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LATERAL WEB DEFLECTIONS OF WELDED TEST GIRDERS

by

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ABSTRACT

This thesis examines the lateral web deflections of twenty-four full sized welded test girders. The purpose of this investigation was to study the web behavior and attempt to establish trends and deflection patterns in connection with different loading conditions.

Initial deflected shapes are discussed, including their effect on deflected web shapes resulting from applied loads. Sudden web movements at critical buckling loads are found to be nonexistent, at least in the test girders investigated. Nominal deflected shapes at "working loads" are established, and the phenonemon of lateral web deflection is discussed in detail.

I. INTRODUCTION

1.1 Background and Scope

Even before work first began on the strength of welded plate girders, it was realized that there was always a certain amount of initial variation from a flat surface in the web plates of fabricated girders. Statically, these initial lateral web deflections do not appear to affect the strength of a girder.[1,2,3,4] However, when considering the stresses in the web initial lateral web deflections must be taken into account. The purpose of this report is to examine the characteristics of initial lateral web deflections and to evaluate their effects on web deflection patterns under load for future stress analysis.

1.2 Causes of Initial Lateral Web Deflections

The causes of initial lateral web deflections are generally attributed to the manufacturing of girder materials and the fabrication of girders. Web plates are hot-rolled into a flat plane at temperatures above 1333 degrees Fahrenheit. As cooling takes place at different rates throughout a plate, non-uniform contraction of the plate results and residual stresses of varying mangitudes are formed.[5] These residual stresses cause the initial out-of-flatness of the plate.

During fabrication of a girder, web plates are usually pushed and pulled along the edges so that the flanges and stiffeners may be spot-welded into place. When final welding takes place, the web plate is heated once again, and the cooling induces new residual stresses which, in turn, create out-of-flatness in the web.[5] The combined effects of plate rolling, forced-fitting, and welding cause the initial lateral web deflections in welded plate girders that are discussed in this report.

1.3 Specimens for Deflection Measurements

To acquire information on lateral web deflections, extensive measurements were taken on twenty-four large-sized test girders containing a total of 119 panels. The testing of these girders included both static and fatigue applications of loads in shear, bending, and combined bending and shear. By loading configuration and material properties, these girders can be grouped into six series. These are sketched in Fig. 1 through Fig. 6.[1,6,7,8,9]

All girders were designed to accommodate the desired loading condition in the "test sections". The only geometric feature common to all test girders was a uniform web depth of fifty inches. This and other geometric properties are given in Table 1, and the characteristic loads are summarized in Table 2. In all girders, the welding sequences used by the various fabricators were in accordance with current practice. The sizes of the welds were determined in consideration of test objectives, and not always according to AWS specifications.[1,6,7,8,9]

The first series of girders, G1, G2, G3, G4, and G5 (Fig. 1), were made of ASTM-A373 steel and were loaded with pure bending in the test section between the web butt welds. Girders G3 and G5 differed from the others in that continuous pipes were used as top flanges in place of rectangular plates. The second group of girders, E1, E2, E4, E5, G8 and G9, all tested under combined bending and high shear, were also fabricated from ASTM-A373 steel. The E girders were fabricated by welding together the unharmed end sections of the tested girders G1, G2, G4, and G5, respectively. The details of these girders can be seen in Fig. 2.

The group of girders tested in high shear included girders G6, G7, F1, and F2 (ASTM-A373) along with F3, F4, and F5 (ASTM-A36). A representative specimen and the test setup are illustrated in Fig. 3. As in most of the other groups, the stiffener spacing differs from girder to girder as well as within the specimen. This variation is listed in Table 1 as the aspect ratio, α , of panel length to web depth. Also listed for all girders is the web slenderness ratio, β , the web depth to thickness.

Girders H1 and H2 were constructional alloy steel girders subjected primarily to shear. The specimens and loading conditions were similar to those of the E series and are sketched in Fig. 4.

