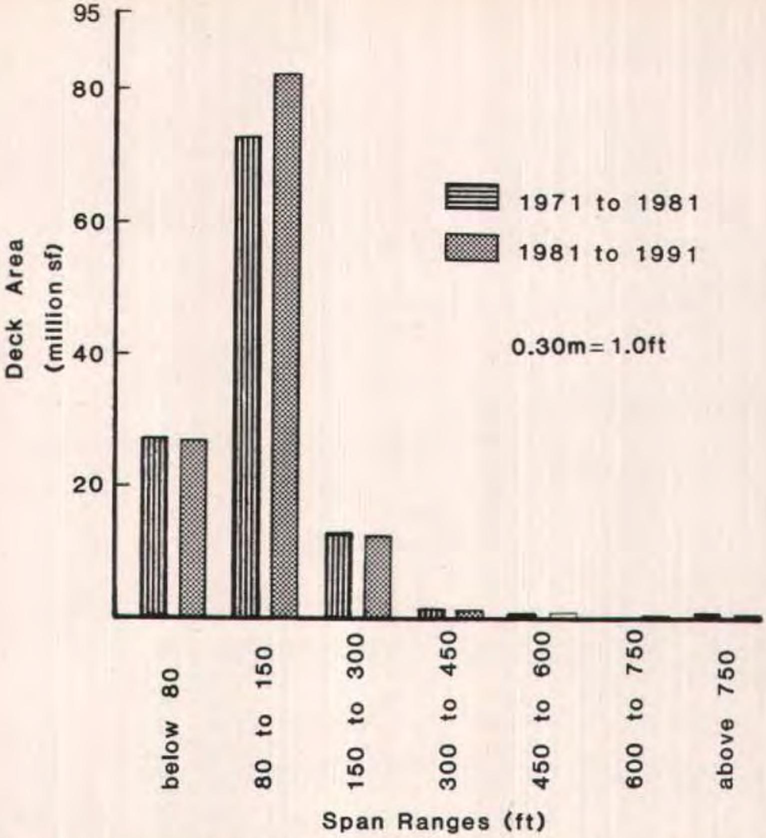

Fig. 19. Comparison of projected total square footage of bridge deck within span ranges for steel, reinforced and prestressed concrete structures.

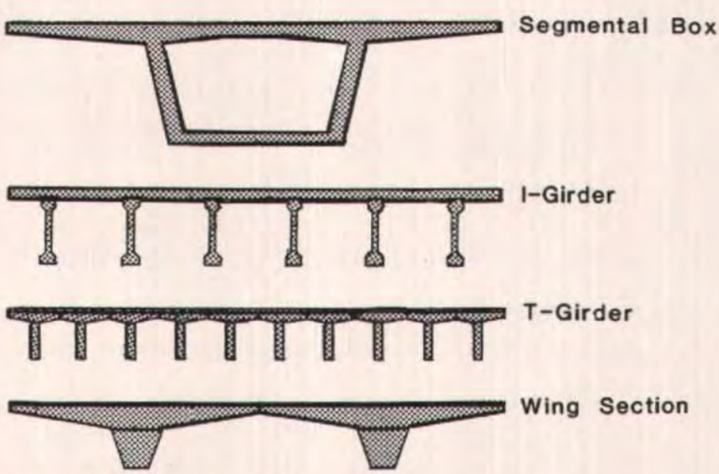

Fig. 20. Configurations of various bridge sections.

