Influence of geometry on structural design of concrete box girder bridge

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A parametric study is carried out to assist the designer in proportioning of the box girder bridge. The effect of relative sizes of segments on forces and design details are assessed. The box is analysed for various combination of sizes of the segments by elastic theory of folded plates. Bending moments and shear forces at critical location are obtained and the sections are designed. A set of graphs illustrating the influence of the design variable are given. Recommendations on the optimum relative sizes of box girder are made.

Efficient load carrying capacity, economy, coupled with elegant appearance have made the box girder bridges quite popular. The sleek geometry with proportional structural elements blends harmoniously with the natural landscape and environment.

Designing the optimum cross-section of box girder consists of selecting appropriate values such as overhang flange, web thickness, web slope and soffit thickness. The optimum values of these parameters depend on the bridge span and live load.

With the data and design experience available in the literature, it was realised that it would be well worth to provide more general design guidance capable of being used directly and interpreted by designers.

This paper is an attempt to give certain design recommendations and to provide an information on box girder bridge.

Cross sectional parameters

The main parameters influencing the design of the cross section of a box girder bridge are briefly discussed.

Cross-section type :

The typical cross-sections of box girder bridges consist of single or multicell boxes with the deck cantilevering sideways. These sections are used both in reinforced concrete and prestressed concrete structures. The number of cells should be kept as small as possible in order to minimise the constructional difficulties and also there is no substantial improvement in the transverse load distribution beyond three cells. For economic reasons, more than two cell are rare'. In the choice of the shape of the transverse section of a box girder, the simplest serves the best. Obviously, a single cell box girder is the simplest form and enjoys the widest application. Many variation of this standard cross-section are possible. If the width of the deck does not exceed 14m, it has been found possible to provide a single cell box section with inclined or vertical webs and fairly large cantilever width.

Overhang flange:

The principal elements of the transverse section of box girder are, its top flange, bottom flange and webs. A top flange can be further subdivided into two :

1. the portion bound by the webs
2. the overhang portion beyond the webs. The deck overhangs on either side. The transverse bending moment across the segments of cross-section is referred as secondary bending moment. The secondary bending moment at root of the overhang strip, due to wheel loads determines the section depth of the overhang. So the flexural design considerations of optimal bending moment at the root of the overhang decides the cantilever overhang.

Web layout:

Exterior webs are often inclined for aesthetic considerations. This, in turn, reduces the width of pier and the span length of the bottom slab between webs. For urban elevated road ways, the adoption of inclined web offers an additional advantage of improving natural lighting intensity at ground level.

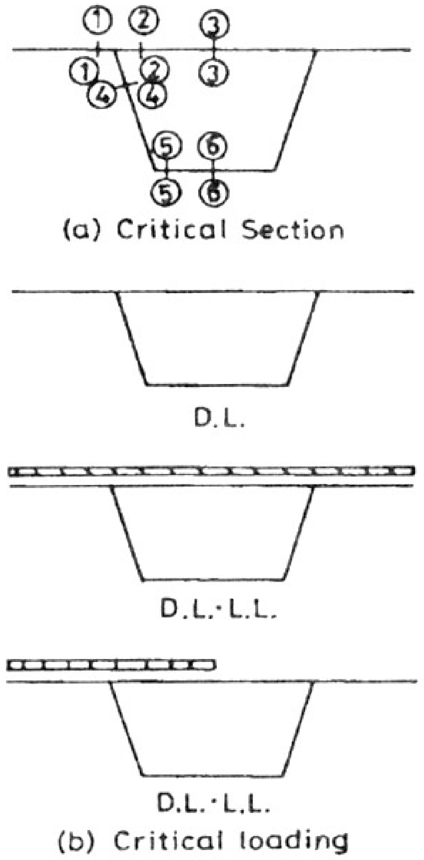

Figure 1. Typical cross-sections for parametric study

Web thickness:

The primary function of the web is to adequately resist the longitudinal shear forces and usually small moments. Placability of reinforcement and concrete in a thin web will have practical problem. The additional concrete in webs increases the quantities of concrete and reinforcing steel in the rest of the structure. The optimum web thickness is thus a compromise between the cost of material, cost of labour, and the compatibility of available construction facilities.

