MODEL STUDIES OF BOX GIRDERS

by 45

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INTRODUCTION

1. Statement of Problem

The box section has been utilized in structural applications for many years, finding wide use for large columns and for members in stationary and moving industrial structures. Box sections are closely related in design and behavior to other thin walled closed sections such as the wings and fuselage of aircraft.

One of the first applications of the box configuration to bridges was the Brittanannia and Conway tubular bridges built in 1849. (1) These bridges involved some unusual problems that prompted extensive research on buckling of thin plates subjected to both shear and bending stresses.

Bridge building was of paramount importance in war-torn Europe after World War II, and many of the new bridges were of steel box girder construction. Since then, this type of bridge has gained increasing popularity in the United States and Canada.

Part of the increased interest in steel box girder bridges is due to the distinct advantages that box girders have over other types of bridges. One important advantage is that the transverse loads are distributed more evenly over the cross section because of the large torsional stiffness of a box section. It can also be argued that the maintenance cost for box girder bridges is less than other types of bridges since a smaller percentage of the total cross section is exposed to the elements. Furthermore, most people agree that the streamlined appearance of box girder bridges is aesthetically pleasing.

Much has been learned about box girders in recent years, but there are still areas which should be investigated more thoroughly. The Subcommittee on Box Girder Bridges of the Joint A.S.C.E.-A.A.S.H.O. Committee on Flexural Members expressed the opinion in a recent report that "studies need to be performed to arrive at design procedures for the determination of the location and size of diaphragms." (2) Such studies are important since the lateral distribution advantages of box girder bridges may be offset by high local warping and distortion stresses unless these stresses are controlled through the use of diaphragms or cross braces.

2. Purpose of Study

The purpose of the study was two-fold. The primary objective was to examine the effect of diaphragms in reducing warping and distortion stresses that are caused by the deformation of the box girder cross section. Tests were conducted on a model plexiglas box girder to determine these stresses. The results were compared with values obtained from the so-called "BEF Analogy" an approximate analytical method of box girder analysis which considers the stresses caused by warping and distortion.

A secondary objective was to study the experimental characteristics of methyl methacrylate (i.e. plexiglas). The experimental techniques used in working with plexiglas are of importance to researchers since plexiglas has several advantages over other model materials. Of primary importance is the fact that plexiglas has a relatively low modulus of elasticity which results in substantial strains with relatively small loads. Plexiglas is also quite suitable for structural models because of its workability and ease of fabrication.

3. Scope of Study

The experimental program was limited in scope to tests on a single rectangular box girder fabricated from plexiglas. Only static loads applied normal to the compression flange of the box girder were applied. These loads were kept small enough that the strains in the plexiglas model were within the elastic range. The model was designed so that the shape of the cross section would be distorted under the test loads thus resulting in warping and distortion stresses of easily measurable magnitudes.

LITERATURE REVIEW

1. Examples of Existing Box Girder Bridges

Lists of some of the box girder bridges now in service or under construction throughout the world are available elsewhere. (2,3) One of the most notable box girder bridges in the United States is the Dartmouth Bridge over the Mississippi River at Minneapolis, Minnesota. (2) It is a three span (170', 340', 170') continuous bridge with box girders spaced 53 ft. center to center. The Poplar Street Bridge over the Mississippi River at St. Louis has five continuous spans ranging from 265' to 600'. (2) Two single cell boxes support the orthotropic deck for each of the two roadways. The San Mateo-Hayward Bridge across San Francisco Bay in California is an orthotropic deck bridge consisting of continuous spans of 375', 750', and 375'. (2) The adaptability of the box girder type of construction is readily shown by the varied span lengths of these bridges.

2. Analysis of Box Girder Bridges

The torsional analysis of box girders may be carried out using any of the following assumptions. (2)

1) The shape of the cross section is not distorted during torsion, and only St. Venant, or pure, torsional shear stresses are computed by membrane analogy for the closed cell.

2) The shape of the cross section is not distorted during torsion, but the stresses caused by warping torsion are incorporated into the analysis.

3) The shape of the cross section is deformed during torsion, and this effect is accounted for in the calculation of stresses. This approach is discussed below in more detail.

4) The effects of torsion are considered negligible, thus the torsion problem is ignored.

5) The behavior of the box girder bridge is related to a grid of longitudinal and transverse beams, each of which may have torsional as well as flexural stiffness. The main advantages of this method are that bridge engineers are more familiar with the structural behavior of grids, and that the effects of intermediate diaphragms are more apparent. Kavanagh (3) discusses this method in more detail.

There are several methods available that adequately account for the influence of the deformation of the cross section on the warping and distortion stresses. The theory of Vlasov (4) is used as the basis for two refined analytical procedures which are variations of folded plate theory. (5) In these analyses the longitudinal plate moments and transverse axial deformations are neglected, and the longitudinal deformations are assumed to be linearly distributed across the width. The first analytical method available is the "plate element" method. In this method, matrix analysis procedures are used to treat the structure as an assemblage of plate elements. A Fourier series solution can be used effectively for simply-supported spans. The second method is called the "generalized coordinate method" and employs a formulation of equilibrium equations for the cross section. This approach permits consideration of flexible interior diaphragms and arbitrary support conditions. The method is applicable only to closed-section girders since the torsional stiffness of open elements is neglected. (5)

Because these complex analytical procedures do not provide the designer with a clear over-all view of the interaction between the structural response and the member proportions, a simplified method of analysis for single cell box girders is desirable. Wright, Abdel-Samad, and Robinson (6) have developed an analogy to the well known "theory of beams on elastic foundations" (B.E.F.) to obtain an approximate analysis procedure which accounts for the effects of diaphragms or cross braces on the warping and distortion stresses of box girders. Comparisons with more refined analyses show that the B.E.F. analogy is an adequate substitute for these refined procedures.

By starting with the governing differential equation for the B.E.F. and by applying the proper boundary conditions, expressions for the dimensionless moments and deflections in terms of the B.E.F. and support properties can be determined. These values are later used in calculating the warping and distortion stresses in the analogous box girder. In the analogy the bending stresses in the B.E.F. are related to the warping stresses in the box girder, and the load on the B.E.F. is related to the torsional load on the box girder.

Warping stresses in the girder may be found by evaluating the moments in the B.E.F. Similarly, distortion stresses are obtained by finding the deflections of the B.E.F. The various parameters and equations used in this analysis are discussed in detail in Reference 6.

Although there are several different methods available for analyzing box girders which provide similar results, these methods still need to be verified by experimental work. One goal of this program is to provide additional experimental data on box girder behavior.

