MODEL STUDIES OF DOUBLE-CELL BOX GIRDER BRIDGE WITH INTERMEDIATE DIAPHRAGMS

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An experimental study on the influence of intermediate cross-bracing diaphragms on the behavior of a simply supported double-cell box girder bridge has been carried out. A perspex model was tested under various loading conditions and the test results, namely the displacements, cross-sectional distortion, longitudinal and transverse normal forces were compared with theoretical values suggested by Nimityongskul, Pama and Lee [1]. In this analysis, the elements in the box section are treated as rectangular plates subjected to lateral and in-plane boundary forces. The end diaphragms are assumed to be infinitely rigid in and flexible normal to their planes. The intermediate diaphragm is assumed to act in such a way that it exerts only concentrated vertical and horizontal reactions on the joints of the box section without introducing resisting moments against joint rotations. Test results indicated that the distortion of the cross-section of a box girder without intermediate diaphragm is more prominent when loaded along the side-joints. With one intermediate diaphragm the distortion at the loaded section remains practically the same when the diaphragm is sufficiently away from the applied loads, but is considerably reduced when the diaphragm is near the load. The use of intermediate diaphragm decreases effectively the cross-sectional distortion, increases the overall stiffness of the bridge and redistributes the longitudinal normal forces. In general, the experimental values confirm the theoretical predictions on the influence of intermediate diaphragms on the load distribution in a double-cell box girder bridge. Careful considerations must be taken in designing these intermediate cross-bracing diaphragms to satisfy the assumptions made in the theory.

Introduction

Box girders which may be either straight or curved in plan are currently used for highway bridges. The cross-section may be single-cell or multi-cell depending on the width of the bridge. A lot of analytical and experimental studies have been reported lately as evidence of the increasing use of box girder bridges in the last few years. Quite a few dealt with the influence of transverse stiffeners or diaphragms which are used to prevent cross-sectional distortion of the box elements. The experimental work reported so far has been limited to single-cell box girders with solid diaphragms.

An extensive review of the methods for analysing box girder can be found in the progress report of the Subcommittee on Box Girders of the ASCE-AASHO Task Committee on Flexural Members [1]. ARENDTS and SANDERS [2] used the concept of replacing the actual cellular structure of a concrete box girder highway bridge with a uniform plate whose structural properties are equivalent to those of the actual bridge. An analysis of box girders of deformable cross-section based on an analogy of beams on elastic foundation was separately studied by WRIGHT, ABDEL-SAMAD and ROBINSON [3] and CAMPBELL-ALLEN and WEDGWOOD [4]. The effects of rigid or deformable interior diaphragms are also treated by determining the stiffness for the beam on elastic foundation. SAWKO and COPE [5] used modified finite element technique for the analysis of multi-cell bridges without transverse diaphragm. ABDUL-SAMAD, WRIGHT and ROBINSON [6] applied thin-walled beam theory to box girders of deformable cross-section. Thin-walled beam theory is extended to cover stiffened plate elements and the effects of deformable interior diaphragms. A further simplified formulation was studied by DALTON and RICHMOND [7] to obtain the solution for girders of trapezoidal cross-section by assuming that only the diaphragms or cross-frames resist the cross-sectional distortion. SCORDELIS [8] applied folded plate theory to obtain the solution for a simply supported box girder bridge. The analysis is limited to straight prismatic box girder composed of isotropic plate elements without intermediate diaphragms. An analysis of box girder by finite strip method was presented by CHEUNG [9], in which harmonic functions which fitted the boundary conditions in the longitudinal directions are used in conjunction with single polynomials as displacement function in the transverse direction.

Recently NIMITYONGSKUL, PAMA and LEE [10] presented an accurate and efficient method of analysis for box girder bridges and takes into account the influence of intermediate diaphragms. The elements in the box section are treated as rectangular plates subjected to lateral and in-plane boundary forces. The solutions due to unit vertical and horizontal loads applied at the joints for the case without intermediate diaphragm are obtained and used as influence coefficinets to derive the solutions for any combination of concentrated live loads applied at the joints as well as the effect of intermediate diaphragms.

MYERS and COOPER [11] experimentally studied the effects of interior diaphragms in a simply supported single-cell box girder bridge and compared the results with those obtained based on the beam on elastic foundation analogy. HEINS, BONAKDARPOUR and BELL [12] presented the results of an experimental study on the behavior of a plexiglass three-cell curved beam model subjected to static loads and compared the deflections and strains with those predicted by the slope deflection theory. GODDEN and ASLAM [13] presented the results of an experimental study on the static response of skew box girder bridges and theoretical result based on a finite element analysis was used for comparison. An experimental investigation to study the behavior of composite simply supported box girder bridge with end diaphragms was carried out by MATTOCK and JOHNSTON [14] and the result agreed well with those obtained by the folded plate theory. ANEJA and ROLL [15] carried out an experimental investigation on a horizontally curved box beam highway bridge model subjected to various loading conditions. A model analysis of a curved prestressed concrete cellular bridge was presented by CHUNG and GARDNER [16]. A 1/24 scale perspex model was used to predict the elastic properties and a 1/6 scale prestressed concrete model to determine the load factor. DAVIS, SHEFFEY, CASTLETON and EVANS [17] presented a model and prototype studies of box girder bridge and correlated the results with the prototype behavior and that predicted by the folded plate analysis.

This paper describes an experimental investigation which was conducted to determine the influence of intermediate diaphragms on the behavior of a simply supported straight double-cell box girder bridge. The intermediate diaphragms are in the form of rigid cross-bracing as shown in Fig. 1. The experimental results are compared with theoretical values suggested by NIMITYONGSKUL, PAMA and LEE [10].

