SHEAR LAG IN STEEL BOX GIRDERS

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ABSTRACT

The efficiency of different systems for stiffening thin wall box girders against shear lag is determined in this paper. The finite element method was used for the analysis. The full details of the girders in the three dimensions were modeled. The general three dimensional four node shell element was used. The case of simple beam subjected to uniform load was considered. Shear lag phenomenon was observed when considering the distribution of the bending stresses of both the webs and flanges. Parametric study was carried out considering the different geometrical details of steel box sections and different girder spans. The results obtained are presented and compared to those of their counterpart cases but with stiffeners.

Keywords: Shear lag, Box sections, Bending stresses.

Notations

The following symbols are used in this paper :

B	Half the flange width.
D	depth of box section.
E	modulus of elasticity.
F	flange thickness.
L	girder span.
LF	length of part of flange at which the thickness was doubled.
RF	thickness of part of flange having length LF.
S	stiffener thickness.
S_a	bending stress value at upper flange web inter-connection.
S_t	bending stress value obtained using the elementary theory of bending
S_s	bending stress when stiffeners are used.
W	web thickness.

INTRODUCTION

When thin wall box girder is subjected to bending moment, the produced bending stresses are not uniformly distributed along flange width as assumed by the elementary theory of bending. Bending stresses at the flange web inter-connection are much larger than that far from the web. This phenomenon is called positive shear lag and explained as follows. The relative displacements between the webs and the flanges can not occur. The longitudinal displacements in the parts of the flange remote from the web lag behind those nearer to the web due to the action of inplane shear strain in the flange, (Moffatt and Dowling, 1975). Negative shear lag phenomenon is known when the bending stresses at the flange web inter-connection are much less than that remote from the web. This was first observed by Foutch and Chang (1982) when they considered a cantilever beam with constant depth subjected to uniform load. Studies in the literature as (Shushkewich, 1991) and (Kristek and Studnicka, 1988 and 1991) have been devoted to explain the phenomenon of shear lag. Other studies were concerned with developing numerical solutions to evaluate shear lag in girders as (Abdel Sayed, 1969), (Chang and Zheng, 1987) and (Song and Scordelis, 1990). Empirical formulas and diagrams have been provided for the determination of shear lag effects, (Song and Scordelis, 1990).

The two criteria which have been used in the literature to quantify the influence of shear lag are the stress ratio and the effective width. The first is the ratio of the longitudinal bending stress at the web flange inter-connection to that obtained when using the elementary theory of bending. The second is an imaginary width for the flange called the effective width. The bending stresses are assumed to be uniformly distributed along this width having a value equal to the stress at the web flange inter-connection. The ratio of this imaginary width to the actual width of the flange is called the effective width ratio .

Moffatt and Dowling (1975) studied the shear lag phenomenon in steel box girder bridges by the means of the finite element method. Part of the study was concerned with the case when the flange is stiffened by longitudinal stiffeners. The values of the effective width ratio were found to decrease by significant amount in linear manner when the ratio of the cross sectional area of the longitudinal stiffeners to that of the flange increases.

The main objective of this paper is to assess the efficiency of different systems for stiffening thin wall box girders against shear lag. The finite element method was used for the analysis. The case of simple beam subjected to uniform load was considered. Shear lag phenomenon was observed when considering the distribution of the bending stresses of both the webs and flanges. This is different to the cases considered in the studies mentioned above. Parametric study was carried out considering the different geometrical details of steel box sections and different girders spans. The results obtained are presented and compared to those of their counterpart cases but with stiffeners.

FINITE ELEMENT MODEL

The behavior of simply supported box girders when subjected to uniform distributed load was modeled using the finite element method. The general three dimensional 4 - node shell element was used .The formulation of the element is a combination of membrane and plate bending behavior. The membrane is an isoparametric formulation including transitional in-plane stiffness components and rotational stiffness components in the direction normal to the plane of the element . The plate bending behavior includes two-way out-of-plane plate rotational stiffness and transitional stiffness components in the direction normal to the plane of the element. Due to the symmetry about the X - Z plane, only half of the girder cross section was modeled, Figure (1). The girder was divided into 720 elements in most of the cases considered. The webs and flanges were assumed to be built in and the welds between them were not modeled. Two diaphragms were modeled, one at each support cross section. In other cases, more diaphragms were added at different positions along the girder span. Each diaphragm was modeled using 100 elements. Again, the diaphragms were assumed to be built into the girder cross section and the welds between them were not modeled.

The analysis was linear elastic and the material was modeled having modulus of elasticity E =205000 N/mm^2 and Poisson ratio = 0.3 . Uniform load was applied over the length of the girder at the inter-connection of the upper flange and the web. The simple supporting conditions were modeled by restraining the nodes at the remote edges of the lower flange against translation in the X, Y and Z axes directions and against rotation about the X axis. One edge, however was made to provide no transitional restrains in the X axis to model roller supporting conditions. All the nodes in the symmetry plane were restrained against translation in the Y axis direction and against rotation about the X axis.

For purposes of comparisons, the following two cases were modeled :

1) The cantilever box girder considered by Chang and Zheng (1987) in their experimental work. In this case, the modulus of elasticity and Poisson ratio were made equal to 29000 Kg / cm^2 and 0.4 respectively .
2) Simply supported plate having dimensions typical to those of the flanges of the box girders considered by Moffatt and Dowling (1975) . In this case, the plate is loaded by shear forces in its plane along the girder span having values equal to the components of the applied bending moments.

DATA PROCESSING

Due to the size of the input file, output files and data required to be investigated, a computer system was developed for data processing. It consists of two main programs. The first was developed to generate the input data in the required format of the analysis program. This facilitated knowing the numbers and positions of the different nodes and elements in the mesh. The second program was developed to read the bending stresses along the section defined by the user from the output file of stresses. Four values of the bending stress were obtained and printed for each node and their average value was determined.