3. Model Tests on Box Girders

A few experiments have been conducted on box girder models. Parr and Maggard (7) carried out an experimental stress analysis of box-like girders for flexural members. The objective was to determine the stress conditions existing in various segments of the section and compare them with the corresponding theoretical values. Experimental values for strain were obtained by using strain rossettes placed at various points on the test section. Theoretical values of bending and shear stresses were computed for concentric and eccentric loading using the fundamental flexure formula, shear formula, and the first torsional analysis procedure discussed on page four. Precautions were taken against buckling of the thin plates which were subjected to combined shear and flexure.

Mattock and Johnson (8) conducted experiments on a model bridge with three box sections to find a general lateral distribution formula for the fraction of a wheel load to be assigned to each box girder. Various truck loading tests were performed to find the deflection along the cross section for different types of concentric and eccentric loadings. These values checked closely with the analytical results obtained by using the "generalized coordinate" method that was discussed earlier.

Since the above-mentioned experiments were conducted on box girder models without interior diaphragms, additional tests should be conducted on box girder models containing diaphragms.

4. Studies Using Plexiglas Models

Chevin (9) and Zanoni (10) have tested a folded plate structure fabricated from plexiglas. They found that since plexiglas creeps, an interval of ten minutes should be allowed between the application of the load and the reading of the strain gages. After this interval the creep rate was negligible. Another problem encountered was that plexiglas had different physical properties in different sheets. Zanoni felt that due to the variation of the Modulus of Elasticity the actual stresses could only be estimated to within 6% accuracy. For these reasons it was deemed advisable to experimentally obtain the material properties of each sheet that was used in the model. Extreme care was necessary when placing and reading strain gages on the model. Eastman 910 cement was found to satisfactorily bond the strain gages to the plastic. In one experiment three consecutive loadings were used to check the linearity of the gages. The three points were plotted and the line of best fit was drawn through the points. Thus a predicted strain for each gage as a function of load was determined.

Macias (11) conducted an experiment on a composite T-beam box girder with frictionless simple supports. A plexiglas load cell was used so that the time parameter was eliminated and the outputs of the load cell and the model itself remained constant, unaffected by creep. The deck was fastened to the web by means of No. 6 countersunk screws. The screws provided an excellent shear connection for developing full composite action of the model.

EXPERIMENTAL PROGRAM

1. Introduction

As stated previously, one purpose of this investigation was to confirm experimentally that deformation of the cross section of a box girder induces an appreciable amount of warping and distortion stresses and that these stresses can be substantially reduced by inserting rigid diaphragms at selected locations. The entire experimental program, including the determination of material properties, establishment of experimental techniques for plexiglas, design and fabrication of the model, test setup, test measurements, and test program, was designed with this goal in mind.

2. Determination of Material Properties

Introduction

Before any meaningful model tests could be conducted, certain physical properties had to be determined for the model material. Two series of tests were conducted on coupons machined from Type G Unshrunk plexiglas, the model material used throughout the investigation. The first test series established the stress relaxation behavior of the plexiglas, and the second involved the determination of stress-strain curves from which the Modulus of Elasticity and the range of elastic behavior could be evaluated.

The literature indicates that more accurate results may be obtained if the Modulus of Elasticity of each model component is determined rather than relying on the results of tests on an isolated coupon. (10) Therefore, one tensile coupon corresponding to each of the four model components, the two webs and two flanges, was fabricated and tested. In all cases the coupons were cut from a piece of plexiglas adjacent to the component they represented. It was found that the Modulus of Elasticity for all model components was nearly identical. The dimensions of the tensile specimens were based on A.S.T.M. Standards for physical and mechanical testing of metals. (12) (Fig. 1)

Stress Relaxation Tests

Creep is defined as "deformation that occurs over a period of time when a material is subjected to constant stress at constant temperature." (13) On the other hand, stress relaxation is the "decrease in stress in a material subjected to prolonged constant strain at constant temperature." (13) All testing in this investigation was conducted on a mechanical screw-type machine, which in effect is a constant displacement machine since the cross heads are fixed after loading and thus permit no additional deformation of the specimen to take place. Thus in these experiments, all the specimens underwent stress relaxation rather than creep although the two phenomena are closely related.

Stress relaxation data was obtained by loading the coupons to a certain level and recording the changes in load at specified time intervals. The amount of stress relaxation which takes place depends on several factors such as the time allowed for loading and the magnitude of the loads. Although the magnitude of stress loss varied slightly among the coupons, the test results indicated that the effects of stress relaxation were practically negligible after five minutes provided the stresses were in the elastic range. A typical stress relaxation curve is shown in Figure 2.

Stress Strain Tests

When electrical resistance strain gages are employed in conjunction with plastic model studies using a constant displacement testing machine, two alternatives are available for recording strains. One method involves waiting a suitable period of time to allow the stress relaxation rate to approach zero before recording the strain data. A typical stress-strain curve determined using this method is illustrated by the solid curve in Figure 3. This curve is the average strain obtained from the two longitudinal gages used on the coupon. (Fig. 1) The tests were repeated with nearly identical results. The value of $E = 0.465 \times 10^6$ psi. obtained from this type of test was used in all of the data reduction. Note that the stress-strain relationship was linear throughout the range of the test (up to 400 psi.).

The second method for measuring strains on plexiglas materials is to take instantaneous readings while loading. A 2 inch extensometer mounted on the coupons was used to obtain the dashed line on Figure 3. Any relative movement of the two knife edge gauge points on this extensometer actuates a differential transformer, the output of which is recorded graphically. Note that the Modulus of Elasticity from the instantaneous readings is somewhat higher than the value obtained when adequate time was allowed for stress relaxation.

3. <u>Experimental Techniques</u>

Since the material properties tests indicated that the effect of stress relaxation becomes negligible after five minutes, this time interval was permitted to elapse after loading the box girder model before measuring strains.

It is known that plexiglas is a poor heat conductor. The heat input during the warming up of a strain gage is not immediately dissipated as in the case of metals, but contributes to an added local deformation. To overcome this problem, a procedure was developed in which each gage was allotted the same amount of time to warm up. Since the differences between strains recorded at the various load levels and those measured at zero load constituted the desired data, the effect of local heating was accounted for. In all cases the current was applied to each gage for exactly twenty seconds before reading the gage. Readings were found to be easily reproducible following this simple procedure.

4. Model Design and Fabrication

The experiments were conducted on a box girder model having a length of 48 inches and cross section shown in Figure 4. The top flange was made from clear plexiglas, while the bottom flange and the two webs were fabricated with a dark colored plexiglas. There was no appreciable difference in the material properties of the colored and clear materials.