General Theoretical Consideration

A double-cell straight box girder bridge with or without intermediate diaphragms, simply supported at the ends by means of supporting diaphragms, and subjected to a concentrated load acting at a joint is shown in Fig. 1. A vertical concentrated load acting on a joint of the top deck can be resolved into symmetrical and antisymmetrical components as shown in Fig. 2. The solution for the antisymmetrical component is treated in detail by NIMITYONGSKUL, PAMA and LEE [10]. The effect of symmetrical component is localized and can be obtained by suitable approximation for design purposes. The elements in the box section are treated as rectangular plates subjected to lateral and in-plane boundary forces. It is assumed that the influence of in-plane forces on the bending of the plate may be disregarded. This leads to two fourth order partial differential equations, which govern the bending of the plate under the action of the normal load components and the membrane action of the plate under in-plane load components (Fig. 3).

Treatment of Intermediate Diaphragm

The end diaphragms are assumed to be infinitely rigid in and flexible normal to their planes. The intermediate diaphragm is assumed to act in such a way that it exerts concentrated vertical and horizontal reactions only at the joints of the box section without introducing resisting moments against joint rotations. It is assumed to be infinitely rigid in its own plane and, under general loading, it undergoes rigid body displacement, i.e., vertical and horizontal deflections as well as rotation about the axis of the bridge. The values of the reactive forces are determined from the conditions that the rigid body displacements of the intermediate diaphragm are compatible with the joint displacements, under the simultaneous effect of the applied loads and the reactive forces, and that reactive forces on the diaphragm are in self equilibrium. Numerical results for a simply supported double-cell box girder bridge subjected to unit loads applied separately at the middle and side joints are initially obtained for the case without intermediate diaphragms. These results are then used as influence coefficients in developing the solutions for cases with one intermediate diaphragm at midspan and three intermediate diaphragms at quarter points.

Experimental Program

Model Design and Fabrication

Tests were conducted on a model of a double-cell straight box girder bridge. The simply supported span of the model is 1520 mm and the cross-section is shown in Fig. 1. All components of the box girder were made of perspex. The parameters suggested by NIMITYONGSKUL, PAMA and LEE [10] were used except that the thickness of the top and bottom decks and the webs were made the same because of the unavailability of perspex plates of different thicknesses. The model was designed such that there is substantial deformation of the cross-section under load. In constructing the model, the side and middle webs were glued into positions on the bottom deck and then all the necessary electrical strain gages were attached to their proper locations as shown in Fig. 4. The intermediate diaphragms were positioned properly at midspan and quarter-span of the bridge girder. Finally, the top deck was glued to the webs and interior diaphragms. Detachable end diaphragms were fixed to the box element by using screws. Circular holes were drilled on the end diaphragms to allow the wires of the electrical strain gages inside the girder to pass through.

Instrumentation

Electrical resistance rectangular strain rosettes were attached to the model as shown in Fig. 4. At quarter-span and midspan, six rectangular strain rosettes were fixed at each section. At three-eighth-span section, twenty-four rectangular strain rosettes were provided. Mechanical dial gages were used for measuring deflections. Temperature effect on strain gages attached to the model which has poor heat diffusion properties was compensated by using dummy gages.

Determination of Material Properties

Prior to testing the model, the mechanical properties of the model materials were determined. Representative samples of each of the box girder components were subjected to axial tension test. Longitudinal and transverse strains were measured by means of electrical strain gages attached to one side of the specimens. The test results gave an average value for the modulus of elasticity E of 2.90×10^6 KN/m^2 and Poissons ratio ν of 0.365. Tensile creep test was conducted on the control specimens and it was observed that the rate of creep diminished appreciably after approximately three minutes of loading.

Test Set-Up and Measurements

The box girder was supported on steel bearing plates (50 mm x 350 mm) with a 15 mm diameter steel rollers. Ball bearings were also provided to prevent the uplift due to eccentric loading but this proved unnecessary during the test. Static point loads were applied monotonically in increments to the box girder by means of a hydraulic jack as shown in Fig. 5. Since it was established that the effect of creep became negligible three minutes after initial loading, strain measurements were only taken after this time interval has elapsed. The strains were automatically recorded by a data logger.

Test Programs

The test program was divided into three major parts corresponding to the number of intermediate diaphragms present. Each test series consists of six minor test programs depending on the variation of the point of application of the load spanwise and transversewise on the top deck. Incremental point loads of 220 N, starting from 880 N to 1540 N were applied at quarter-span, three-eighth-span and midspan on the top left edge and on the middle joint of the cross-section. The application of an initial load was necessary to remove the slack in the loading system. The test series started with three intermediate diaphragms present. After this test the two diaphragms at quarter-span were sawed off by a jacksaw and a similar set of tests repeated. Finally the diaphragm at midspan was removed and another set of tests was conducted on the model. The test results are compared with theoretical values obtained by the use of a digital computer.

Test Results and Discussions

Deflections

Deflections were recorded at mid-joint and side-joints of the cross-section at quarter-span, three-eighth-span, midspan, and three-quarter-span. Figures 6 to 8 show the average experimental deflections and the corresponding theoretical values of the simply-supported box girder for the case without diaphragm, with one diaphragm, and with three diaphragms due to unit loads acting at quarter-span, midspan, and three-eighth-span respectively. The horizontal displacements observed from the experiment were small and were not included. The experimental values are generally in good agreement with the corresponding theoretical values. It is observed that for the case with one diaphragm (Figs. 6b, 7a and 8c) the deflected shape of the model at the diaphragm section especially for the case of unit loads acting at the left edge is slightly different from that obtained theoretically. This difference is due to the fact that the box section did not distort as a rigid body as predicted in the theory. In other words, there was still a certain degree of local distortion even at the intermediate diaphragm section. It is to be noted that the intermediate diaphragm is assumed in the analysis to be infinitely rigid in its own plane and, under general loading undergoes rigid body displacement only. The type of intermediate diaphragms used in this test is in the form of cross-bracings and therefore they are not as rigid as those assumed theoretically. This effect is less evident for the case with three diaphragms. On the whole, the correlation between the experimental and theoretical deflections is good.