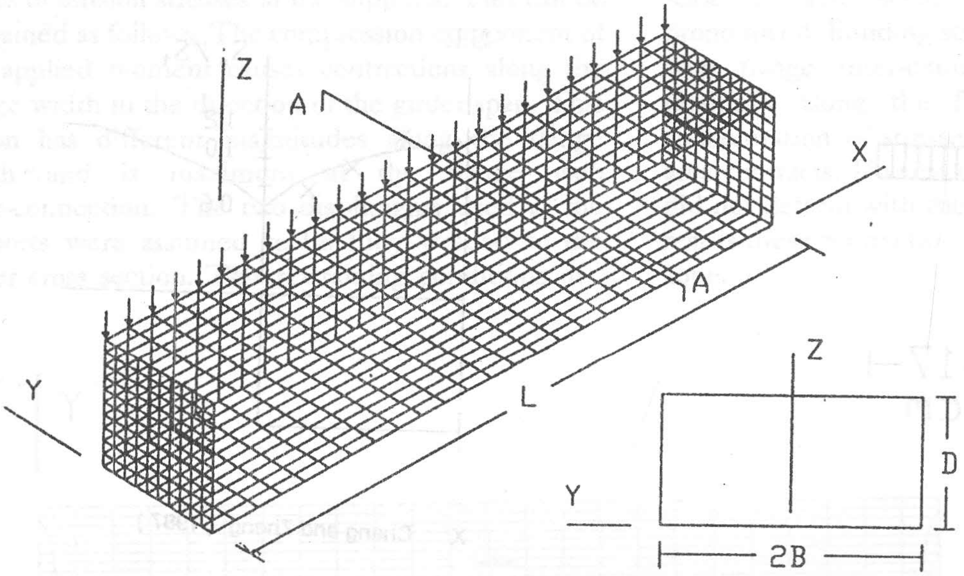


Figure 1. Finite element mesh.

COMPARISON BETWEEN EXPERIMENTAL AND FINITE ELEMENT RESULTS

For the purpose of comparison, the finite element method was used to model the behavior of the cantilever box girder considered by Chang and Zheng (1987) in their experimental work. The bending stresses at section C - C, 17.0 cms from the free end of the cantilever, were obtained and presented in terms of the stress ratio, Figure (2). The figure presented by Chang and Zheng (1987) were magnified and the values of the stress ratio were measured and then super imposed on Figure (2). The results in general show good agreement and indicate the phenomenon of negative shear lag.

DISTRIBUTION OF BENDING STRESSES

The finite element model described above was used for the analysis of simply supported box girders subjected to uniform load. Three different cases were considered. The dimensions of the cross sections of the girders are typical and similar to those of case 4 - table 1 presented by Moffatt and Dowling (1975). Three values for the span L of the girders were chosen so that the ratio L / B were made equal to 1, 1.67 and 10 where B is half the cross section width. The bending stresses at the sections in the middle of the girders spans were obtained and presented in Figure (3). The distribution of the bending stresses along the web in case A, where the ratio L / B = 10, is linear. The maximum positive and negative stresses are equal. Their values are nearly equal to those obtained using the elementary theory of bending S_t. However, the distribution of the bending stresses along the flanges is having a parabolic form. This is shown more clearly in case B where L / B = 1.67 . In this case, the bending stress at the web flange inter-connection is much higher than the stress remote from this area. The upper flange is subjected to both positive and negative, i.e. tension and compression, bending stresses. The stresses are distributed linearly along the web. The maximum positive and negative values equal 1.36 S_t

and 2.0 S_t respectively. The difference between them is balanced by the positive stresses induced in the upper flange. When L / B ratio equals 1, the distribution of the stresses along the web is no longer linear. The phenomenon of shear lag is observed clearly for both the webs and the flanges. Again, the relative increase in the stress at the web flange inter-connection is balanced by the positive stresses in the upper flange .

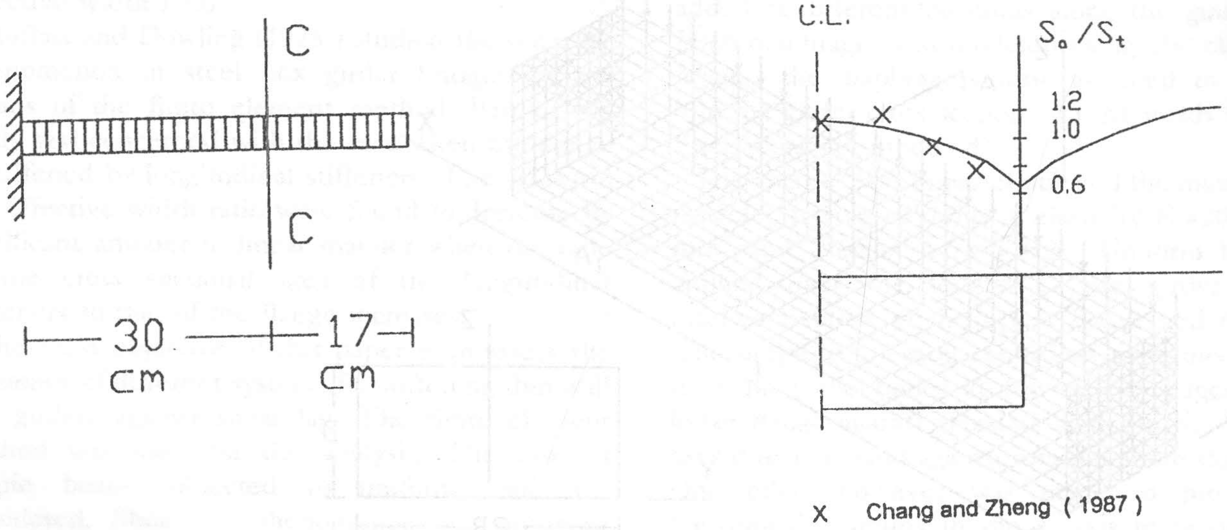


Figure 2. Comparison between experimental and finite element results.