The last two groups of girders had two-point loading setups as shown in Fig. 5 and 6. Each group had two identical girders of ASTM-A36 steel. The test sections of F6 and F7 were the pure bending portions between the load points (Fig. 5). F8 and F9 had unsymmetrical cross sections outside of the load points. There, the smaller top flanges caused the neutral axis to lie below mid-depth of the web, thus emphasizing any lateral deflection of the compression part of the web.

The weld and stiffener sizes of all girders are indicated in the sketches of the girders. For other details, material properties, and computation of characteristic loads, reference is made to the test reports of the girders (Ref. 1,6,7,8,9).

1.4 Method of Measuring Lateral Deflections

Lateral web deflection measurements were taken using an Ames dial gage rig. This is a 49 inch-high frame with a number of 0.001-inch Ames dial gages mounted in a horizontal direction along the height as shown in Fig. 7. The number of dial gages varied from five to eleven depending on type of loading condition and the chronological sequence of testing. As the investigation progressed from the static strength of girders to their fatigue behavior, and then to web deflection pattern, more dial gages were used. Also increased were the number of positions where the dial rig was stationed.

For measurement, the dial rig is held vertical with its lower leg resting at the web-to-bottom flange boundary and its upper leg temporarily fixed to the web by a magnet just below the top flange. By placing the rig first on the 50-inch deep girder web and then on a sturdy, flat surface and comparing the corresponding dial readings, the lateral position of web points could be obtained. Table 3 gives an example of recorded data and computation of lateral web deflections along one vertical cross section of a girder.

It should be mentioned that any lateral deflection of the top flange with respect to the bottom flange is not recorded by this method. For the purpose of obtaining lateral deflections of the web with respect to its boundary, the dial rig has proved to be very convenient.

II. INITIAL LATERAL WEB DEFLECTIONS

2.1 Initial Deflected Shapes

From measurements made on the girders presented in Chapter 1, it was found that none of the webs were initially plane.

In order to study initial web deflections, cross-sectional shapes of girders at locations of measurements are sketched. Examples are given in Fig. 8 which includes 6 vertical cross sections in two panels of a girder.(1) In each section, the measured positions of the web points are connected by straight lines to depict the approximate shape of the cross section. With the enlarged scale for lateral deflections, it can be seen clearly that all sections in this figure are not plane. Two of these cross-sections have single "curvature" and the rest have reversed curvature.

The effects of welding sequences on these initial lateral deflections have been examined to a degree limited by available information. For all the girders of which the welding sequence is provided by the fabricators,(7,8,9) no consistency can be found on the number of "curvatures" or on the direction of deflection. It is believed that the influences of plate flatness and fabrication procedures (fitting and welding), not the latter alone, determine the initial deflected shape.

In theory, a cross section can have any initial deflected shape as determined by the flatness of the web plate and the fabrication procedure. In this study, almost all cross-sections have single, reversed or triple curvature as illustrated in Figs. 8 & 9. Of nearly 300 cross sections from the 24 test girders, about 60 percent had single curvature and 20 percent each were with double or triple curvature.

Perhaps a good way to compare the shapes of initial deflection is to consider the web depth and the web thickness, or the web slenderness ratio of depth to thickness. Figure 10 shows this ratio $w_{i\ max}/t$ plotted against (β), where $w_{i\ max}$ is the maximum initial lateral deflection of the web at a specific cross section and t the thickness of the web. For the moment, consider only β and its relation to the three types of deflected shape represented by the different symbols in the figure. It is clearly evident that a majority of cross sections with single curvature fall in the lower ranges of β while double and triple curvature occur mainly in the higher ranges of β. In other words, the more slender the web, the more likely it is to have initially deflected shapes with double or triple curvature.

Such a result is obviously expected and can be extended to the horizontal cross sections. By examining the 119 panels measured, it was found that about 90 percent of them contained initial single-waved shapes in horizontal cross sections. All horizontal cross sections with double or triple curvature were in panels with aspect ratios much greater than one, in fact with stiffness spaced at distances two to three times the depth of the web.