Cross-Sectional Distortion

The influence of intermediate diaphragms can be observed clearly for loads acting at quarter-span. The distortion of the cross-section remains practically unchanged (Fig. 6) when an intermediate diaphragm is introduced at midspan, whereas, this distortion vanished when three intermediate diaphragms were provided. For loads acting at midspan and three-eighth-span respectively as shown in Figs. 7 and 8, the distortion is considerably reduced by adding one diaphragm only at midspan. The cross-sectional distortion was further reduced when three intermediate diaphragms were present. As expected, the twisting of the box section for cases with one and three intermediate diaphragms is less than for the case without diaphragm when the loads act at the side-joint.

Longitudinal Normal Forces

Figures 9 to 11 show the experimental and theoretical results for the longitudinal normal forces N_y at various locations indicated in Fig. 4. In general the strain readings varied linearly with the applied load. The experimental values are generally in good agreement with the theoretical values. The influence of intermediate diaphragm can be seen clearly for points at the loaded section in which values of longitudinal normal forces for loads at mid-joints and side-joints are getting closer to each other or almost the same for the case with one and with three intermediate diaphragms. Without intermediate diaphragm, the values of N_y are significantly higher at the locations near the loaded joint. For loads applied at the side-joints, the values of N_y at the point near the loaded joint are slightly decreased by the addition of a diaphragm at the loaded section and the transverse distribution of load is evident from the distribution of N_y to the other point of the loaded section. For sections sufficiently away from the diaphragm, the values of N_y are hardly influenced by the presence of intermediate diaphragm as can be seen in Fig. 12.

Transverse Normal Forces

The experimental and theoretical results for transverse normal forces N_y are summarized in Tables 1, 2 and 3. The agreement between the experimental and theoretical values are in general not very good. The experimental results give smaller values but it can be clearly seen that the transverse normal force is insignificant for the model without intermediate diaphragm except in the vicinity of the loaded joint. With intermediate diaphragms, the concentrated dia-

phragm reactions introduce significant values of N_x locally in the neighborhood of the joints. For values at three-eighth-span, the influence of the intermediate diaphragms on N_x are hardly evident. The difference between experimental and theoretical values may be due to the convergence of the series solution in the theory. Also, at the loaded section, the theory does not take into account the effect of symmetrical loading on the transverse normal force in the web. Moreover, the cross-bracing diaphragm attached to the plate element may be giving additional transverse stiffness to the plate element which may also contribute to this discrepancy between the theoretical and experimental results for N_x.

Conclusions and Practical Applications

1. The distortion of the cross-section of a box girder without intermediate diaphragm is more prominent when loaded along the side-joints. With one intermediate diaphragm the distortion at the loaded section remains practically the same when the diaphragm is sufficiently away from the applied loads, but is considerably reduced when the diaphragm is near the load.

2. The use of intermediate diaphragm decreases effectively the cross-sectional distortion, increases the overall stiffness of the bridge and redistributes the longitudinal normal forces.

3. For side-joint loading, the deflection along the left profile passing through the loaded joints for the case without intermediate diaphragm is larger than that for the case with intermediate diaphragms while the situation is reversed at the other side-joint.

4. In general, the experimental values confirm the theoretical predictions on the influence of intermediate diaphragms on the load distribution in a double-cell box girder bridge. Careful consideration must be taken in designing these intermediate cross-bracing diaphragms to satisfy the assumptions made in the theory. For model studies, it is recommended to use a different material for the intermediate diaphragms especially one which is considerably stiffer compared with the other components of the model and to make it slender enough to eliminate the occurrence of resisting moments at the joint as much as possible.

5. Since transverse stresses are relatively small, transverse stiffness is therefore more significant than transverse strength in the design of intermediate diaphragms.

The reversible nature of the transverse normal stresses necessitates that restrictions should be imposed in the design such that low strength limits are prescribed in order to avoid fatique failures.

List of Symbols

b	=	span length of the bridge
D	=	flexural rigidities of decks and webs
E	=	modulus of elasticity
M_x, M_y	=	transverse and longitudinal bending moment per unit length respectively
M_{xy}, M_{yx}	=	torsional moment per unit length
N_x, N_y	=	transverse and longitudinal normal forces
P	=	vertical concentrated load
t	=	thickness of decks and webs
w	=	vertical displacement
y	=	longitudinal position of cross-section
ν	=	Poisson's ratio

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Summary

An experimental study on the influence of intermediate cross-bracing diaphragms on the behavior of a simply supported double-cell box girder bridge has been carried out. A model made of perspex was tested under various loading conditions and the test results are compared with theoretical values suggested by NIMITYONGSKUL, PAMA and LEE [10]. The experimental results for deflection and longitudinal normal forces are shown to be in good agreement with the theoretical results. This study showed that the use of intermediate diaphragm decreases effectively the cross-sectional distortion throughout the span, increases the overall stiffness of the bridge and redistributes the longitudinal normal forces.

Table 1. Transverse normal forces $N_x b$ due to unit load at quarter-span.

(a) Unit load at left edge

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphragms
M_1	-0.560	1.470	2.475	0.400	1.000	1.400
M_2	0.150	1.170	0.235	0.100	1.250	0.100
M_3	0.300	17.370	11.800	0.600	3.200	3.100
Q_1	4.310	3.940	3.990	4.230	4.100	-8.850
Q_2	24.840	24.670	20.600	-10.800	-13.400	-16.550
Q_3	4.435	4.045	16.910	4.350	5.700	10.800

(b) Unit load at center

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphgrams
M_1	0.100	3.370	3.335	0.215	1.720	1.700
M_2	0.350	2.000	0.180	0.650	1.400	0.430
M_3	0.150	10.350	10.420	0.220	0.800	0.820
Q_1	0.100	0.150	12.135	0.170	0.450	14.650
Q_2	6.020	8.035	9.360	5.000	2.900	8.630
Q_3	-12.040	-12.150	6.260	19.500	-3.350	2.820

Table 2. Transverse normal forces $N_x b$ due to unit load at three-eighth-span.