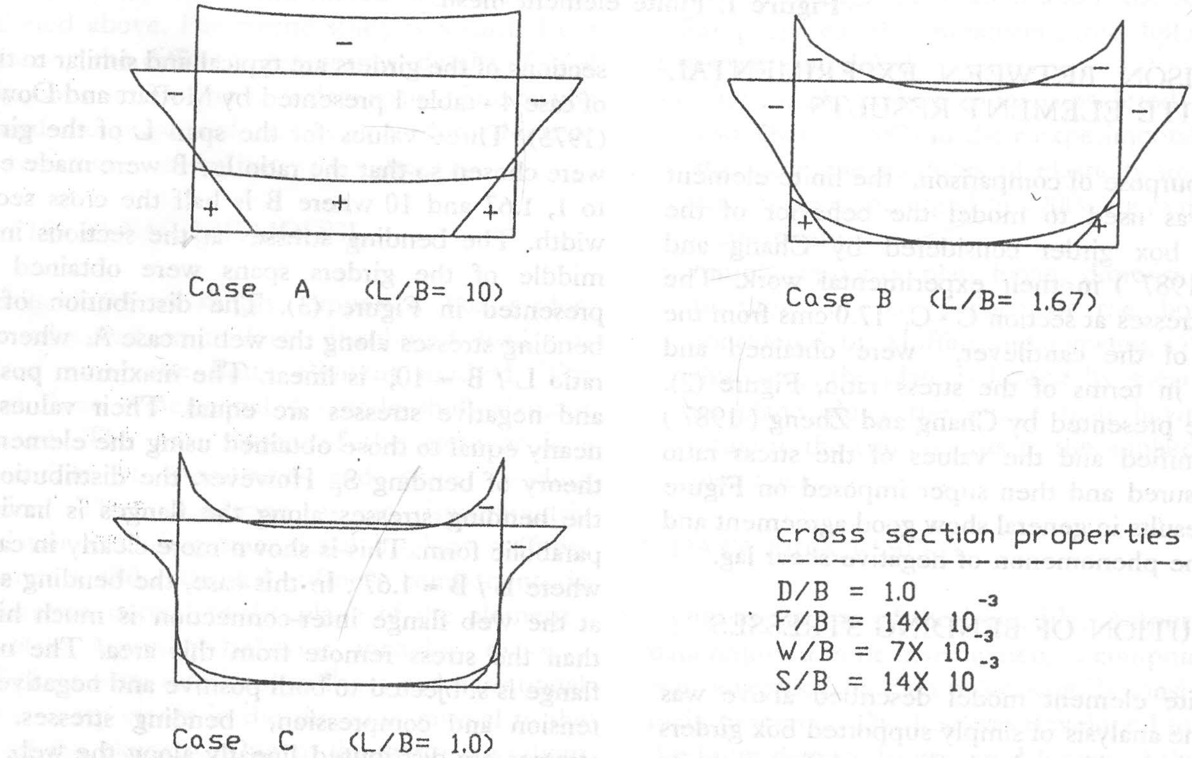
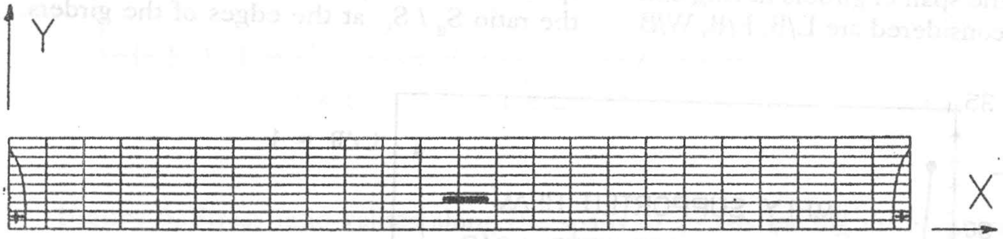
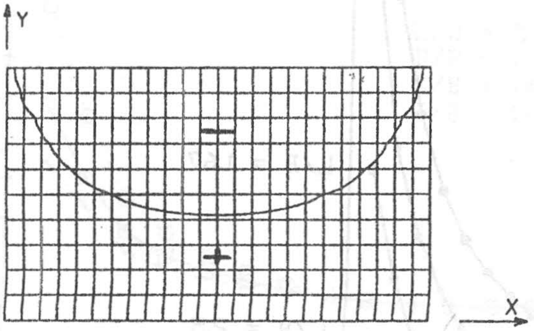


Figure 3. Distribution of bending stress in the cross section of thin wall box girders.

Figure (4) shows the areas of tension and compression bending stresses induced in the upper flange along girder span. In case A where L/B=10, the flange was divided into three zones. A zone of compression bending stresses was defined by two zones of tension stresses at the supports. This can be explained as follows. The compression component of the applied moment causes contractions along the flange width in the direction of the girder span. This action has different magnitudes along the flange width and is maximum at the flange web inter-connection. The two diaphragms used at the supports were assumed to be fully welded to the girder cross section. This restraining conditions of the diaphragms in addition to their flexural stiffness resist these contractions. They work in this case as elastic transitional springs producing these zones of tension stresses. When the ratio L / B = 1.67, different stress distribution was produced, Figure (4) -case B. The shear lag phenomenon is more pronounced. Bending stresses are concentrated at the web flange inter-connection while they vanish gradually along the flange width. Due to this concentration of stresses, the material at this local area contracts. However, the material surrounding it did not deform with the same magnitude and hence resists these contractions producing the tension stress zone.



Case A : (L / B = 10)



Case B : (L / B = 1.67)

Figure 4. Distribution of compression and tension bending stresses in the upper flange of box girders.

The values of the bending stresses at the web flange inter-connection in box girders were used to calculate the effective width ratio. These results were compared to those values obtained when considering plate having the same dimensions of the flanges and subjected to shear loads along its edge as described above and to those presented by Moffatt and Dowling (1975) . The effective width ratio values of the latter two cases were found nearly typical . However, Their values are different to those of the box girders considered in this study. This refers to the assumptions considered in these cases. "The webs behave in accordance with the elementary theory of bending and the diaphragms at each support cross section had infinite in-plane rigidity but no out-of-plane rigidity ", (Moffatt and Dowling, 1975).

PARAMETRIC STUDY

A parametric study was carried out to evaluate the actual bending stresses S_a at the upper flange web inter-connection along the span of girders having box sections. The variables considered are L/B, F/B, W/B and D/B where F, W and D are flange thickness, web thickness and section depth respectively. One diaphragm was modeled at each support cross section. The thicknesses of the diaphragms S were made constant for all the cases considered. The results are presented in Figures (5,6,7) and (8). The abscissa in these figures represents the length of the girder span while the ordinates represents the stress ratio S_a / S_t. The most significant variable affecting the stress ratio value and hence the magnitude of the shear lag phenomenon is L/B. Figure (5) shows the stress ratio values for girders having the same cross sections properties but different spans. It is noticeable that for cases of L/B equal to or less than 5 the differences in the bending stresses values at the flange web inter-connection along the girder span are relatively small. This caused the increase in the ratio S_a / S_t at the edges of the girders.