Soffit thickness:

Soffit slab must be of adequate thickness to resist the secondary moments and shears due to loads. An important practical consideration is that the soffit slab must be sufficiently thick to accommodate the reinforcing steel and prestressing tendons that will be embedded in them.

Box design considerations

The design of box girder for secondary stresses in the transverse direction consists of determining the adequate concrete section and the amount of prestressing or reinforcing steel required to resist the flexural and shear stresses. In order to determine the critical sections in different load combinations one has to incorporate the moving load concept in the analysis.

Figure 1 illustrates typical cross-sections selected for the parametric study. The critical sections where moments or shears in the secondary bending analysis of the box are indicated in Figure 1a. Different symmetric and anti-symmetric loads are shown in Figure 1b. Figure 2 illustrates some design variables and notations of the box.

The main geometrical parameters that influence the design of the cross-section of box girder consists of selecting appropriate values from the key layout parameters such as overhang ratio C_c web thickness ratio C_w, web slope S and soffit thickness ratio C_b where the ratios are :

C_c = cantilever overhang/top slab width

C_w = web thickness/top slab width

C_b = soffit thickness/girder depth.

Overhang ratio, C_c is defined as the ratio between the length of overhang of top slab deck to the width of the bridge deck. The ratio C_c is very much dependent on the transverse bending stiffness of the slabs, web, as well as the vehicle loading, and sidewalk. The optimum C_c value can be achieved when the absolute difference between the secondary bending moment in section 1 and 2, Figure 1a, is as minimum as possible or approximately equal as far as practical aspects are considered for a specific span length and type of loading, while the absolute value of maximum moments should tend to be least.

Web thickness ratio, C_w is defined as the ratio between the web thickness to the width of bridge deck. The optimum value depends upon the shear design consideration and minimum thickness to accommodate the embedded items as well as to provide for the necessary minimum concrete covers over.

Web slop, S , is influenced mainly by economic, construction and appearance considerations.

Soffit thickness ratio, C_b, defined as the ratio between the soffit thickness to the girder depth. C_b value depends on the ability of providing space to accommodate the reinforcement and minimum concrete cover.

The optimum values of C_c, C_w, S and C_b depend on the span length, L , and type of design live loads.

Structural modelling

A folded plate programme called BOX has been developed based on Scordelis works[2,3,4] and is used to conduct numerical computation in the present study. BOX is capable of modelling and analysing straight prismatic folded plate bridge structures made up of isotropic plate elements and simply supported at the two ends. Rigid diaphragms are assumed at the two end supports. The folded plate system is modelled as an assembly of longitudinal plate elements possessing both membrane and plate bending stiffness. The elements extend over the full length of the structure and are interconnected at joints along their longitudinal edges with constant thickness plate elements.

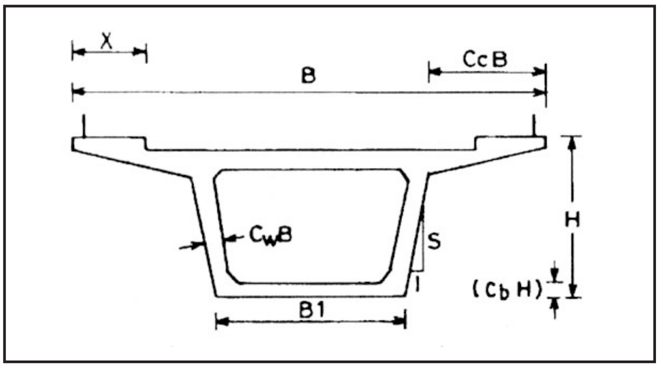

Figure 2. Paramatic notations. B - Deck stab width, CcB -Overhang width, X - Foot path width, B1 -Soffit width, CbH -Soffit thickness, H -Total bridge height, S - Web slope, CWB - Web thickness

Formulae based on theory of elasticity for the stiffness coefficients defining membrane and plate bending actions of plates are utilised in the direct stiffness harmonic solution.

Joint coordinates, material properties and element location are the inputs to the programme. Uniform surface loads and concentrated loads may be applied on the structure. All loads are expanded into fowler harmonic series solution. Output consists of joint displacements, the plate element internal displacements, stresses and stress resultants.

Parametric study

To assist the designers in proportioning of the box girder, a parametric study is carried out. The effect of different ratios and their significance is assessed by analysing as large as 2,592 geometrical proportions of single cell, single span, simply supported and straight box girder, using the computer programme BOX. The range of geometrical proportions of some of the existing concrete box girder bridges are also considered.