The significance, or unsignificance of the initial deflected shapes is discussed in following sections. The point to make here is that, given a plate girder web panel, there can be assumed some initial deflections with a cross-sectional shape of single, double, or triple curvature as shown in Figs. 8 and 9.

2.2 Magnitude of Initial Lateral Deflections

The quantitative results from measuring initial lateral deflections of girder webs are partially summarized in Table 4. Listed in this table are the maximum initial lateral deflection values for all girders, the ratio of these deflection magnitudes to the web depth, and the ratio of the same magnitudes to the corresponding web thickness. The highest value of initial lateral deflection was 0.642 inches, recorded in girder G9 in a 75 inch by 50 inch panel with a 1/8 inch web thickness ($\alpha = 1.5$, $\beta = 382$).

Current practice specifies that the out-of-flatness of a girder web should not be more than 1/150 of the maximum vertical or horizontal unstiffened dimension for web thicknesses greater than 1/150 of web depth, and not more than 1/120 of the maximum vertical or horizontal unstiffened dimension for web thicknesses less than 1/150 of the web depth.[10] All except one of the test girders conformed to this specification. The only initial lateral deflection which was higher than allowed by this specification was at the same place where the highest value of web deflection was ever recorded in these test series.

The values in the last column of Table 4, as well as values from all measured panels have been plotted in Fig. 10. By examining this figure, it can be seen that initial web deflections vary from about 5 percent to more than 3 times the web thickness for the girders of this report. It is evident that more slender webs have larger initial deflections as compared to the web thickness. Below $\beta = 200$, no deflection larger than the web thickness was measured. For higher values of β, the magnitude of deflection extends over a wide range. However, it should be pointed out that stiffener spacing may also play a role. Almost all the cases of large deflections (say more than 2 times the web thickness) were obtained from slender-web panels with stiffeners positioned far apart ($\alpha > 1.5$).

To incorporate both slenderness ratio and stiffener spacing in examining initial web deflections, Fig. 10 is modified to show the relationship between $w_{i\ max}/t$ and the ratio of the larger panel dimension to the web thickness, Fig. 11. From this figure, it can be concluded that both the magnitude of the non-dimensionalized initial deflection, as well as the variation of the magnitude, increases when the larger panel dimension increases.

Further discussion on the maximum magnitudes of initial web deflections can be made if more data are available. For example, Fig. 12 compares the maximum deflection with the web thickness. A statistical analysis can be made if there are enough data to be included. For the time being, one could only arrive at the reasonable speculation that the possible out-of-flatness of girder webs is inversely proportional to the web thickness.

Before leaving the subject of magnitude of initial web deflection, the variation of the magnitude within a girder panel should be examined. To do so, a web deflection contour diagram is drawn for a panel of girder F6 and is shown as Fig. 13(b). Solid lines indicate equal deflections toward the reader, dotted lines into the paper. This panel has "double curvature" vertical cross-sectional shapes. Delfections increase from zero at the panel boundary to about 0.15 inches and 0.12 inches at the ridge and the valley, respectively. Distances between contour lines are relatively far and uniform, indicating gradual change of deflection magnitude anywhere within the web. Such is the typical pattern of magnitude changes for all the girder panels after fabrication. This is further seen in Figs. 13(a) and 13(c) for single and triple "curvature" panels. Further examples will be given in later sections in connection with deflections under load.