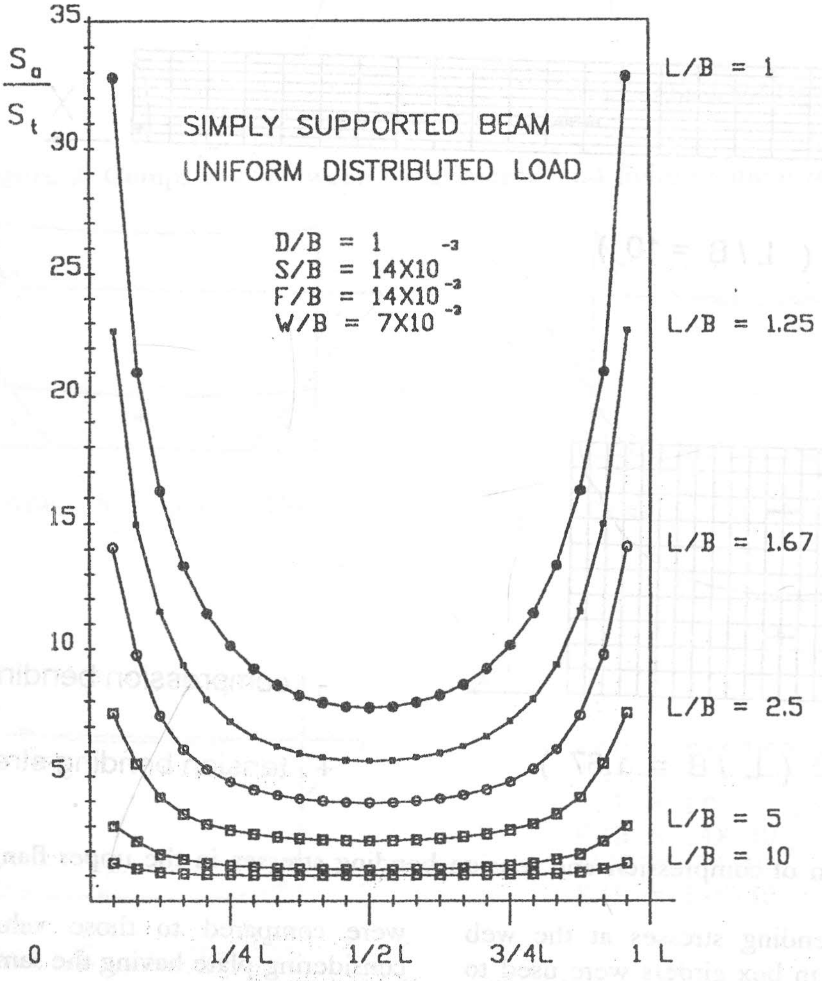


Figure 5. Stress ratio values along the spans of girders having different values of L/B.

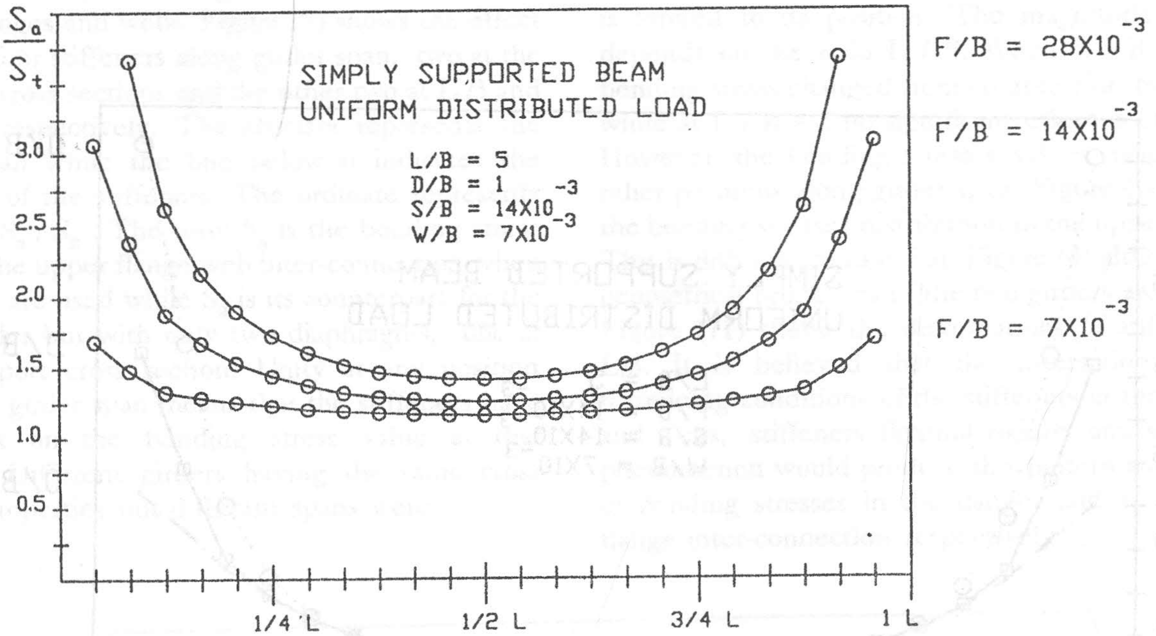


Figure 6. Stress ratio values along the spans of girders having different values of F/B.