The study has been carried out in groups and the methodology adopted is as follows :

1. ***Group A :*** Reinforced concrete box girder.
   Spans in metres : 18, 21, 24, 27 and 29
   Types : type Al - with sidewalk, type A2 - without sidewalk
   Span to depth ratio :18.

2. ***Group B :*** Prestressed concrete box girder
   Spans : 30, 35, 40, 45, 50, 55 and 60m
   Types : type Bl - with sidewalk, type B2 - without sidewalk
   Span to depth ratio : 20

3. ***Lim loads :*** The design loads and constraints are based on American Association of State Highway and Transportations Officials (AASHTO) specifications. Two types of live loads are considered.
   They are HS-20 and H-20

4. ***Load combinations :*** Girder of type Al, A2, B1 and B2 are analysed for each live load in the three load combinations:
   (a) D.L. (b) D.L + L.L (c) D.L + unsymmetrical L.L

5. Forces considered for study are shear forces and secondary bending moments, Ml, M2, M3, M4, M5, M6 and M7, Figure 1a.

6. ***Parametric variation***
   (a) For each group, type and load comb:nation, study has been carried out for a chosen span to show the effect of deck overhang on secondary bending moments; effect of web thickness on secondary bending moment; effect of web slope on secondary bending moment; and effect of

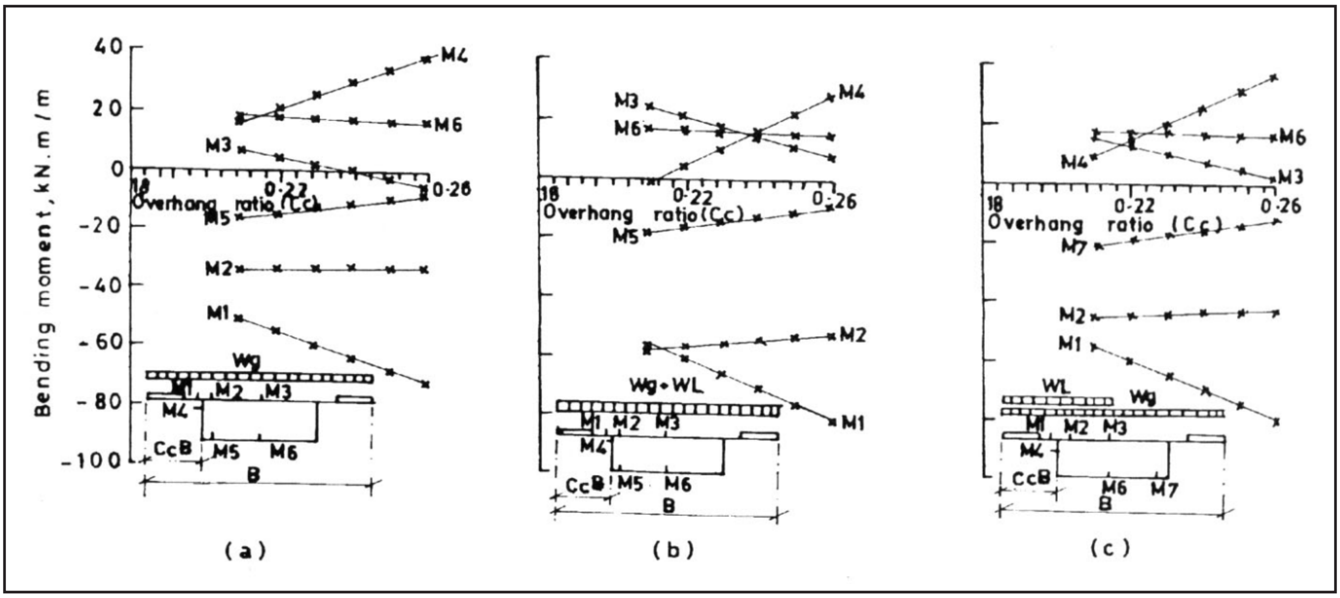

Figure 3. Effect of overhang on bending moment (section with sidewalk). (a) Due to selfwelght, (b) Due to selfwelght and live load (HS -20), (c) Due to seifweight and unsymmetric live load (HS-20)