III. LATERAL DEFLECTIONS AT WEB BUCKLING LOADS

Theoretically, plane webs of plate girders buckle at critical loads which are determined by the loading and boundary conditions and the geometry of the web.[11] In the series of test girders reported here, there were no initially plane girder webs (as pointed out in Chapter 2) and the buckling phenomenon was not observed.[1,6,7,8,9]

By considering simple forms of initially deflected shapes and simple boundary conditions, deflections below and above the theoretical web buckling load can be computed for a few cases.[11] Figure 14 shows the result for a simply supported rectangular plate under a given edge strain by using the energy method and large deflection theory of plates.[2] The ordinate in the figure (Y) represents non-dimensionalized lateral web deflection of a point in the web, and the abscissa is the applied strain in terms of the theoretical web buckling strain (ϵ/ϵ_{cr}). If there exist certain initial lateral deflections ($Y_i \neq 0$ at $\epsilon_a/\epsilon_{cr} = 0$), their magnitudes increase as compressive strain is applied to the web. There is no sudden buckling to be observed unless the web is originally plane.

The qualitative results of Fig. 14 are typical of plate girder webs under other types of loading and boundary conditions. This is borne out by measuring the lateral deflections of web points and plotting their magnitudes against the applied loads. Figures 15, 16, and 17 are three plots of this kind for points in the compressive regions of panels subjected to bending, shear, and combined bending and shear, respectively. The ordinate of P/P_{cr} is equivalent to that of ϵ/ϵ_{cr} within the elastic limit of the material and the values of w/t are similar to those of Y in Fig. 14. The fact that there was not buckling when the applied loads were equal to the critical loads ($P/P_{cr} = 1$), is signified by the continuity of the curves and absence of sudden change in these figures. From the initial magnitudes, deflections increased or decreased gradually as loads were increased to and above the buckling values.

In Figs. 15, 16, and 17, it can be seen that the rate of deflection varied from curve to curve as well as long each of them. The randomness of these curves does not indicate a direct correlation of loads and the rates of deflection. There does not seem to be any elastic increase of rates at the web buckling load.

Because of these observations, and the result drawn from static strength studies that P_{cr} has no bearing on the load carrying capacity of girder panels, (1) web buckling loads are not considered significant in this report. Further examination of web deflections is directed at those corresponding to "post buckling" loads for possible deflection trends and patterns.

IV. LATERAL WEB DEFLECTIONS AT "WORKING LOAD"

4.1 "Working Load" Defined

The load-deflection curves of web points in the last chapter illustrated the gradual change of deflection magnitudes in the post-buckling range of loading. Figures 18 and 19 further demonstrate this phenomenon by the deflected cross-sectional shapes and deflection contours. In both cases the gradual change of deflection is obvious from zero load to loads much beyond the magnitudes of the web buckling values.

Since the buckling load seems to be insignificant with regard to web deflection and to the ultimate load carrying capacity of a girder (P_u), and since the load carrying capacity can be predicted for each girder panel[2,3,4] thus offering a meaningful reference, P_u or percent of P_u appears to be a better basis for the comparison and discussion of web deflections. In anticipation that the possible working load of a girder panel is somewhere around 55-65% of P_u, these magnitudes are arbitrarily and loosely defined as "working loads" by convenience. The deflections of girder webs at this load level are discussed in the following sections.

4.2 Lateral Deflections Under Bending

When it is known that there are only gradual changes of web deflection under load, it is relatively simple to speculate on nominal deflected cross-sectional shapes of a panel under pure bending. The part of the web under compressive stress would tend to bulge out, whereas the part under tensile stress would be stretched toward a flat surface. This trend is clearly indicated by the successive cross-sectional shapes at increasing loads in Fig. 18. The deflected shapes in Fig. 20 provide further evidence of this nominal bending deflection pattern.