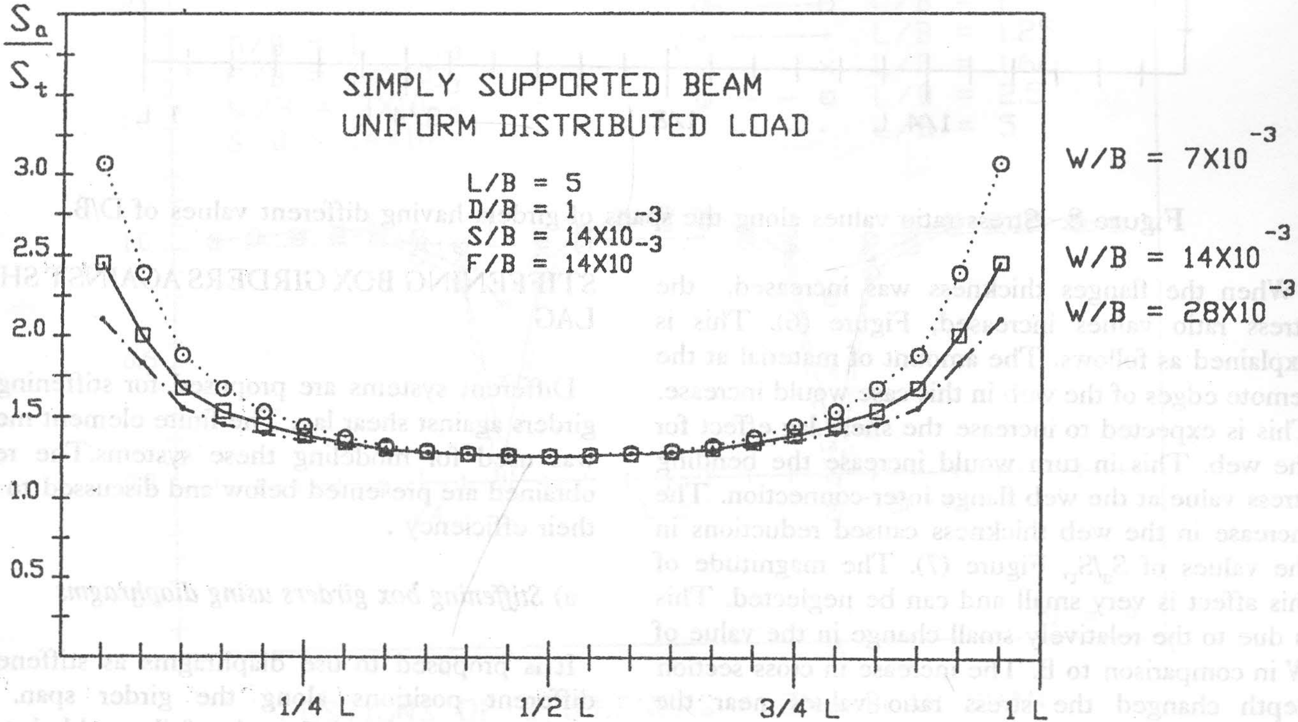


Figure 7. Stress ratio values along the spans of girders having different values of W/B.

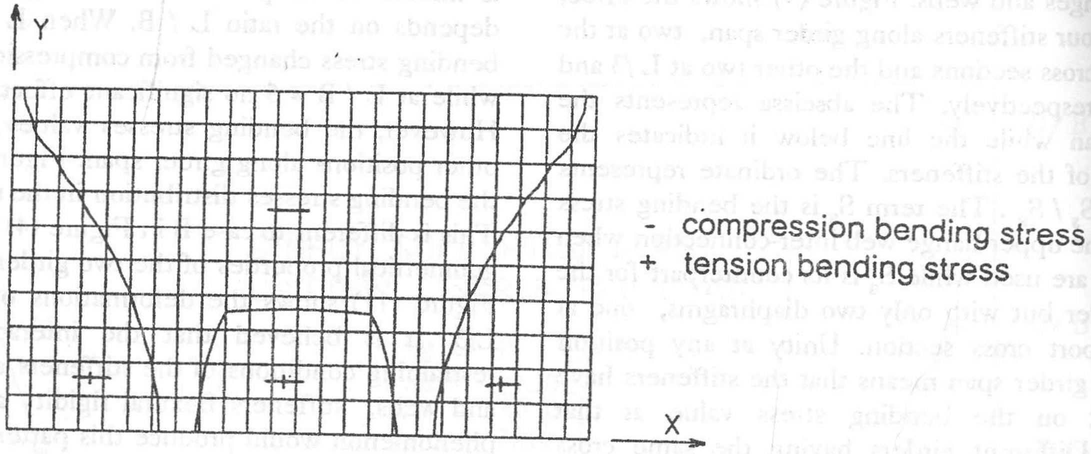


Figure 10. Distribution of compression and tension bending stress in the upper flange when 4 stiffeners were used.

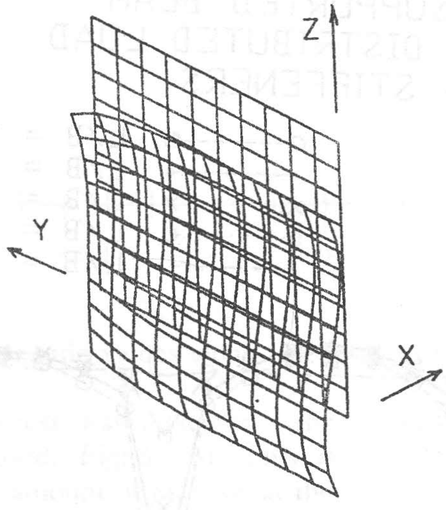


Figure 11. Deformation of stiffener at L/3.

The bending stresses are inversely and directly proportional to the stiffeners thickness at the positions of the stiffeners and at other positions along girder span respectively, Figure (12). The effect of using different numbers of stiffeners is shown in Figures (13) and (14). In the latter, the ratio L / B equals 5 and the number of stiffeners is 9 . This case showed acceptable reductions in S_s / S_a ratio specially at the middle of the girder span. Generally, using numerous number of stiffeners along girder span is a common solution in practice specially for girders subjected to heavy loads. This would increase the girder cross section capacity against shear loads and is seen above to be beneficial against shear lag phenomenon and hence making the girder section more efficient in carrying bending moments.