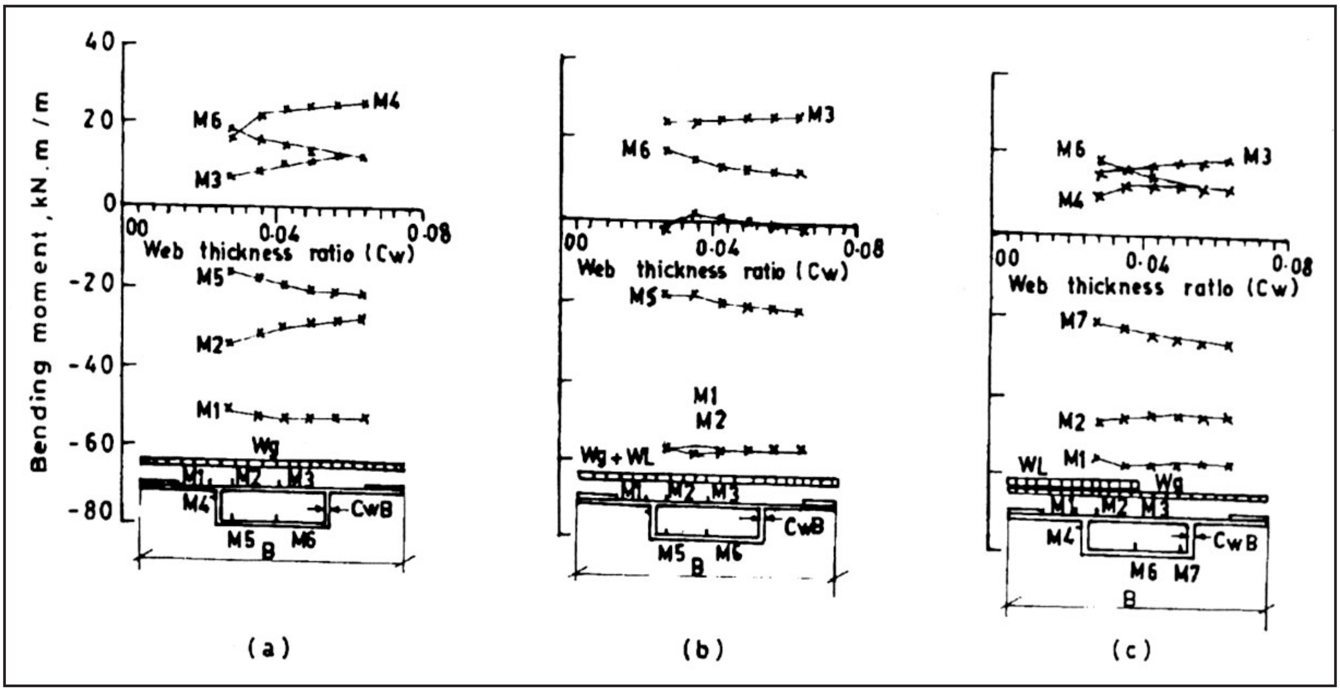

Figure 4. Effect of web thickness on bending moment (section with sidewalk). (a) Due to selfwelght, (b) Due to sellwelght Ilve load (HS-20), (c) Due to selfwelght and unsymmetrlc Ilve load (HS-20)

soffit thickness on secondary bending moment.

(b) The above mentioned study, that is, set (a), is repeated for various spans and linear regression analysis is performed using the vast amount of data obtained from the detailed numerical computation to formulating a best fit mathematical equation for the optimum overhang ratio C_c, optimum web thickness ratio C_w, as a linear function of span length L and the results are presented graphically to show effect of span length on overhang ratio, C_c and effect of span length on web ratio, C_w.