Naturally, the initial deflections and the boundary conditions of a panel affect the deflection pattern under load. The cross-sections in Fig. 18 (G4) and those in the two smaller panels of Fig. 20 (G5) and "triple curvature" with little initial deflection at the neutral axis (y=0). The increase and decrease of deflection magnitudes under load as described above, thus, is easily seen. The initial shapes of the sections in the long panel of Fig. 20 were of "double curvature". When subjected to bending, the increase of deflection above the neutral axis forced the web below to conform and to move across the flat plane to the other side, resulting in "single curvature" deflected shapes. In Fig. 21, the initial deflected shapes of girder G1 were all of "single curvature". At the working load, in the long panel, the compression region deflected laterally quite an amount and forced the web in the tension region to increase (rather than decrease) the magnitudes of deflection. The relatively large lateral deflection under load is due to the tilting of the slim compression flange (Fig. 22). In fact, the tilting, which eventually caused the failure of the girder in testing, was the reason for the cross section (x=-25) in the neighboring panel to deflect opposite to its initial direction.

Therefore, the pattern of web deflection under pure bending depends on the initial deflections. The magnitude of load, and the boundary conditions of flange and neighboring panels. Their relative importance differ for each panel. One case has been observed (F6) where the direction of deflection of the whole panel was completely reversed from that of the initial deflection because of the deflection patterns in the neighboring panels and the movement of the flange. Nevertheless, for the majority of the panels in bending the nominal trend seems generally true that web deflections tend to increase above the neutral axis and decrease below the neutral axis. This trend, and the nominal deflection pattern, are depicted by the deflection contours in Fig. 23 for a panel of girder F6.

4.3 Lateral Deflections Under Shear

The tendency of deflection is quite definite for panels under shear. The pattern of deflection, however, is strongly influenced by the initial deflections.

Figure 24 shows the initial and subsequent deflections of a panel of girder F8 under load, and serves as a typical example of the trend. When shear force was applied to the panel and tension field action induced,(3) the web plate was stretched and remained straight in the general direction of the tension diagonal. Along the compression diagonal, the applied force shortened the distance and caused lateral deflections. The result was the typical, inclined pattern of deflection contours for panels under shear.

The panel in Fig. 24 had "double curvature" initial deflections. This panel could be divided into two parts of fairly even shape, with the upper half buldging into the plane and the lower half out of the plane. Under shear, when the inclined pattern took shape, the panel still could be divided fairly uniformly into two parts. The dividing line of zero deflections was in the general direction of the tension diagonal. The upper and the lower half had about the same maximum magnitude of deflection. In Fig. 25, the panel had "single curvature" deflections at the left and a fairly flat web at the right. When subjected to shear, the typical trend of inclined tension diagonal was identical to that of Fig. 24, but the deflection pattern naturally assumed a single, dominant valley. In the lower-righthand corner, the small ridge out of the plane evidently indicated the influence of the initial condition there.

Unlike the cases in bending where they were the main load-carrying components, the flanges carry little stress in the shear girders. Thus, their influence on the web deflections are much less prominent than before. The possible influencing boundary conditions were the stiffeners and the deflection patterns of the neighboring panels. Plate stiffeners, such as those reported here, provided strength for tension field action as well as rigidity against transverse deflections at the stiffener. Against twisting, as a result of lateral web deflection, they offered only small resistance. Consequently, if lateral deflections of the web on one side of a stiffener are predominant, they may well force the web on the other side to deflect in the opposite direction. This conformity of neighboring panels was observed for all the test panels in shear.

For all panels in shear, the overall influence of initial deflection appeared to be dominant in the formation of the specific panel deflection pattern at working load. Regardless of this specific pattern, the general trend is definitely toward inclined deflection contours, Fig. 26.

4.4 Lateral Deflection Under Bending and Shear

For plate girder panels, the loading condition is either pure bending or combined bending and shear. No pure shear cases exist. Thus, the trend and patterns of deflection under shear, as discussed in last section, are actually for cases where the effects of shear dominated and those of bending moments were negligible. From this point of view, the examination of web deflections under bending and shear should be made by tabulating their relative magnitudes and comparing the corresponding deflection shapes. Practically, for panels of the test girders where tension field action existed, the trend of shear deflection was observed, regardless of the magnitude of bending. The effects of bending moments were mainly on the magnitude of deflections.