ABDELFATTAH: Shear Lag in Steel Box Girders

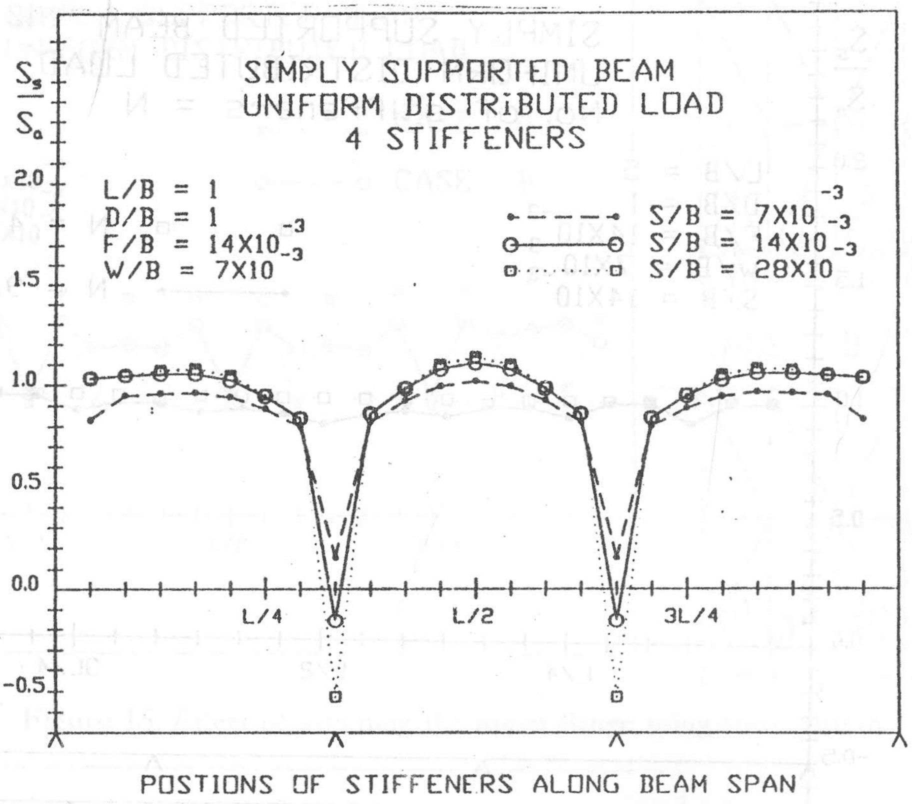


Figure 12. Effect of S/B on the stress ratio values.

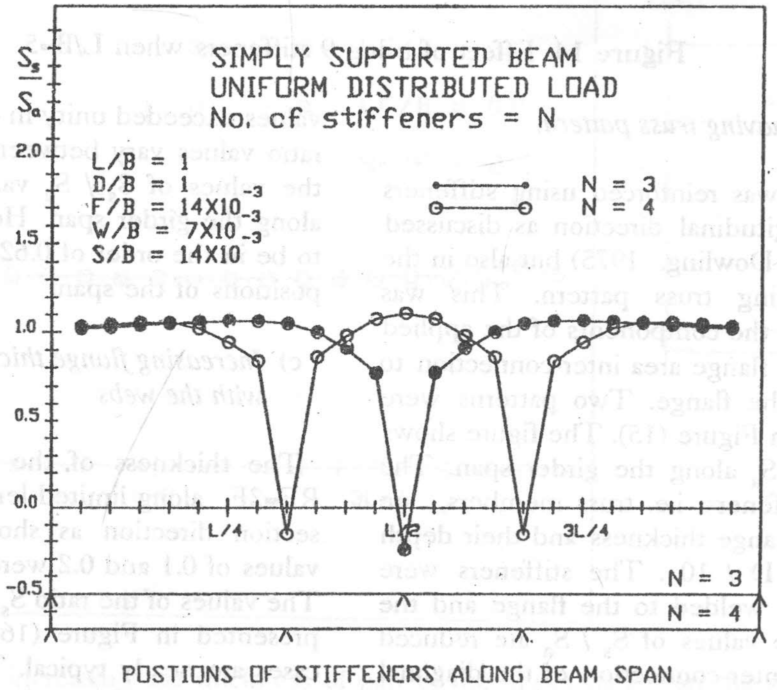


Figure 13. Effect of using 4 stiffeners when L/B =1.