Discussion

A large number of geometrical proportions of the box are performed and only a few in the form of plots are presented herein while the rest are compiled in Tables. Figures 3, 4, 5 and

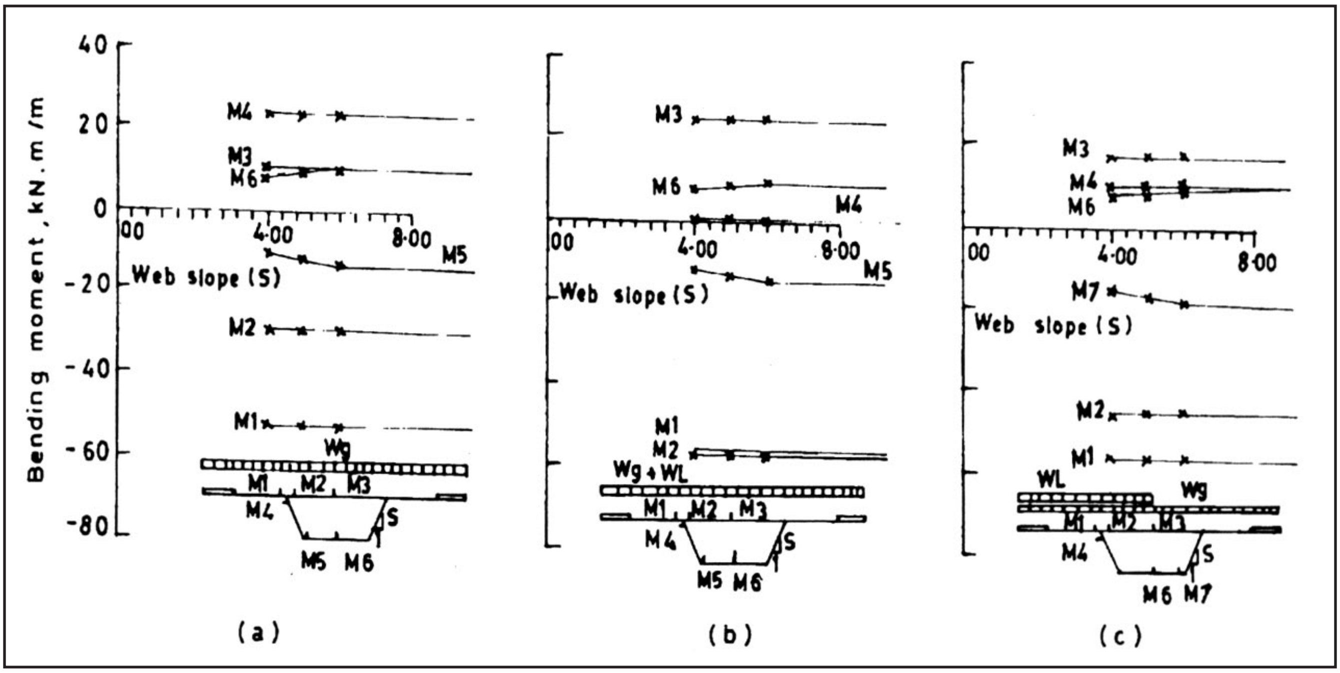

Figure 5. Effect of web slope on bending moment (section with sidewalk). (a) Due to selfwelght, (b) Due to selfwelght and live load (HS-20), (c) Due to selfwelght and unsymmetrlc live load (HS-20)