(a) Unit load at left edge

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphragms
M_1	-0.210	0.570	-4.030	0.105	0.300	-3.100
M_2	0.225	-1.795	-1.250	0.150	-1.500	-1.000
M_3	0.510	19.615	24.300	0.200	1.750	4.250
TE_1	2.830	2.340	3.740	2.400	2.250	3.050
TE_4	46.170	46.150	46.680	26.200	24.500	23.000
TE_5	4.065	4.640	3.815	3.950	4.600	4.000
Q_1	-0.640	-0.120	5.140	-0.420	3.750	-7.500
Q_2	-0.330	-0.980	-1.880	-0.050	-1.700	-2.000
Q_3	0.435	0.320	10.800	-0.050	-7.050	2.000

(b) Unit load at center

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphragms
M_1	0.185	4.535	6.055	0.395	5.050	7.400
M_2	0.205	10.465	3.875	0.550	6.200	3.700
M_3	0.365	13.665	14.000	0.160	5.250	5.500
TE_1	0.570	0.570	0.270	0.850	0.900	0.700
TE_4	3.470	9.650	6.460	3.000	8.300	5.500
TE_5	-1.960	-1.290	-1.460	-1.400	-1.000	-1.100
Q_1	0.285	0.375	10.420	0.120	0.700	9.000
Q_2	0.140	0.470	4.290	0.050	0.200	3.100
Q_3	-0.010	0.105	4.970	-0.100	0.060	6.500

Table 3. Transverse normal forces $N_x b$ due to unit load at mid-span.

(a) Unit load at left edge

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphragms
M_1	2.310	-6.020	-7.310	3.100	-3.200	-3.100
M_2	0.220	3.500	-2.920	-0.250	3.300	0.250
M_3	0.710	28.040	30.670	1.050	5.050	6.055
Q_1	-0.590	-0.090	8.125	-0.205	-0.200	5.850
Q_2	-0.190	-0.035	0.690	0.150	-0.600	0.950
Q_3	-0.255	-0.015	4.765	0.550	-0.550	4.640

(b) Unit load at center

Point	Theoretical Results			Experimental Results		
	Without Diaphragm	One Diaphragm	Three Diaphragms	Without Diaphragm	One Diaphragm	Three Diaphragms
M_1	-1.880	6.075	6.815	-1.650	4.850	4.650
M_2	4.040	6.550	7.420	3.300	6.055	6.920
M_3	0.575	16.780	17.800	0.650	6.400	7.040
Q_1	0.315	-0.025	8.995	0.300	-0.240	7.250
Q_2	0.070	-0.005	0.795	-0.150	0.550	1.625
Q_3	0.500	-0.080	3.800	-0.640	-1.050	3.700

Figure 1. Simply supported double-cell box girder bridge.

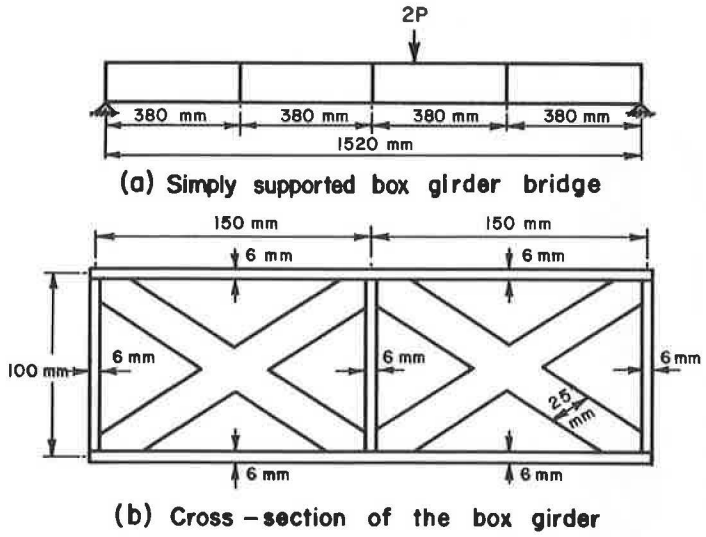

Figure 2. Components of loading.

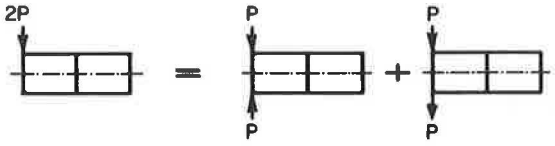

Figure 3. Positive directions of bending and membrane stress resultant.

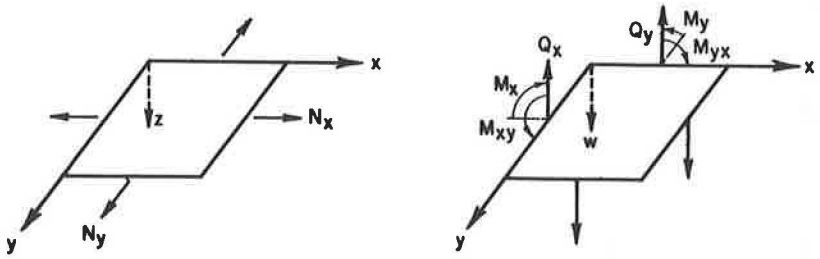

Figure 4. Location of strain gages.