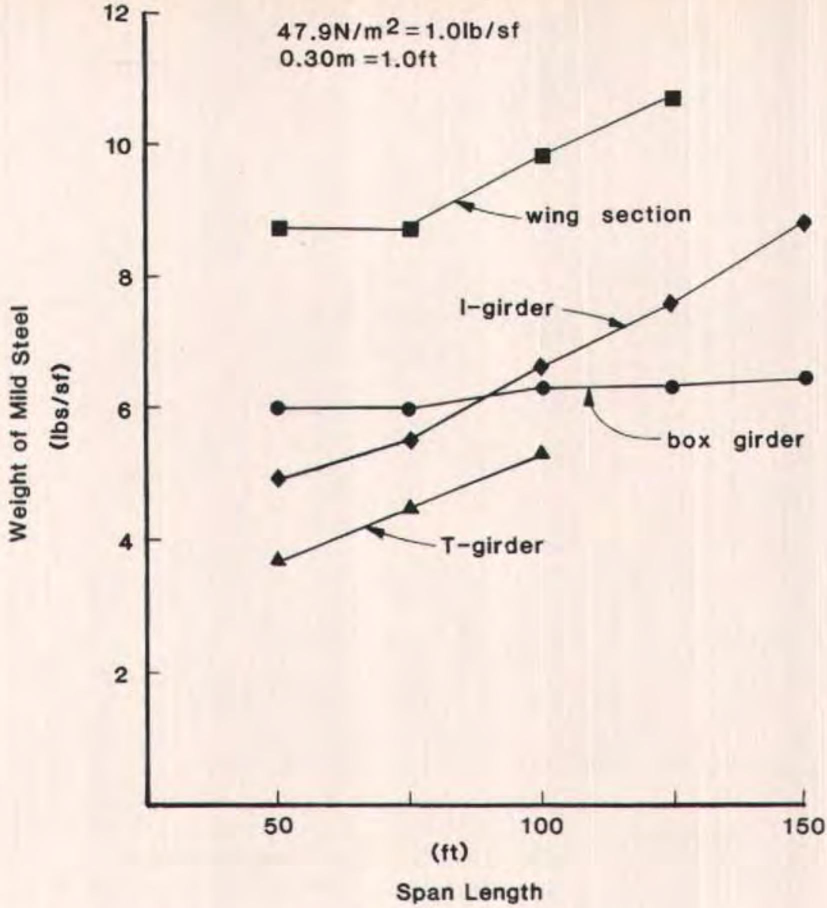

Fig. 21. Volume of concrete for various girder types.

tal box girder construction will have to compete with other types of construction which have shown economies in these particular span ranges. For that purpose a comparative study was made between the box section and other sectional forms.

Comparative Studies of Bridge Sections

An analytical study produced the comparison of quantities for the box section, I-girder, T-section, and wing section, as shown in Fig. 20.

Fig. 21 plots the volume of concrete versus span length, showing that the volume is lowest for the T-section. There is a cross-over point at about 90 ft (27 m) between the box section and the I-section. Comparing the weight of longitudinal post-tensioning steel, as shown in Fig. 22, the I-section is lowest, but there is a cross-over point at about 110 ft (33 m) with the box section. Comparing the mild steel required, the T-section is again lowest (see Fig. 23). The I-section and the box section have a cross-over point at about 85 ft (26 m). Assessing the cost, as shown in Fig. 24,

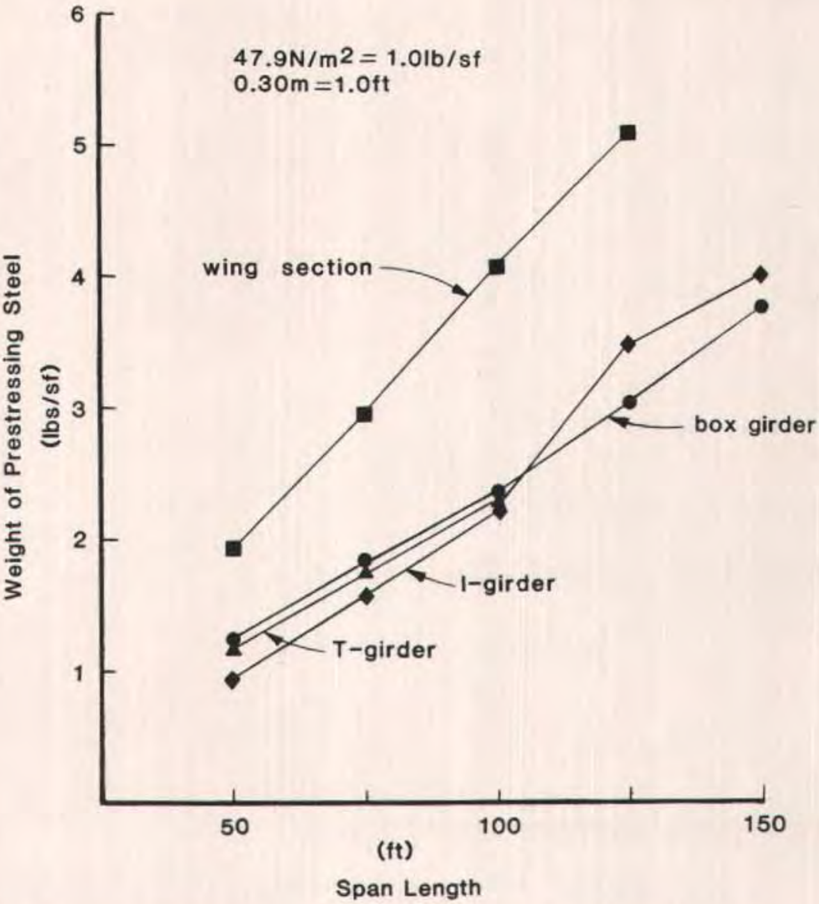

Fig. 22. Weight of longitudinal prestressing steel for various girder types.

the T-girder appears to be the most economical in the lower spans. The box section becomes most economical above about 140 ft (43 m).