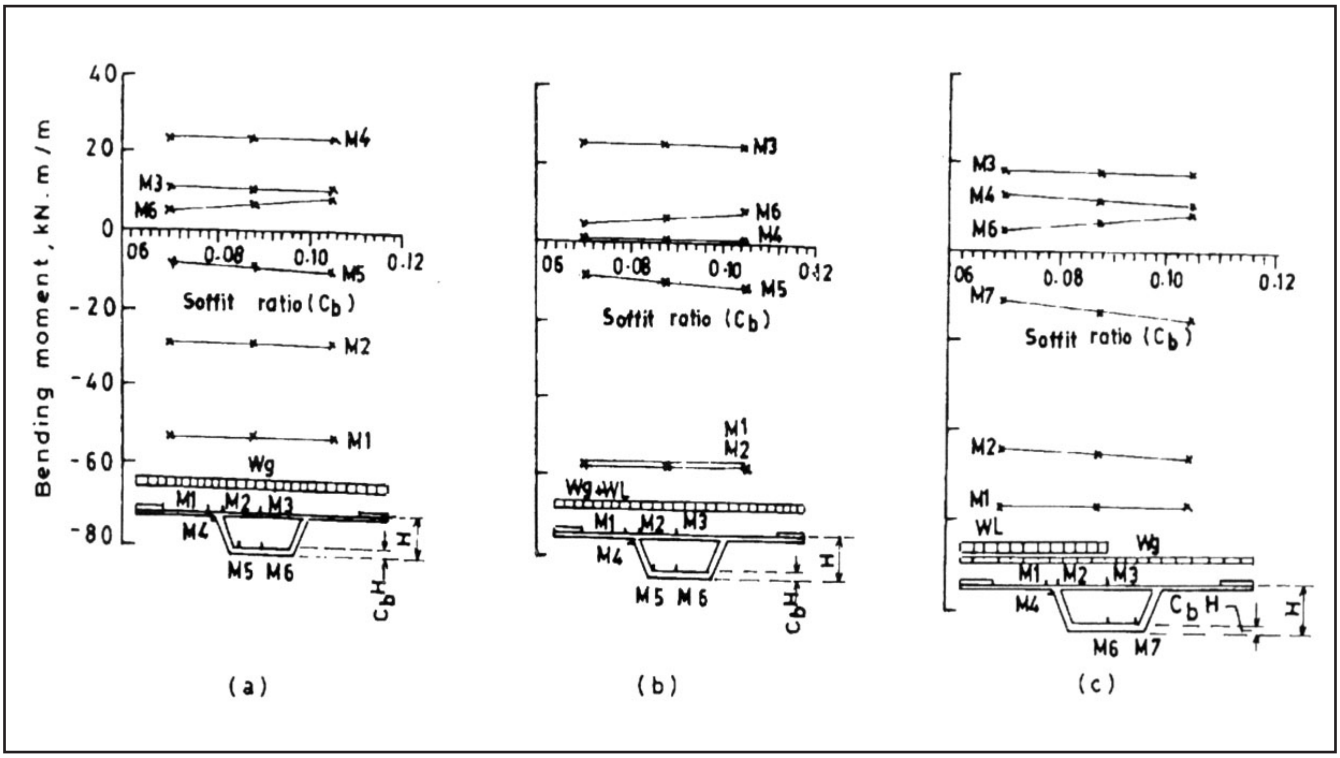

Figure 6. Effect of soffit thickness on bending moment (section with sidewalk). (a) Due to selfwelght, (b) Due to selhvelght and live load (HS-20), (c) Due to selfwelght and unsymmetrlc live load (HS-20)

6 are taken as samples for a specific span lengths and loading conditions. The same procedure has been repeated for the various span lengths and load conditions as mentioned before for generating different design graphs to study the effect of deck overhang, web thickness, web slope and soffit thickness.

Figure 3 shows the effect of deck overhang on secondary bending moments. It is observed from Fig 3 that the secondary bending moments vary almost linearly in all the cases of loading at various sections. The secondary bending moments at section 1, 2 and 3 are affected predominantly by the overhang length. Among the set of secondary moments, M1 is the most critical and sensitive, while M2 is less sensitive. M1 and M2 are close to each other. Ml and M3 vary considerably. The optimum point C, is obtained as mentioned earlier, when M1 is approximately equal to M2. So Ml and M2 play a decisive roll in determining the optimum value of C_c.

Figure 4 illustrates the effect of web thickness on secondary bending moment. It can be seen from Figure 4 that C_w has little effect on secondary bending moment and no effect for C_w greater than 0.04. So the optimum web ratio is governed by the shear design, reinforcement details and constructional limitations.

The effect of inclination of web on secondary bending moment is highlighted in Figure 5 from which it can be observed that the slope, S , beyond 4 in 1 has no effect. Web slope has no effect on deck slab bending moment but it reduces the bending moments in soffit slab and in webs. Increase in the inclination of web will decrease the bending moments in soffit for the given C_c.

Figure 6 illustrates the negligible effect of soffit thickness on secondary bending moment.

Linear regression analysis is performed using the results obtained from the detailed numerical computation to find approximate equation for the optimum overhang ratio C_c and optimum web thickness C_w. as a function of span L and are shown in Figures 7 and 8 as samples for a specific condition. The same procedure is repeated for the various group types and load conditions as mentioned before for generating