As indicated in preceding sections, the model was designed so that there would be substantial deformation of the cross section when no interior diaphragms were used. Since the calculated distortion stresses were much larger than the corresponding warping stresses for a given torsional loading, the model was designed so that the smaller warping stresses would be easily measured at the anticipated load levels. A peak ratio of warping to bending stresses of one-half was used as the design criteria.

A maximum load of 125 lb. was chosen so that the peak bending plus warping stresses would not exceed the elastic range of the plexiglas. The material properties tests had indicated that plexiglas behaves elastically up to 400 psi., which is compatable with previous experiments. (10) Actually some extreme fibers may have been subjected to stresses slightly above the yield point due to the unequal distribution of the warping stress across the bottom flange. (Fig. 32)

A detachable top flange (Fig. 5) was used to permit the installation of interior diaphragms for the later tests. The top flange was fastened to the webs with No. 6-32 flathead machine screws which were longitudinally spaced every four inches. This fastening method has been shown to result in adequate shear transfer to develop full composite action. (10) After fastening the top flange to the webs, the bottom flange and end diaphragms were cemented into place with Ethylene Dichloride, a plexiglas solvent cement that is easy to use and produces medium strength joints. When interior diaphragms were needed for later tests, the top flange was removed to permit cementing them into position.

5. Test Setup

For all of the tests the box girder model was supported on the rounded surfaces of steel bearing blocks spaced 46" center to center. (Figs. 5 and 6) These blocks were bolted to a 8" x 2-1/4" channel which served to transmit the model end reactions to the table of the testing machine. The load was transmitted from the testing machine cross head to the model by a 1" x 1/2" plexiglas bearing block.

6. Test Measurements

Static loads were applied to the box girder with a model FS-20 Riehle screw-type testing machine, a constant displacement machine. (Fig. 6) Loads can be measured accurately to the nearest tenth of a pound with this equipment, which is ideal for the small loads used in these experiments. All load readings were taken after five minutes had elapsed to allow stress relaxation in the model. The machine was located in a temperature controlled room.

Since the warping stresses are maximum under the load point, strains were measured at the loaded sections with Budd Metal film C40-141B gages which are temperature compensated for plexiglas. These gages were mounted at the locations indicated in Figures 7 and 8 using Eastman 910 cement. The gages on the webs were used to measure the transverse strains (corresponding to the distortion stresses), while the gages on the flanges were used to measure longitudinal strains. The measured longitudinal strains include both bending and warping strains. For concentric loading the longitudinal strains were due to bending only, and thus the experimental flexure strains could be determined. With eccentric loading the difference between the flexural strains and the measured strain in the flanges could be directly attributed to warping. Hooke's Law was used to convert the strains to stresses. The value for Young's Modulus of Elasticity was taken to be 0.465×10^6 psi. as determined from the material properties tests.

A Budd Model A110D strain indicator used in conjunction with a Budd Model C101C switch and balance unit was used to measure the strains. In order to facilitate the handling of the data, a printer control unit and printer were also used to establish an automatic printout system. (Fig. 6)

Throughout the model testing all load cycles were repeated so that the strain gages and instruments could be checked. The maximum deviation between the strains of two test cycles was 20×10^{-6} in./in., while in most cases the strains were reproduced exactly. Considering the problems inherent with plexiglas, this small discrepancy is considered to be within the accuracy of the strain measuring equipment and the procedures used.

Dial gages, located at midspan and shown in Figure 6, were used to measure vertical deflections of the model due to both concentric and eccentric loading. This data proved valuable in establishing the distortion patterns of the cross section. (Fig. 11c) Such patterns were used to verify the signs of the distortion stresses at various points on the cross section.

7. Test Program

The testing program was divided into three major parts. Initially for Case I, the model contained only the end diaphragms. The loading, ranging in 25 lb. increments from 0-125 lb., was applied at two cross sections (Fig. 9) and separately at three points across each cross section. (Fig. 10) Strains were measured at various points on cross sections

A and B (Fig. 7 and 8) for all of the loads on each of the six load locations.

For Case II two interior diaphragms were inserted, and for Case III four more interior diaphragms were placed in the model. (Fig. 9) The same loading and measuring procedures were employed as in Case I. Table 1 summarizes the load and diaphragm locations which were used in the program.

TEST RESULTS

The graphical presentation of the data from the test program is given on Figures 12-40. These results can be divided conveniently into four sections: deflections, bending stresses, distortion stresses, and warping stresses. A general discussion of the results, including qualitative and quantitative comparisons with theory and explanations of any discrepancies is presented in this chapter.

1. Deflections

Deflections at midspan due to loading at midspan were recorded by two dial gages as shown in Figure 8. The average value of the dial gage reading was compared to the sum of the bending and shear deflections as computed from elastic theory, for concentric loading. The experimentally determined deflections are somewhat higher than those predicted from theory (Fig. 12-19). This discrepancy can be attributed to the stress relaxation that occurred before the dial readings were recorded. The two dial readings were almost identical for concentric loading because there was no deformation or twisting of the cross section. (Fig. 11a)

When eccentric loads are applied to a model, two types of cross section motion are possible in addition to that observed for concentric loading. The first is the rigid body rotation where the cross section is not deformed. (Fig. 11b)

The second type of motion is the deformation of the cross section as shown in Figure 11c.

With eccentric loads the deflection of one edge of the cross section increases approximately as much as the other side decreases relative to that for concentric loading. (Fig. 15) In Cases II and III (Fig. 16-17) there is not as much difference between deflection caused by concentric and eccentric loadings as there is in Case I. This is an indication that additional diaphragms tend to decrease the deformation of the cross section.

2. Bending Stresses

The bending stresses in the bottom flange due to concentric loading were checked with theoretical values to give an indication of the effectiveness of the strain gages and the experimental techniques. The average of the gage readings was used to represent the strain in the middle surface of the flange plate.

There appeared to be a shear lag (14) on the bottom flange at the loaded cross section. The stresses across the bottom flange for concentric loading were not linear as conventional beam theory predicts. (Fig. 18) It may be hypothesized that a short distance away from the load the stress distribution would approach linearity. The average of the flexure stresses for all of the gage locations on the bottom flange was compared with simple beam theory. In general the results were reasonably close regardless of the diaphragm locations. Therefore the comparison for Case I only is shown in Figures 19-22.

From these results it was concluded that the gages were working properly and that the girder was acting as a composite section.