This comparison is not absolute, and all types of construction could be economical under certain conditions. Much depends on the mobilization cost, which is a constant cost to be added to the individual curves, but one which is very subjective, and hence cannot be accurately determined. It shows that bridge design should emphasize the option of the contract and permit appropriate redesign of important features within the scope of the specifications.

CONCLUSIONS

The survey of segmental prestressed concrete box girder bridges yielded results which are very encouraging for potential standardization. A sufficient degree of uniformity was found among the various parameters indicating that certain aspects of design and construc-

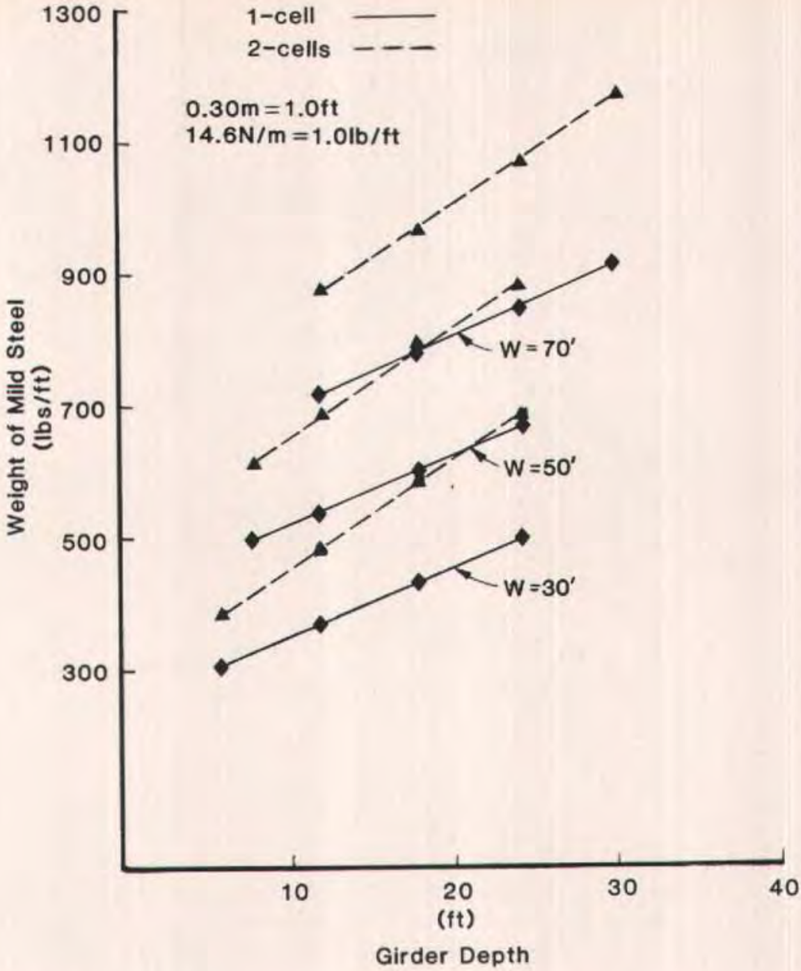

Fig. 23. Weight of mild reinforcing steel for various deck widths and girder depths.

tion can be standardized. The following recommendations are suggested:

1. Only the single-cell box should be standardized. The cross-sectional dimensions to be covered by standardization should accommodate bridge widths between 30 and 70 ft (9 and 23 m). Twin cell bridge box sections can be used to reach roadway widths beyond 70 ft (21 m). Multiple-cell sections should be left to individual design. Both precast and cast-in-place segments should be included in the standardization.

2. The standard sections should specify primary dimensions, as well as secondary dimensions, defining the shape, but permitting variable segment lengths for cast-in-place segments and specifying the segment length for precast segments.