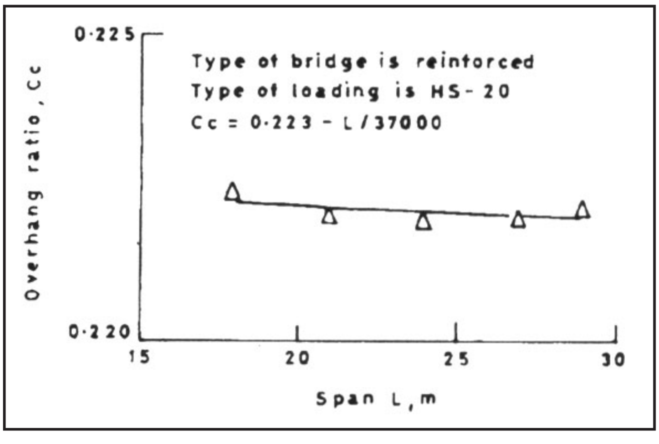

Figure 7. Linear regression fit for optimum overhang ratio versus span (with sidewalk)

Table 1. Variation of C_c and C_w, with span length L under H-20 loading

Type of cross-section	Type of bridge Reinforced	Prestressed
With sidewalk	$C_c = 0.212$	$C_c + 0.213 - \frac{L}{4,000}$
	$C_w + 0.025 + \frac{L}{3,000}$	$C_w + 0.038 - \frac{L}{10,000}$
Without sidewalk	$C_c = 0.215$	$C_c + 0.215 - \frac{L}{50,000}$
	$C_w + 0.026 + \frac{L}{4,000}$	$C_c + 0.0406 - \frac{L}{12,200}$

L is span length in metre

Table 2. Variation of C_c and C_w, with span length L under H-20 loading

Type of cross-section	Type of bridge Reinforced	Prestressed
With sidewalk	$C_c = 0.223 - \frac{L}{37,000}$	$C_c + 0.215 - \frac{L}{30,000}$
	$C_w + 0.026 + \frac{L}{3,000}$	$C_w + 0.038 - \frac{L}{10,000}$
Without sidewalk	$C_c = 0.223 + \frac{L}{37,000}$	$C_c + 0.216 - \frac{L}{38,700}$
	$C_w + 0.025 + \frac{L}{3,000}$	$C_c + 0.041 - \frac{L}{12,200}$

L is span length in metre

different linear functions to represent the relation of deck overhang ratios and web thickness ratios with span length. These functions can be adopted for finding out C_c and C_w as design graph.

The results obtained through regression analysis are presented in the Tables 1 and 2, where C_c and C_w are expressed as linear function of span length, L. It is felt that these tables could be used directly as the design charts to assist the designer in proportioning the box girder bridge.

Conclusion

Numerical analysis of single cell, single span, simply supported and box girder bridge has been carried out by means of the folded plate programme, modelling the system as an assembly of longitudinal plate elements possessing both membrane and plate bending stiffness. Formulae based on theory of elasticity for the stiffness coefficients are utilised in the direct stiffness harmonic solution.

The following conclusions are drawn :

1. Secondary bending moments at various sections vary almost linearly with respect to overhang, web thickness, web inclination and soffit thickness.

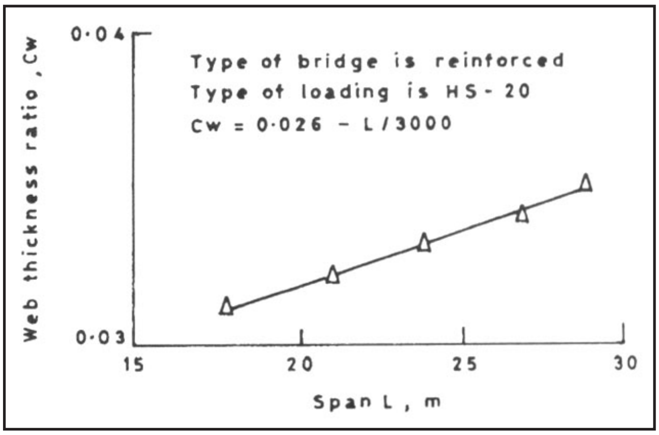

Figure 8. Linear regression fit for optimum web thickness ratio versus span (with sidewalk)

2. The overhang ration Cc has a considerable effect on secondary bending moments.

3. Web thickness ratio Cw has little effect on the magnitude of secondary bending moment.

4. Web slope S and soffit thickness ratio C_b have no effect on the magnitude of secondary bending moment.

5. Tables 1 and 2 give linear functions which express the relation of the overhang ratio C_c and web thickness ratio C_w with span length, L.

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