The gage readings varied linearly with the load and were reproducible which indicates that the strain gage techniques developed for this investigation were effective in counteracting the problems presented by stress relaxation and heating of the gages. These results make it apparent that plexiglas can be an effective model material if the proper experimental procedures are followed.

3. Distortion Stresses

The evaluation of distortion stresses was accomplished by subtracting the stresses measured by the transverse web gages due to concentric loading from those due to eccentric loading.

Distortion stresses measured in sections A and B were compared with theoretical values obtained from the B.E.F. analogy. Only distortion stresses at the loaded cross section are plotted because the stresses were negligible at the other section that was gaged. The signs of these stresses were consistent with the deformation pattern. (Fig. 14c) It is also easily seen from a comparison of Figures 23-31 that diaphragms are quite effective in reducing distortion stresses.

However the distortion stresses at the bottom of the webs are generally higher than expected from the theory while those near the top of the webs are lower than the B.E.F. predictions. These differences may be explained in part if the screws fastening the top flange to the webs were not completely effective in maintaining a rigid joint. This would tend to relieve the stresses near the top flange while increasing those near the bottom flange because of the double curvature of the web plate.

The ratio of the distortion stress caused by medium eccentric loading to that due to maximum eccentric loading varied from 35-65%. This ratio should always be 1/2 according to theory. The largest variation occurred in the gages near the top of the web which could be explained by the fact that the stresses were so small at these positions that a minor difference could be easily magnified out of proportion.

4. <u>Warping Stresses</u>

The experimental warping stresses were determined by subtracting the flange stresses due to concentric loading from those obtained when the model was loaded eccentrically. However the warping stresses at the loaded cross section are not exactly linear across the bottom flange as B.E.F. theory predicted. (Fig. 32) A possible explanation of this observation can be that there is a shear lag caused by shear deformation at the point of loading, and that a short distance away the warping stress pattern becomes linear. In an effort to verify this interpretation, the warping stresses were measured at cross section B when load was applied at cross section A. These values appeared to be linear, but they were too small in magnitude to formulate a firm conclusion. In the comparisons with the B.E.F. analogy, the average of the stresses at the outside gage locations were used.

The warping stresses at B due to load at B (Fig. 33-35) are somewhat higher than the B.E.F. theory. However, the panel under consideration is assumed to be restrained by adjacent panels at each end when in reality it is not. Thus the predicted stresses may be too small.

When the model was loaded and the stresses were measured at A, (Fig. 36-38) the experimental and theoretical values for warping stress in Case I and II were similar. The results of Case III, however, indicate that the experimental stresses are somewhat smaller than the theoretical stresses. It should be noted that B.E.F. values for warping stresses are very sensitive to changes in diaphragm spacing when the distance between diaphragms approaches L/10 where L is the span length. According to the theory, one-half of the peak warping stress exists with a diaphragm spacing of L/10 and practically no warping stress is present when the load is applied over a diaphragm.

The experimental warping stresses for medium eccentricity were quite close to 1/2 the values obtained with maximum eccentricity. Also as mentioned previously the warping stresses at the section not being loaded were small. In addition they had opposite signs which is compatible with the B.E.F. Analogy. (Fig. 39-40)

Warping stresses were reduced by using interior diaphragms although not nearly as much as the distortion stresses were. The maximum warping stress at A for load at A was approximately 40% of the maximum flexure stress at this point, and the maximum warping stress at B for load at B was very nearly equal to the flexure stress. Thus it would appear to be inadvisable to ignore completely the stresses induced by deformation of the cross section for a prototype having the same general dimensions as the model under consideration.

CONCLUSIONS

The following conclusions were substantiated in this experimental investigation. All of the conclusions apply only to conditions as specified in the scope of the study.

1) The effect of deformation of the cross section induced substantial warping and distortion stresses in the model box girder. Thus for the model dimensions and test conditions under consideration, it would seem to be inadvisable to employ design procedures that do not account for deformation of the cross section.

2) Diaphragms are much more effective in controlling distortion stresses than in controlling warping stresses. Thus in the design process it would seem reasonable to space diaphragms to control distortion stresses and then check warping stresses.

3) The distortion and warping stresses determined from the B.E.F. theory agreed qualitatively with the experimental stresses although the magnitudes varied somewhat.

4) The tension flange stresses and midspan deflections of a concentrically loaded box girder model can be predicted fairly accurately using simple beam theory including the shear deflections.

5) Plexiglas can be a very effective model material if the proper experimental techniques are employed.

RECOMMENDATIONS FOR FURTHER RESEARCH

Several improvements in the experimental program would be helpful for future model box girder investigations.

To gain a better understanding of diaphragm spacing in reducing distortion and warping stresses, removable diaphragms should be used. Rather than cementing the diaphragms in place, it might be possible to fasten the diaphragms with screws along the web or bottom flange. Since plate diaphragms may be transformed into cross braces having an equivalent stiffness for the purpose of analysis, cross braces could be used in the model instead of diaphragms.

It would be of interest to measure strains at cross sections other than the loaded section. In this way the problem of shear lag could be eliminated.

Distortion stresses should be investigated more thoroughly using additional strain gages on the webs.

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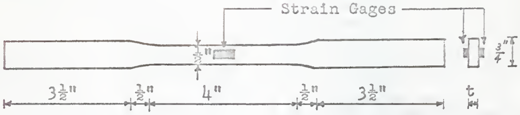
Diaphragms (Fig. 9)	Loading	
	Section (Fig. 9)	Point (Fig. 10)
Case I	A	p_1
		p_2
		p_3
	B	p_1
		p_2
		p_3
Case II	A	p_1
		p_2
		p_3
	B	p_1
		p_2
		p_3
Case III	A	p_1
		p_2
		p_3
	B	p_1
		p_2
		p_3

Table 1. Summary of Testing Program



t = ½" for top flange and ¼" for bottom flange and web coupons

Fig. 1.-Tensile Coupon Dimensions.

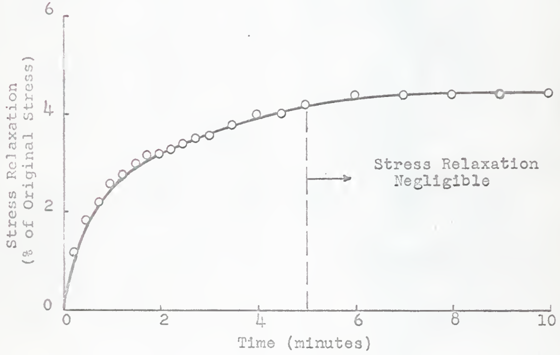


Fig. 2.-Typical Stress Relaxation Curve.