3. Only bridges with constant depth should be considered. Span-to-girder-depth ratios could be specified for constant depth sections.

4. Standardization of sections should be directed to straight bridges with span lengths between 80 and 300 ft (24

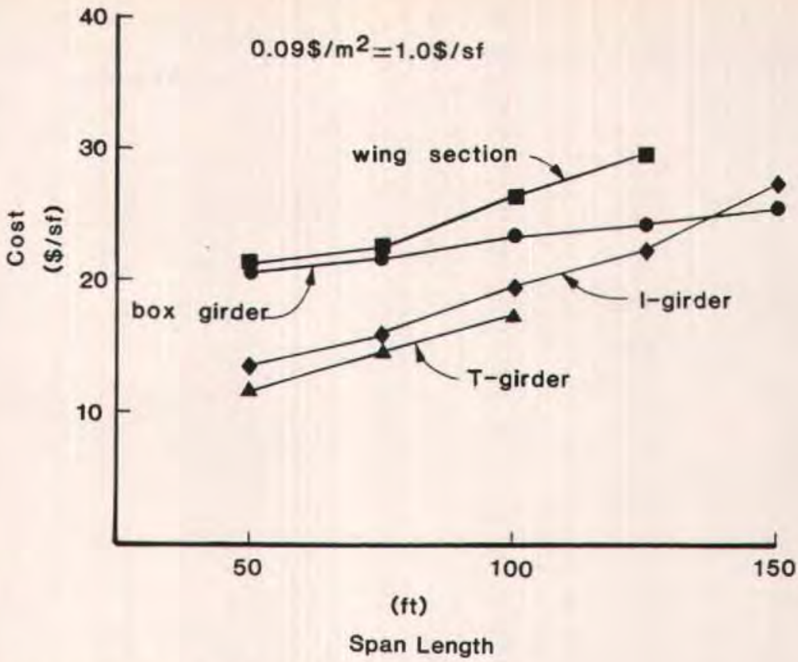

Fig. 24. Cost comparison for various girder types.

and 91 m). For spans greater than 300 ft (91 m), standardization does not yet seem practical, but guidelines for design and construction could be provided. Similarly, recommendations for the accommodation of curved bridges should be included.

5. Construction methods themselves should not be standardized, but the standardization of sections should consider the balanced cantilever method and the span-by-span method, both cast in place and precast. The progressive placing and incremental launching methods are not as yet sufficiently in use to be included in standardization of sections.

6. Longitudinal prestressing design and tendon layout should not be standardized, but the magnitude of prestressing force and eccentricity required for the final condition of the structure should be indicated. Their effect on section dimensions should be considered, especially in conjunction with the transverse prestressing tendon layout in the deck.

7. Transverse prestressing design and tendon layout should be standardized, since they can seriously affect top slab dimensions.

8. Vertical prestressing design and tendon layout for the webs should not be standardized, since they are generally not needed for spans under 250 ft (76 m). The design procedure and detailing may be recommended.

9. The possible use of external tendons for shorter spans should be treated, and recommendations for differential localities and environments should be made.

10. Joints, both match-cast and wet, should be standardized. Single or multiple shear key designs using epoxy betweeñ abutting precast segments could be standardized. The possibility of eliminating the epoxy between the precast segments should be studied further.

11. Typical designs of anchorages and blisters for continuity and cap tendons may be suggested, but not standardized.

12. The use of bonded mild steel reinforcement for partial prestressing, temperature and shrinkage control, stress concentration, prevention of delamination, and other local problems may be recommended.

13. Design of sidewalks, bicycle paths, barriers, and railings should not be standardized.

14. Deflection control, both during construction and after completion, should be taken into account in the dimensioning of standard sections.

15. Location of expansion joints, both temporary and permanent, may affect the design of standard sections, and guidelines should be established.

16. Uniformity in design and specifications should be addressed.

It would be very desirable, indeed, if standardization of segmental prestressed concrete box girder bridges could be accomplished to the same degree as AASHTO I-girders. The approach could certainly be similar to that of the I-girders, inasmuch as dimensional standards and construction practices could be made uniform.

The extent to which such standardization could be carried out is not as clear in the case of box girder bridges, given their complexity, difference in construction methods, span ranges, and other variables. In any event, standardization should be done to enhance the use of segmental bridges by designers and contractors, but it should be conceived and applied so as not to impede new developments which might bring about greater economy, higher safety and better performance.

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NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by May 1, 1984.