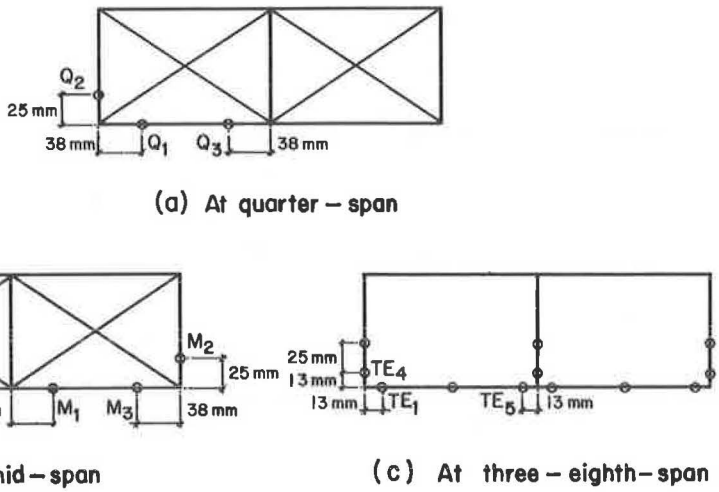

Figure 5. Test set-up.

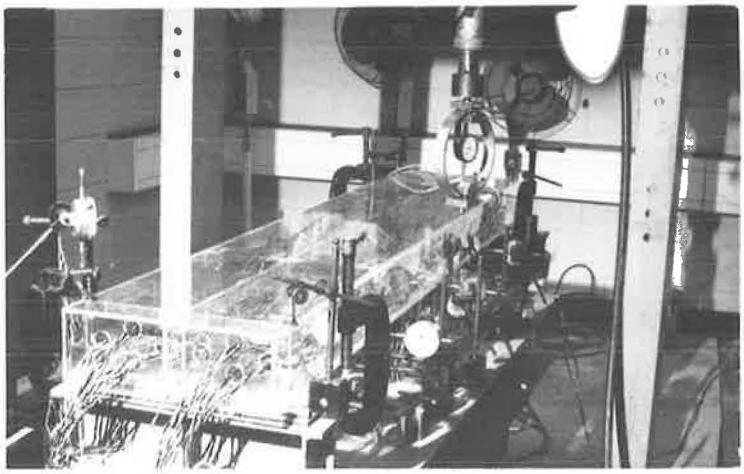

Figure 6. Deflections $(w)(D/b^2) \times 10^4$ due to unit load at quarter-span.

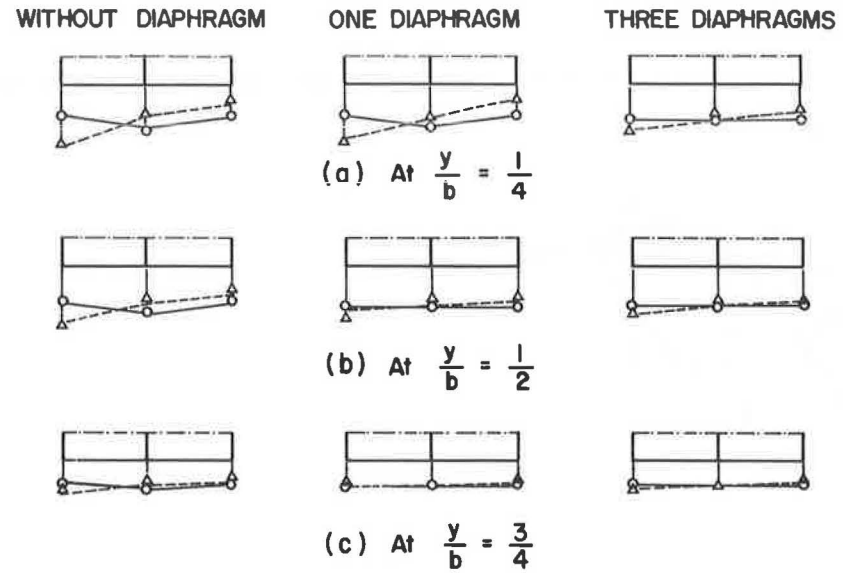

Figure 7. Deflections $(w)(D/b^2) \times 10^4$ due to unit load at midspan.

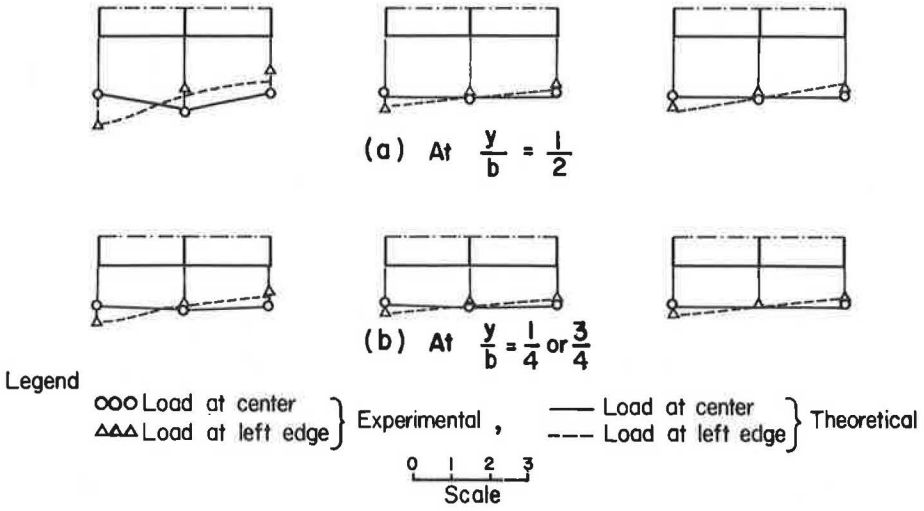

Figure 8. Deflections $(w)(D/b^2) \times 10^4$ due to load at three-eighth-span.