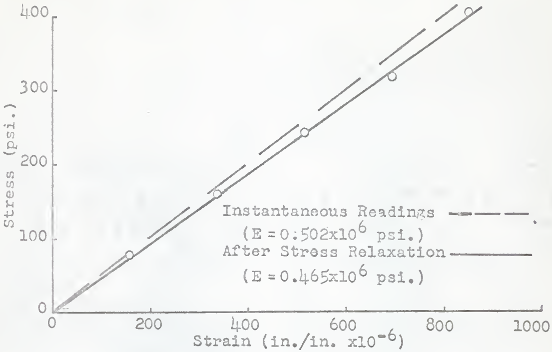


Fig. 3.-Coupon Stress-Strain Curves.

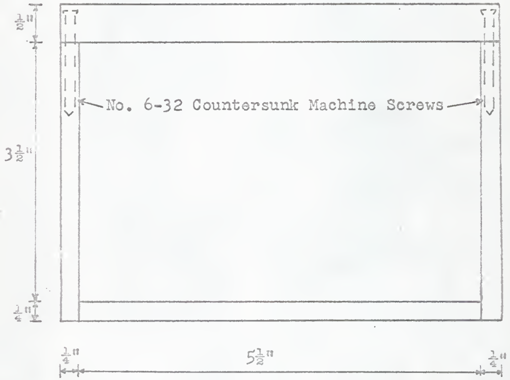


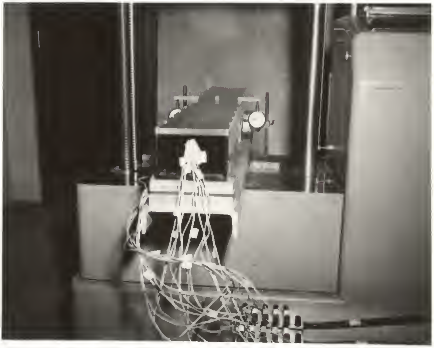
Fig. 4.-Model Cross Section.

A) Top Flange in Place

B) Top Flange Removed

Fig. 5.-Model and Supports.

A) Overall View



B) Model Close-up

Fig. 6.-Test Setup.

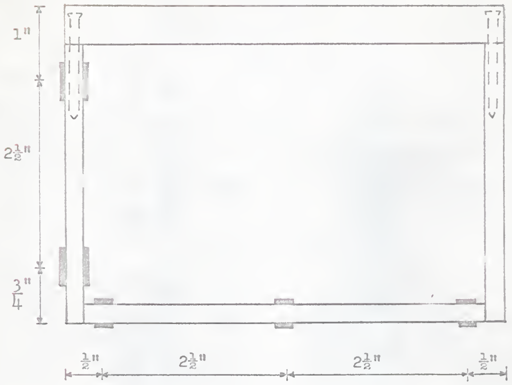


Fig. 7.-Location of Strain Gages on Cross Section B.

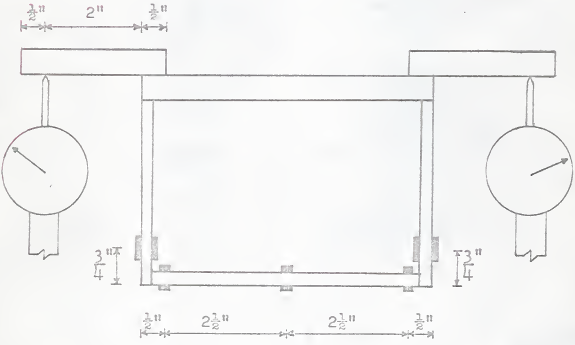


Fig. 8.-Location of Strain Gages and Dial Gages
at Section A (Midspan).

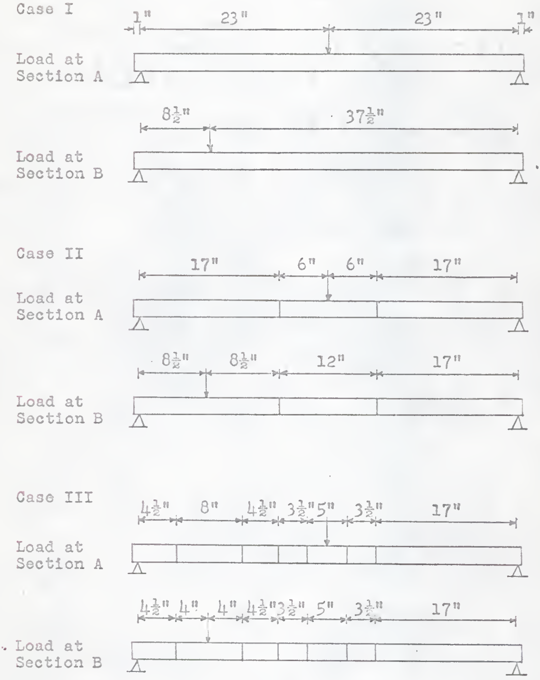


Fig. 9.-Location of Diaphragms and Test Loads.

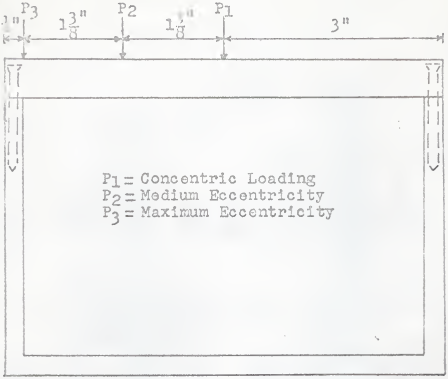


Fig. 10.-Cross Section Loading Points.

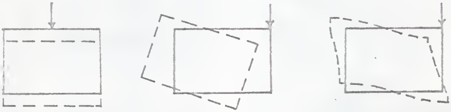


Fig. 11.-Types of Cross Section Movement.

(a) Deflection Due to Concentric Loading
(b) Rigid Section Deflection Due to Eccentric Loading
(c) Deformation of Cross Section

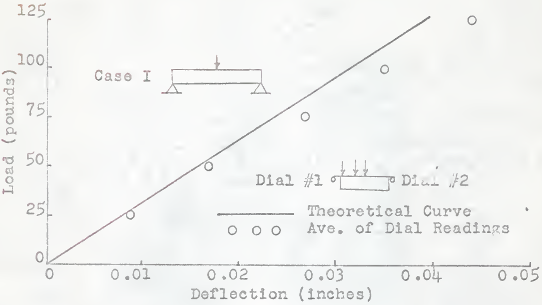


Fig. 12.-Load Vs. Ave. Centerline Deflection Concentric Loading-Case I.