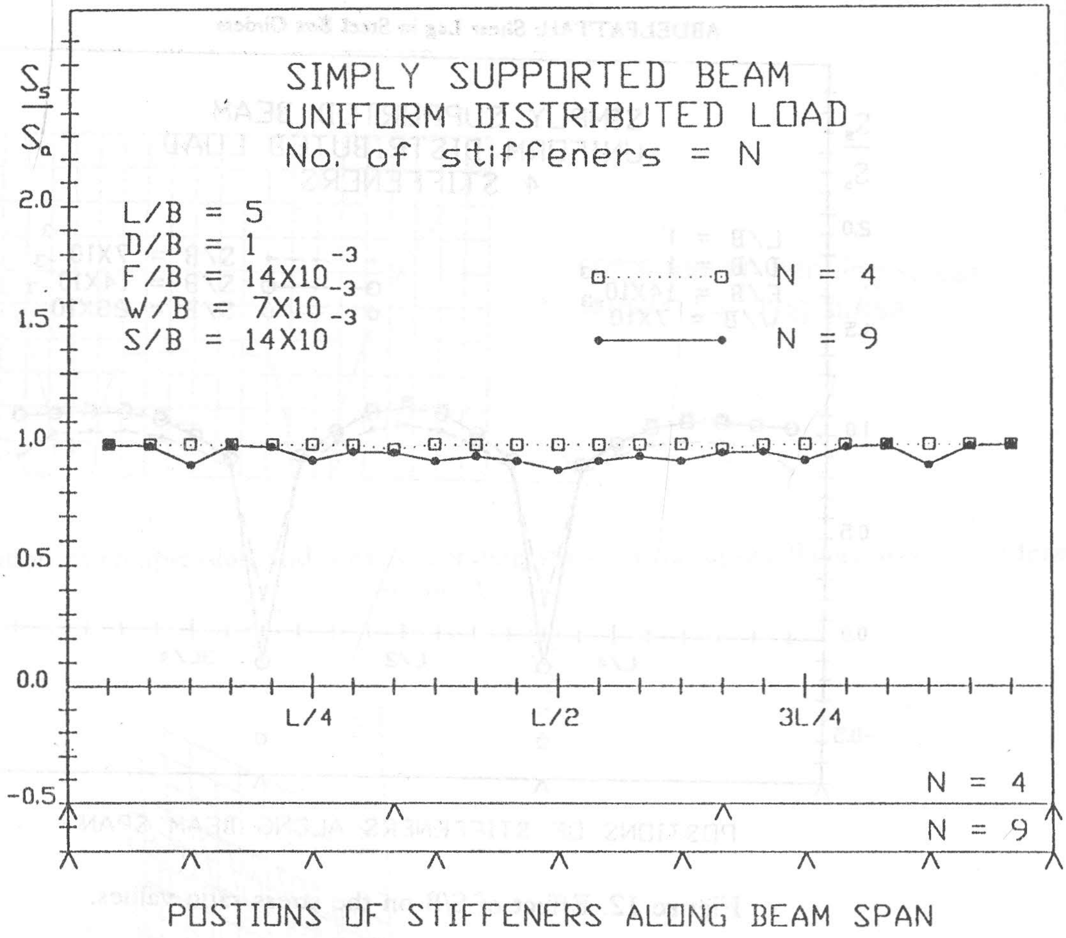


Figure 14. Effect of using 9 stiffeners when L/B=5.

b) *Using stiffeners having truss pattern.*

The upper flange was reinforced using stiffeners not only in the longitudinal direction as discussed before (Moffatt and Dowling, 1975) but also in the cross direction having truss pattern. This was expected to transmit the components of the applied moments at the web flange area inter-connection to the whole area of the flange. Two patterns were proposed as shown in Figure (15). The figure shows the values of S_s / S_a along the girder span. The thickness of the stiffeners, i.e. truss members, are taken equal to the flange thickness and their depth are made equal to D / 10 . The stiffeners were assumed to be fully welded to the flange and the webs. In case A the values of S_s / S_a are reduced significantly at the inter-connection of the diagonal stiffeners with the web and flange . However, its values exceeded unity in other positions. The S_s / S_a ratio values vary between 0.56 and 1.2 . In case B, the values of S_s/ S_a vary between 0.9 and unity along the girder span. However, its values reduced to be in the order of 0.62 at the quarter and middle positions of the span.

c) *Increasing flange thickness at its inter-connection with the webs*

The thickness of the flanges was doubled, i.e. RF=2F, along limited length LF in the flange cross section direction as shown in Figure (16). Two values of 0.1 and 0.2 were taken for the ratio LF/B. The values of the ratio S_s / S_a along girders spans are presented in Figure (16). The results of the two cases are nearly typical. The values of the bending stresses reduced by value between 10 % and 14 %:

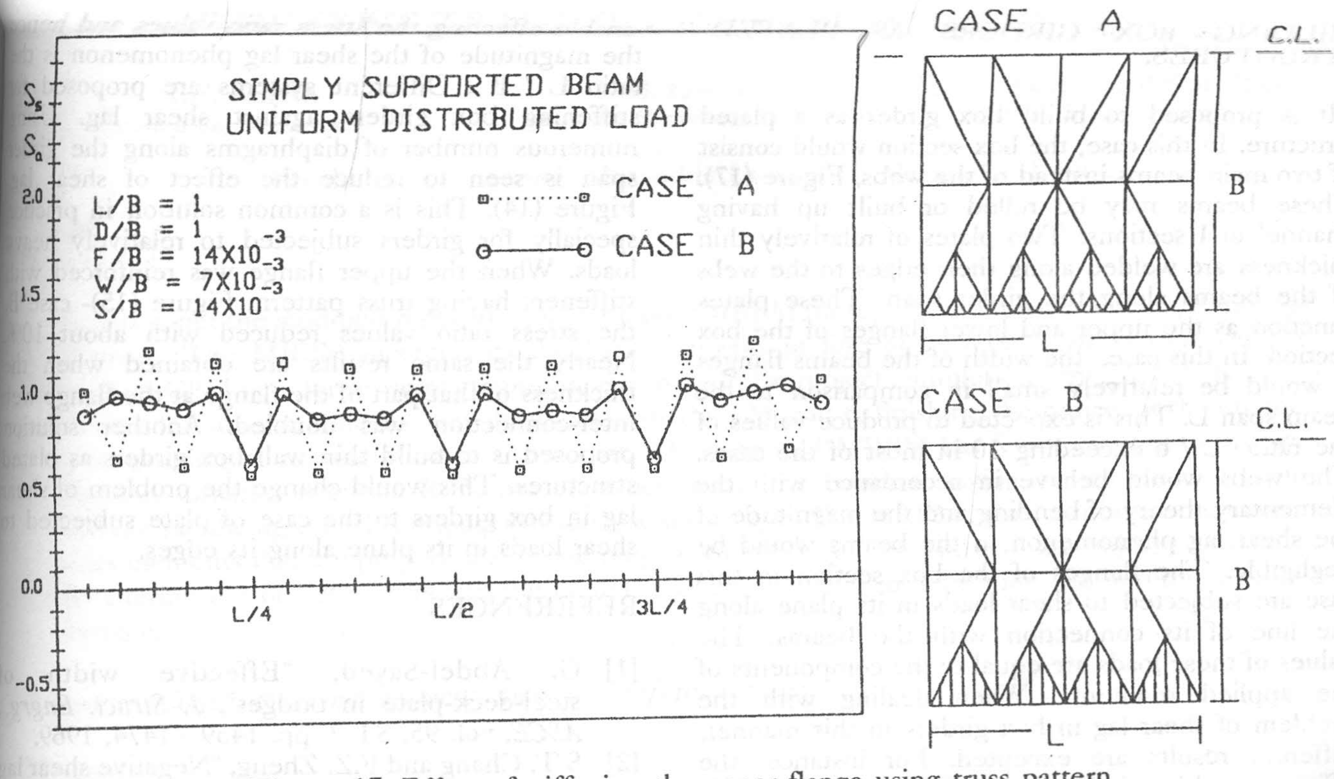


Figure 15. Effect of stiffening the upper flange using truss pattern.