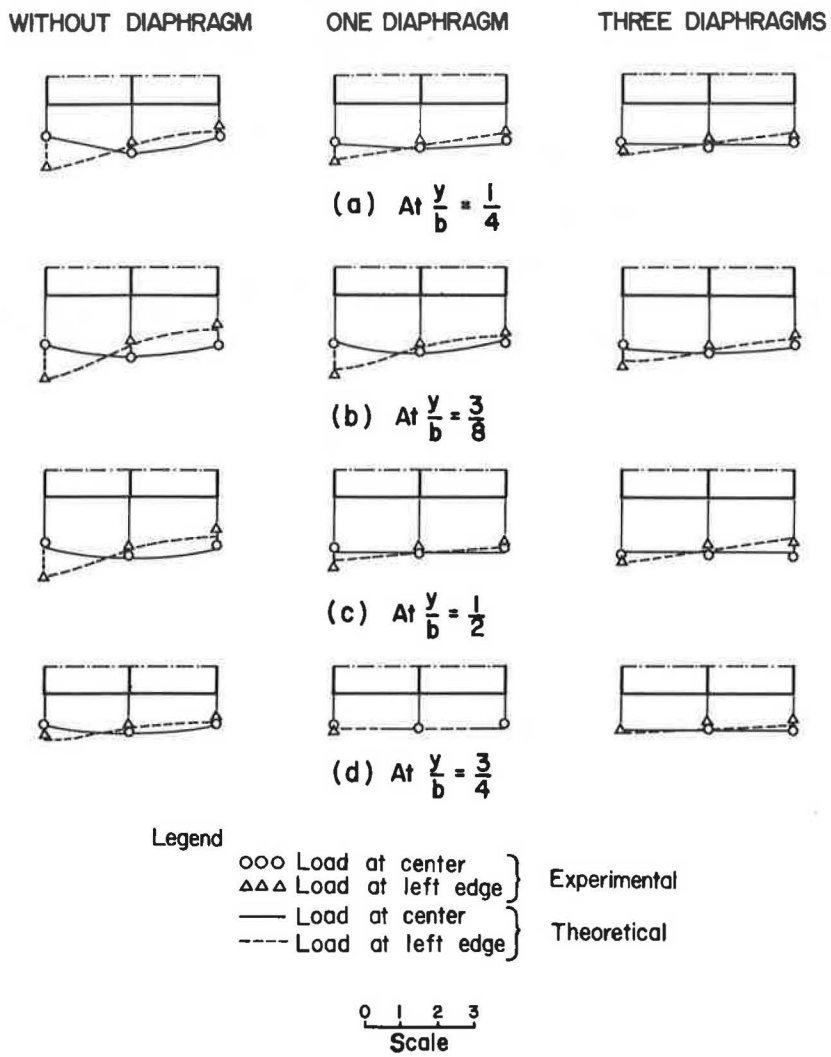

Figure 9. Longitudinal normal forces $(N_y/t) \times 10^{-2}$ at M_1 and M_3.