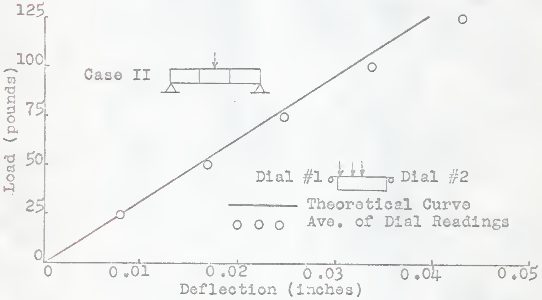


Fig. 13.-Load Vs. Ave. Centerline Deflection Concentric Loading-Case II.

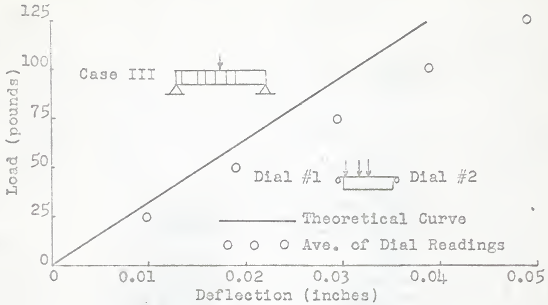


Fig. 14.-Load Vs. Ave. Centerline Deflection
Concentric Loading-Case III.

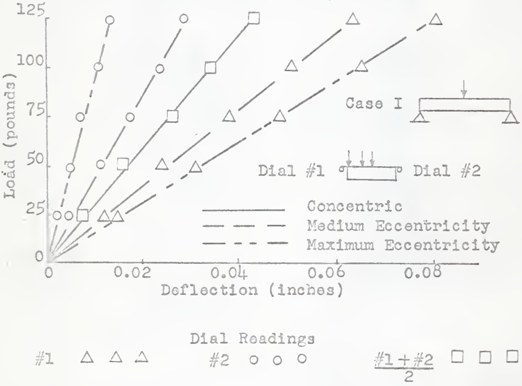
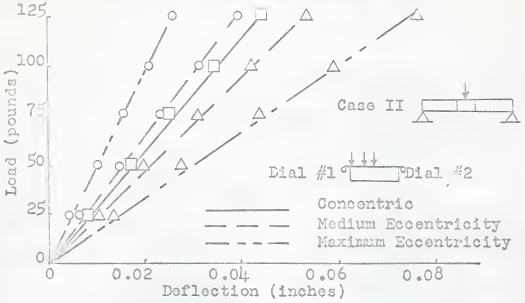


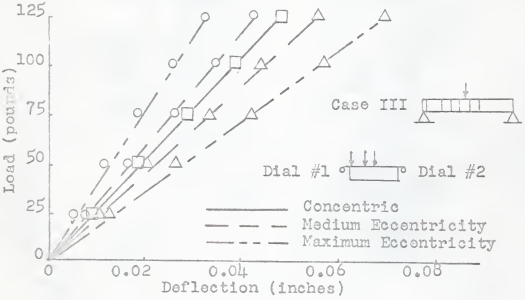
Fig. 15.-Load Vs. Centerline Deflection-Case I.



Dial Readings

#1 △ △ △ #2 ○ ○ ○ $\frac{\#1 + \#2}{2}$ □ □ □

Fig. 16.-Load Vs. Centerline Deflection-Case II.



Dial Readings

#1 △ △ △ #2 ○ ○ ○ $\frac{\#1 + \#2}{2}$ □ □ □

Fig. 17.-Load Vs. Centerline Deflection-Case III.

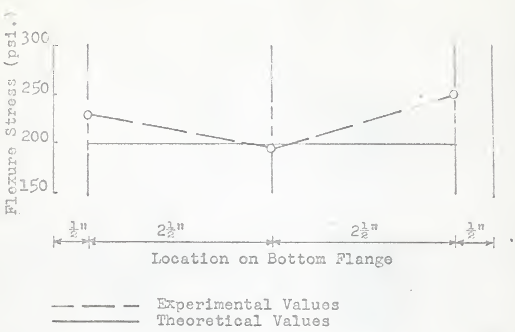


Fig. 18.-Typical Flexure Stress Pattern at Loaded Section.

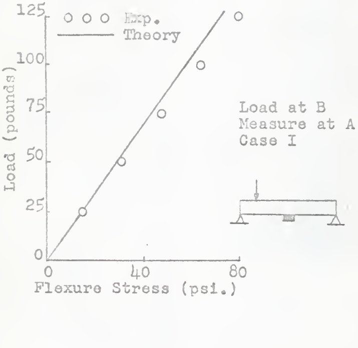


Fig. 19.-Load Vs. Flexure Stress at Middle of Bottom Flange.

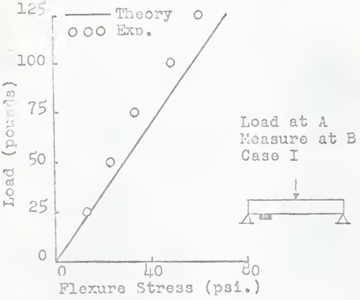


Fig. 20.-Load Vs. Flexure Stress at Middle of Bottom Flange.

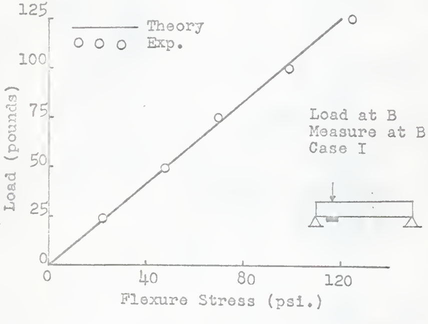


Fig. 21.-Load Vs. Flexure Stress at Middle of Bottom Flange.

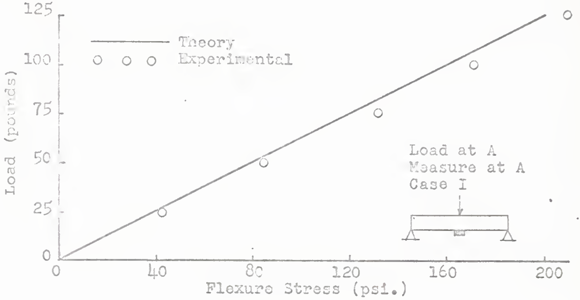


Fig. 22.-Load Vs. Flexure Stress at Middle of Bottom Flange.