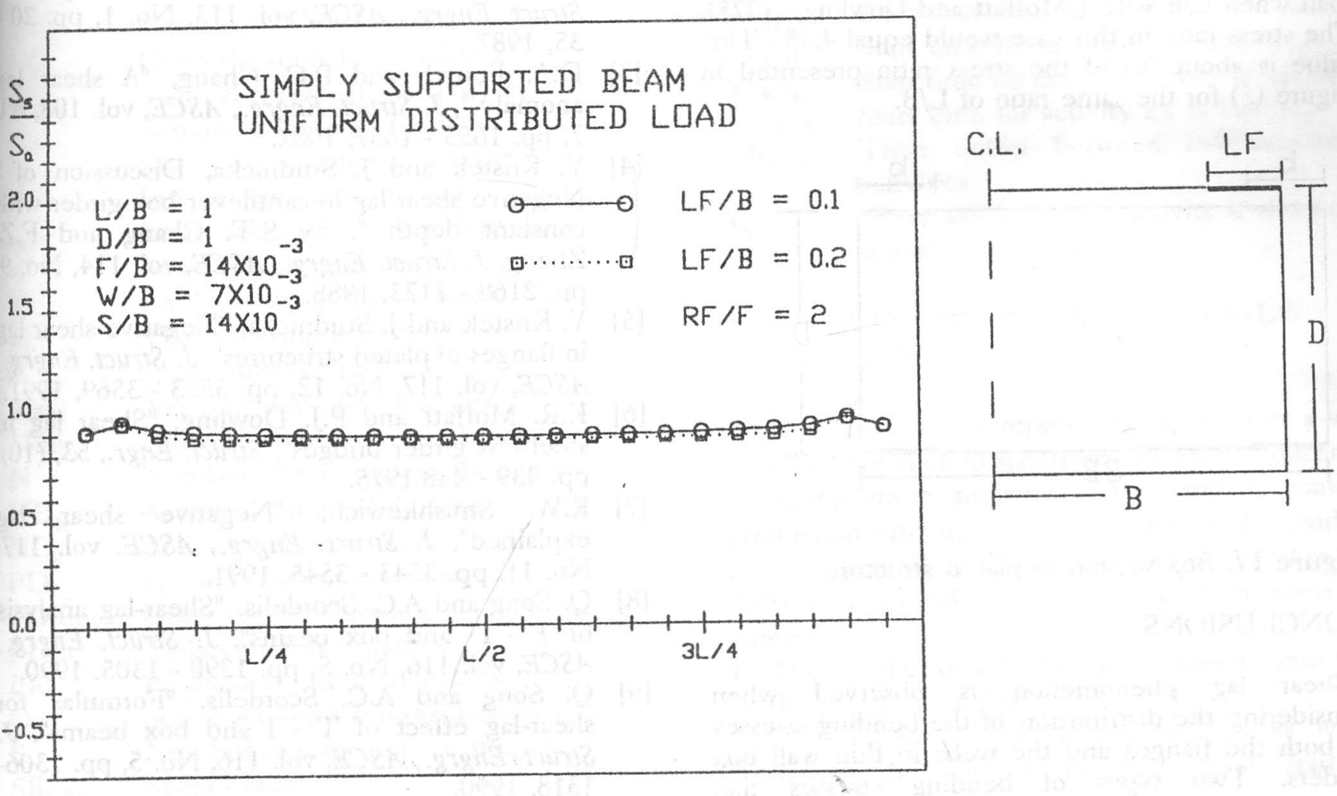


Figure 16. Effect of increasing the thickness of part of the upper flange on the stress ratio values

BUILDING BOX GIRDERS AS PLATED STRUCTURES.

It is proposed to build box girder as a plated structure. In this case, the box section would consist of two main beams instead of the webs, Figure (17). These beams may be rolled or built up having channel or I sections. Two plates of relatively thin thickness are welded along their edges to the webs of the beams along the girder span. These plates function as the upper and lower flanges of the box section. In this case, the width of the beams flanges b would be relatively small in comparison to the beam span L. This is expected to produce values of the ratio L / b exceeding 10 in most of the cases. The webs would behave in accordance with the elementary theory of bending and the magnitude of the shear lag phenomenon in the beams would be negligible. The flanges of the box section in this case are subjected to shear loads in its plane along the line of its connection with the beams. The values of these loads are equal to the components of the applied moments. When dealing with the problem of shear lag in box girders in this manner, different results are excepted. For instance, the effective width ratio is equal to 0.16 at the middle of span when L/B = 1, (Moffatt and Dowling, 1975). The stress ratio in this case would equal 4.45 . This value is about 0.6 of the stress ratio presented in Figure (5) for the same ratio of L/B.

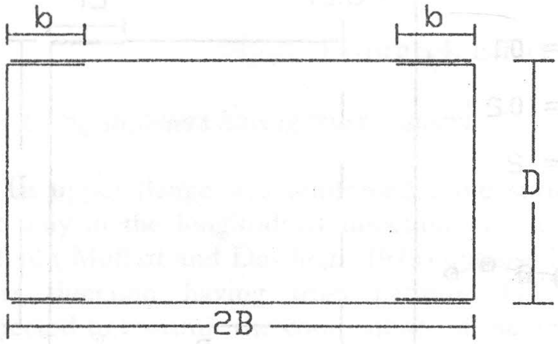


Figure 17. Box section as plated structure.

CONCLUSIONS

Shear lag phenomenon is observed when considering the distribution of the bending stresses at both the flanges and the webs in thin wall box girders. Two types of bending stresses ;i.e. compression and tension, are induced in the upper flange as shown in Figure (4). The most significant variable affecting the stress ratio values and hence the magnitude of the shear lag phenomenon is the ratio L / B . Different systems are proposed for stiffening box girders against shear lag. Using numerous number of diaphragms along the girder span is seen to reduce the effect of shear lag, Figure (14). This is a common solution in practice specially for girders subjected to relatively heavy loads. When the upper flange was reinforced with stiffeners having truss pattern, Figure (15)- case B, the stress ratio values reduced with about 10%. Nearly the same results are obtained when the thickness of that part of the flange at the flange web inter-connection was doubled. Another solution proposed is to build thin wall box girders as plated structures. This would change the problem of shear lag in box girders to the case of plate subjected to shear loads in its plane along its edges.

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