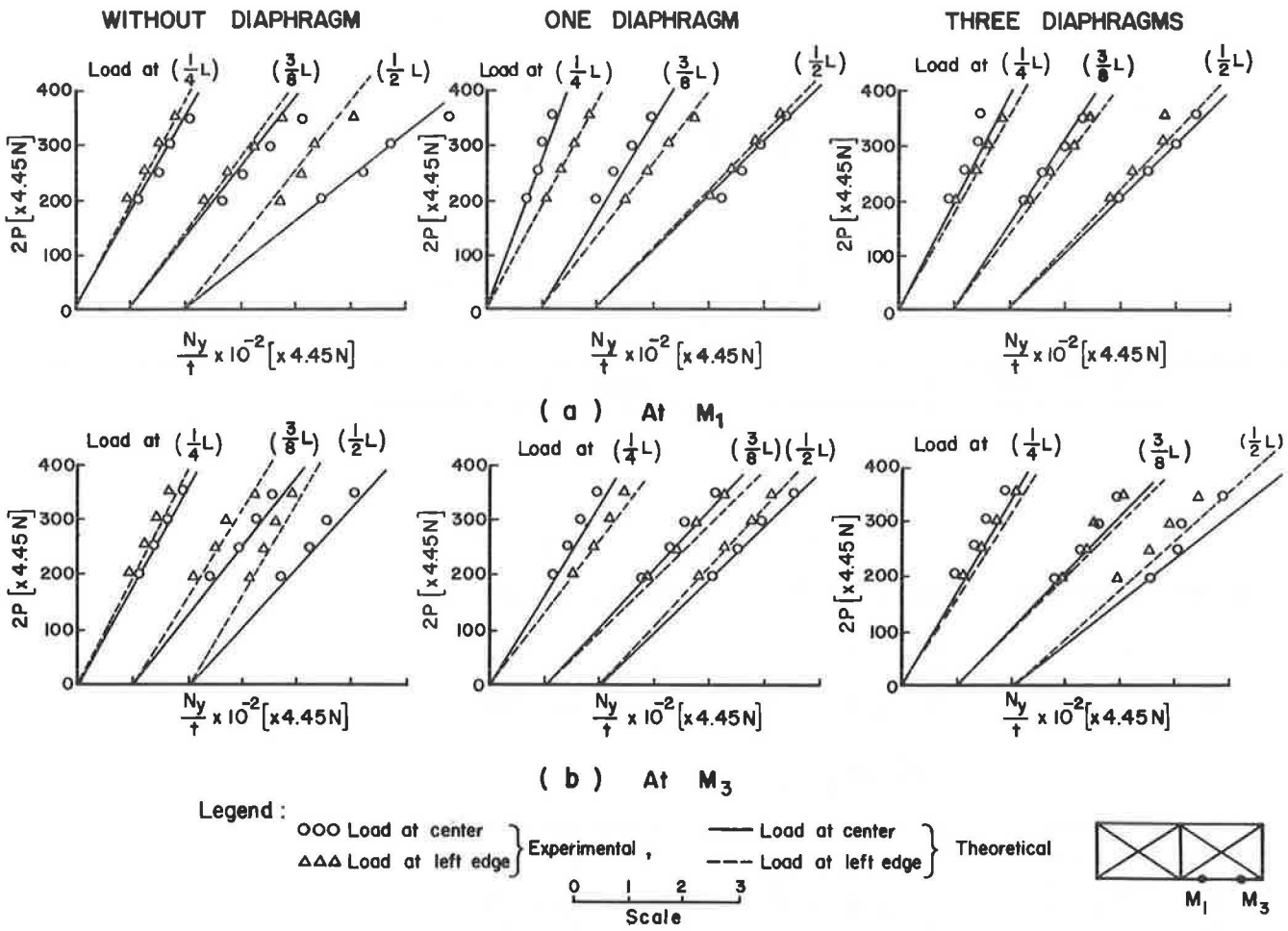

Figure 10. Longitudinal normal forces $(N_y/t) \times 10^{-2}$ at M_2 and Q_2.

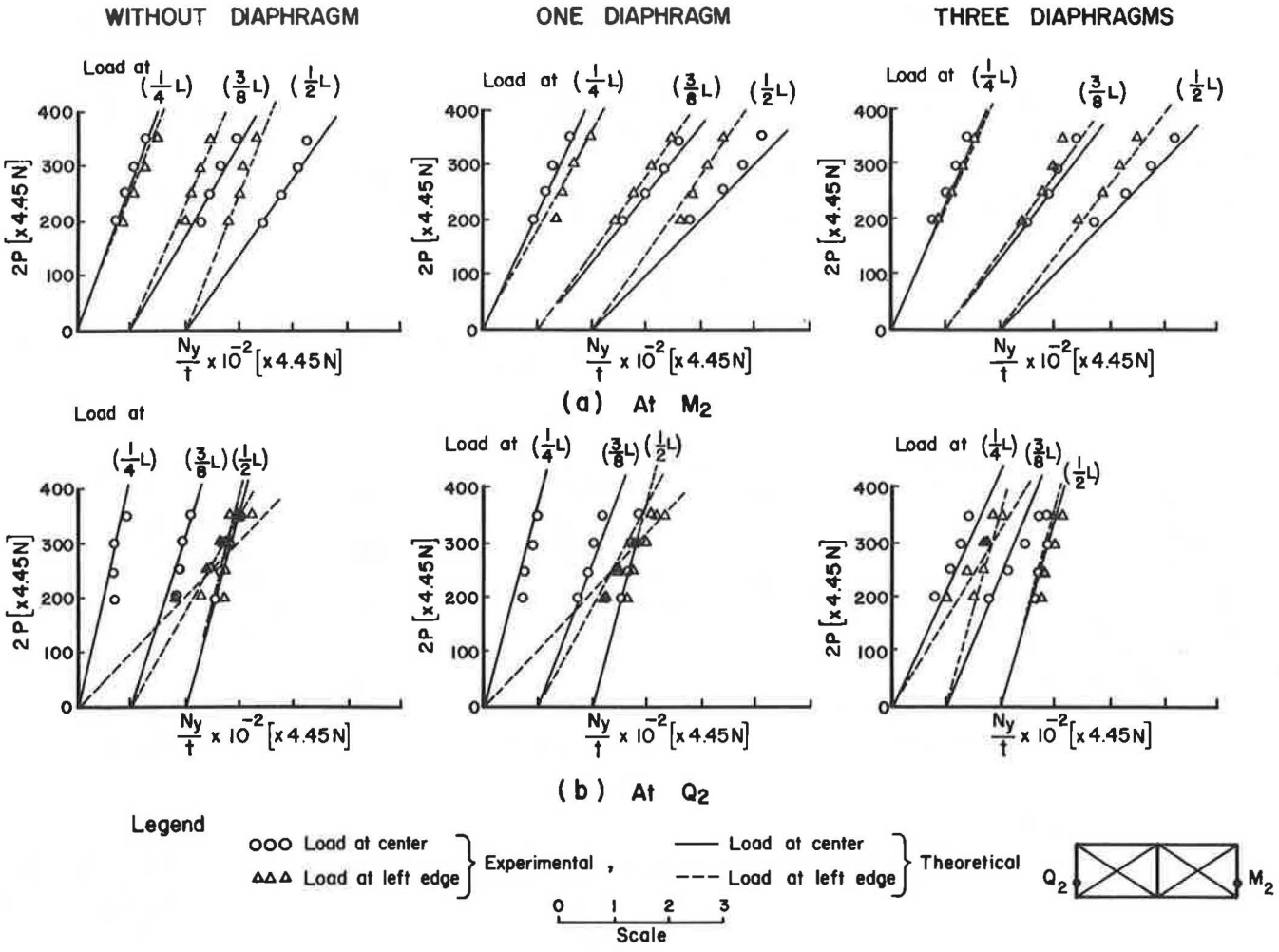

Figure 11. Longitudinal normal forces $(N_y/t) \times 10^{-2}$ at Q_1 and Q_3.