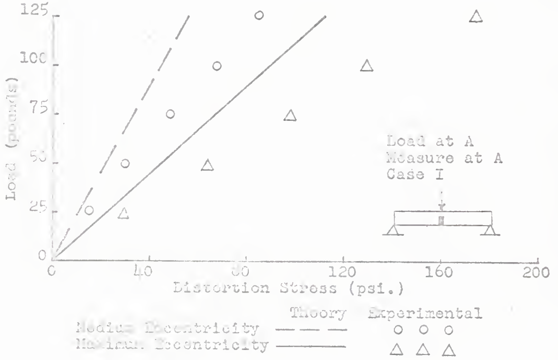


Fig. 23.-Load Vs. Distortion Stress at Lower Gage Location.

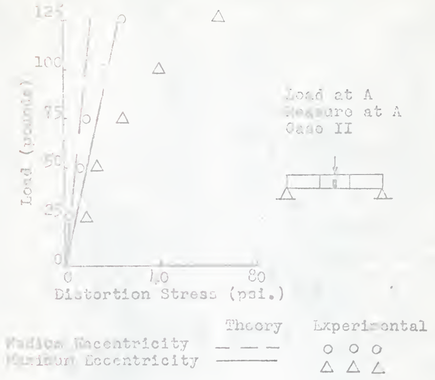


Fig. 24.-Load Vs. Distortion Stress at Lower Gage Location.

Fig. 25.-Load Vs. Distortion Stress at Lower Gage Location.

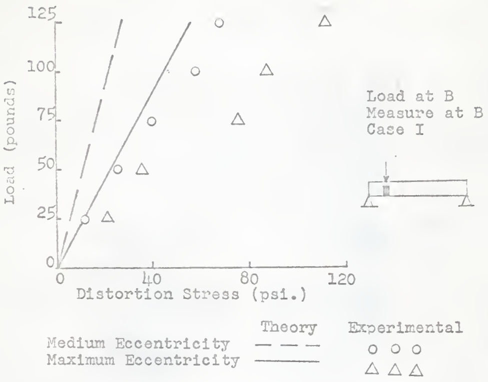


Fig. 26.-Load Vs. Distortion Stress at Lower Gage Location.

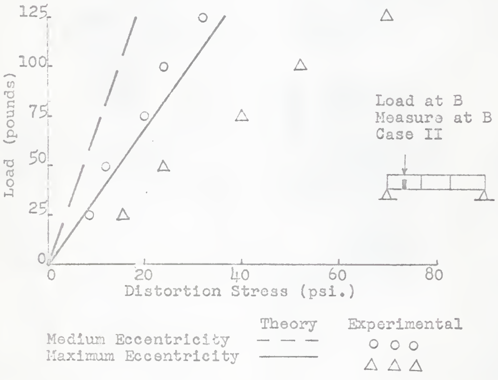


Fig. 27.-Load Vs. Distortion Stress at Lower Gage Location.

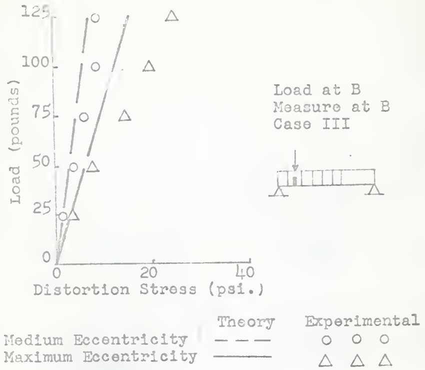


Fig. 28.-Load Vs. Distortion Stress at Lower Gage Location.

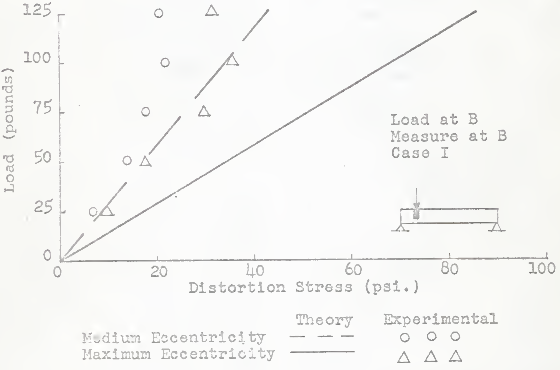


Fig. 29.-Load Vs. Distortion Stress at Upper Gage Location.

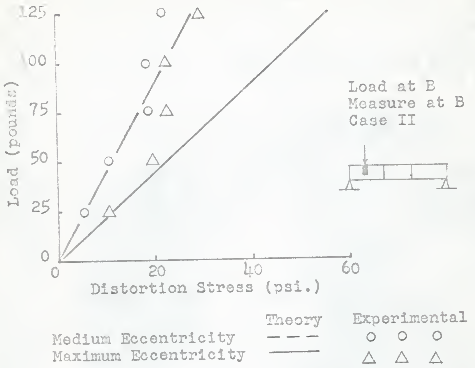


Fig. 30.-Load Vs. Distortion Stress at Upper Gage Location.

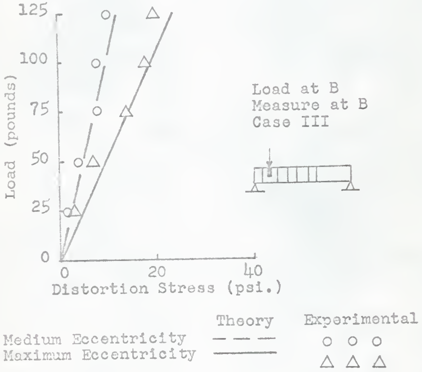


Fig. 31.-Load Vs. Distortion Stress at Upper Gage Location.

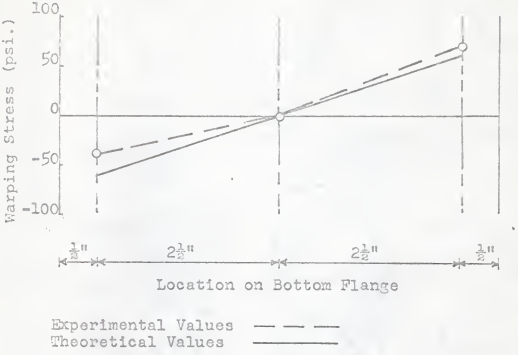


Fig. 32.-Typical Warping Stress Pattern at Loaded Section.

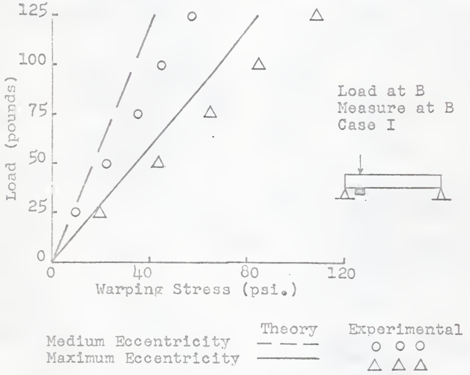


Fig. 33.-Load Vs. Warping Stress at Outside Gage Locations.

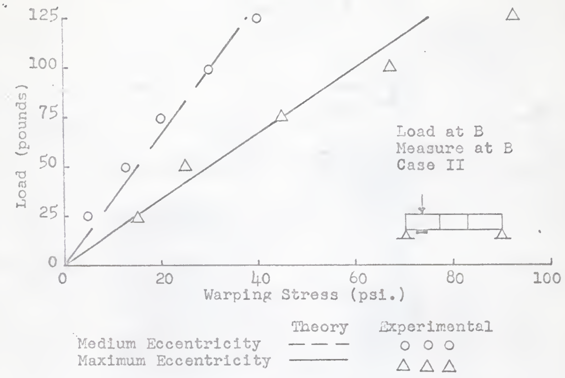


Fig. 34.-Load Vs. Warping Stress at Outside Gage Locations.

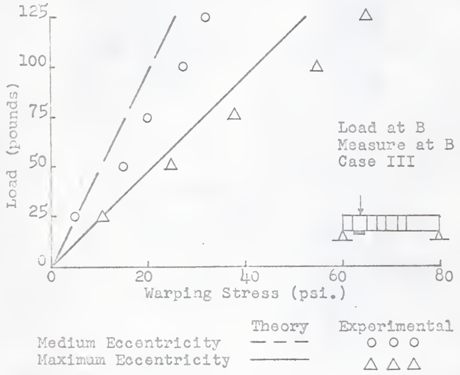


Fig. 35.-Load Vs. Warping Stress at Outside Gage Locations.

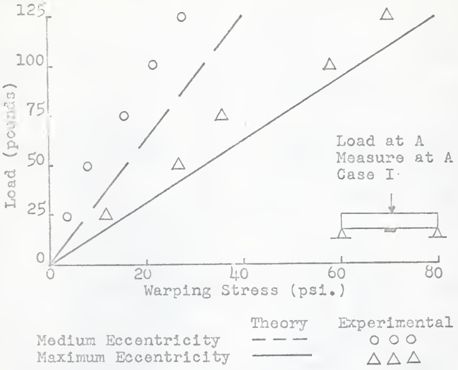


Fig. 36.-Load Vs. Warping Stress at Outside Gage Locations.

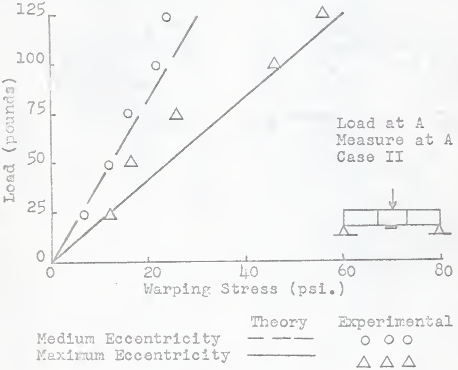


Fig. 37.-Load Vs. Warping Stress at Outside Gage Locations.

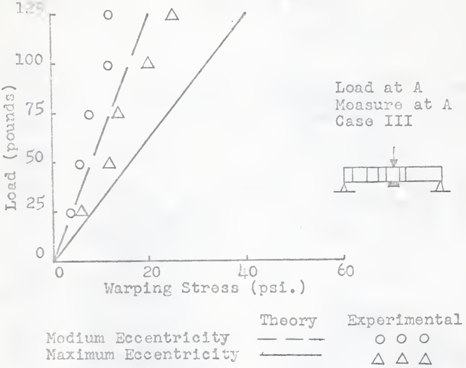


Fig. 38.-Load Vs. Warping Stress at Outside Gage Locations.

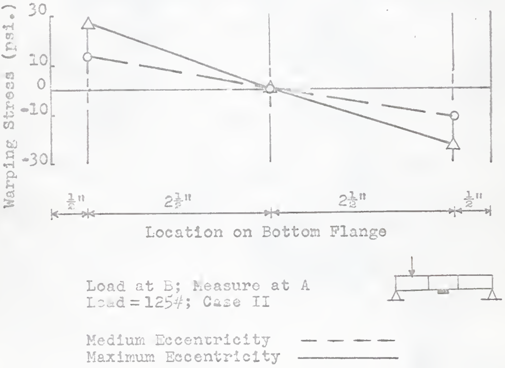
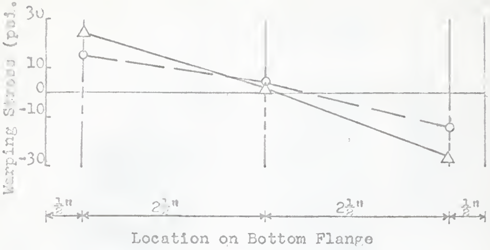


Fig. 39. - Warping Stress on Bottom Flange.



Load at A; Measure at B
Load 125#; Case II

Medium Eccentricity — — — —
Maximum Eccentricity ————

Fig. 40.-Warping Stress on Bottom Flange.

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MODEL STUDIES OF BOX GIRDERS

by

DENNIS EUGENE MYERS

B. S., Kansas State University, 1967

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

ABSTRACT

This thesis describes an experimental study of the stresses in thin walled box girders subjected to various loading configurations.

The primary purpose of the study was to examine the effect of rigid diaphragms in reducing warping and distortion stresses which are developed in box girders due to deformation of the cross section. Tests were conducted on a box girder model to determine these stresses. The results were compared with values obtained from the so-called "B.E.F. Analogy", an analytical analysis which accounts for the warping and distortion stresses. A secondary purpose was to study the experimental characteristics of plexiglas, which was used as the model material.

The model had overall cross section dimensions of 6" x 4-1/4" and was tested as a simply supported beam with a 46 inch span. Six separate loading positions were used for each of the three diaphragm spacing conditions. Thus 18 separate loading tests were conducted in order to obtain sufficient data to accomplish the purpose of the investigation. Test measurements included applied load, deflections, and strains at various locations on the webs and bottom flange.

The results indicate that deformation of a box girder cross section may cause substantial warping and distortion stresses, and that these stresses can be effectively controlled by prudent diaphragm placement. The B.E.F. Analogy gave

reasonable predictions for the measured warping and distortion stresses. Finally, it is concluded that plexiglas can be a very effective model material if proper experimental techniques are employed.