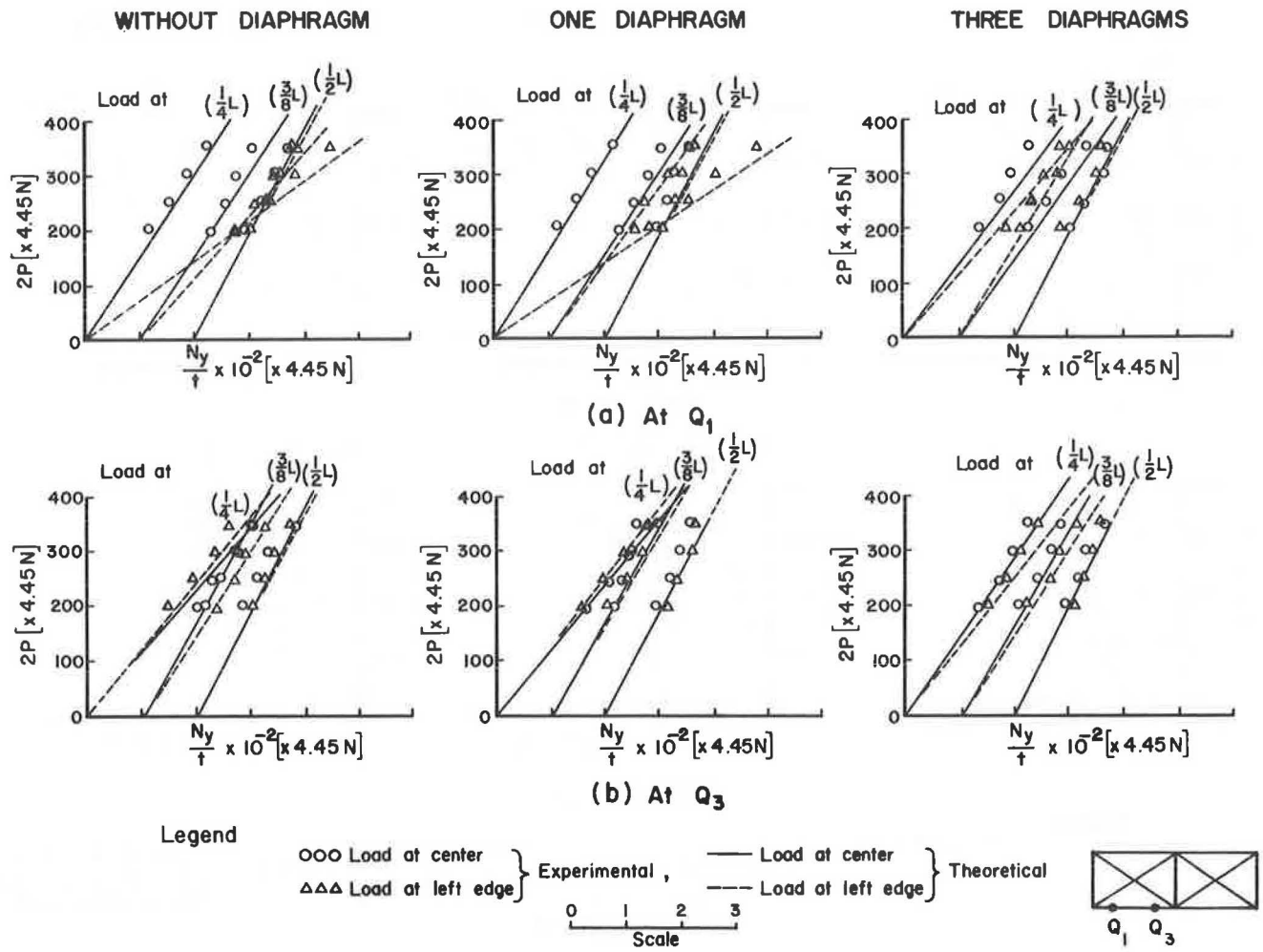
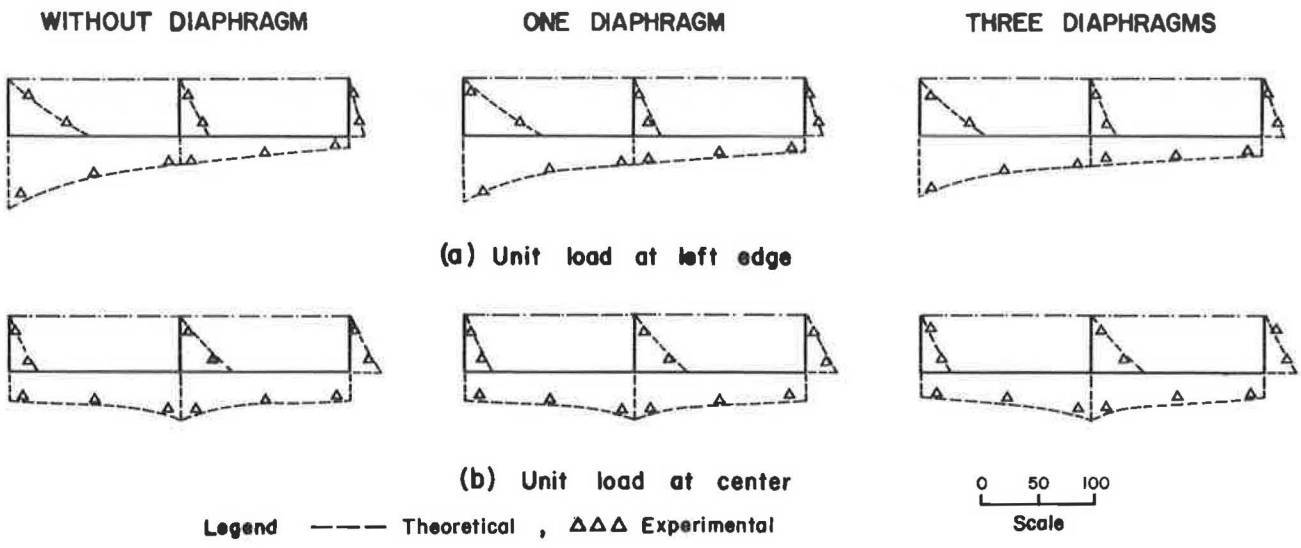
Figure 12. Longitudinal normal forces $N_y b$ at y/b = 3/8 due to unit load at three-eighth-span.