This is illustrated by Fig. 27 and 28 which are the deflection contours of two panels of girder F8. Both panels had unsymmetrical cross sections with their neutral axes about seven inches below the midheight to emphasize the bending effect (Section 1.3). The static failure mode of both were governed by bending, that is, failure of the compression flange. Yet, when subjected to bending an shear, the prominent deflection pattern was that of shear. In Fig. 27, the panel has higher initial deflection magnitudes at the upper portion of the web do the larger deflections there under load might not be all due to bending. The panel of Fig. 28 was very close to being planar initially. Here the deflections at load could definitely reflect the influence of shear to form the diagonal deflection contours and the effect of bending moments to increase the magnitude of deflection in the compression region.

Since the loading is a combination of bending and shear, the influence of initial deflections and boundary conditions are, by speculation, that of bending and shear superimposed. The conformity of deflection directions in the panel of Fig. 27 was typical of shear loading, as was the formation of the small valley in the panel of Fig. 28 when subjected to load. The flange had remained straight and exerted no apparent influence on the web deflection of these two panels. Because any participation of the flange would be emphasized here, but none was observed, nor was it detected on any other panels in combined loading with tension field action, it would seem that the conditions of shear are the prevalent factors for lateral deflections under bending and shear.

V. SUMMARY

From the examination of lateral web deflections initially and under load, the following conclusions can be made.

1. Initial deflections tend to be larger as web thickness decreases and as slenderness ratios increase.
2. The more slender the web, the more likely it is to contain initially deflected shapes with double or triple curvature.
3. More than 90 percent of the panels examined had single curvature in the horizontal direction.
4. Sudden web movement was found to be non-existant at critical buckling load. Rather, all load-deflection plots showed gradual increases.
5. Typical behavior of the webs under the three loading conditions considered were characterized by:
    a) Bending - Increase of web deflection above the neutral axis and decrease below.
    b) Shear - Web deflection contours inclined approximately along the panel diagonal with concave and convex sections being about the same. This may be modified by dominant initial deflection patterns.

c) Combined Bending and Shear - Web deflection contours similar to those under shear with the deflected region above the neutral axis of greater magnitude than that below.

This quantitative review of initial lateral web deflections and qualitative examination of the corresponding deflections under load gives future investigators experimental evidence as to the behavior of slender webs of welded plate girders. It is anticipated that this data will be used in determining stresses throughout the webs of the test girders, including both membrane (axial) and plate bending stresses. Once these stresses are known, another step in the process of fully understanding girder behavior under static and fatigue loadings will be completed.

Table 1 Dimensions of Component Parts

(All dimensions in inches)

Girder	Center Section			End Section		
	Flanges	Web** Thick.	Stiff. Space.	Flanges	Web** Thick.	Stiff. Space.
G1	20.56x0.427 *12.25x0.760	0.270	37.5,37.5, 75	20.56x0.427 *12.25x0.760	0.382	75,75
G2	12.19x0.769	0.270	37.5,37.5, 75	12.19x0.769	0.507	75,75
G3	t8.62x0.328 *12.19x0.770	0.270	37.5,37.5, 75	t8.62x0.328 *12.19x0.770	0.492	75,75
G4	12.16x0.774	0.129	37.5,37.5, 75	12.16x0.774	0.392	75,75
G5	t8.62x0.328 *12.25x0.767	0.129	37.5,37.5, 75	t8.62x0.328 *12.25x0.767	0.392	75,75
G6	12.13x0.778	0.193	75,75	12.13x0.778	0.369	37.5,37.5, 37.5
G7	12.19x0.769	0.196	50,50,50	12.19x0.769	0.381	37.5,37.5, 37.5
G8	12.00x0.752	0.197	150,75,75			
G9	12.00x0.755	0.131	150,75,75			
E1	*12.25x0.760	0.382	150,75,75			
E2	12.19x0.769	0.507	150,75,75			
E4	12.16x0.774	0.392	75,75,37.5, 37.5,37.5, 37.5			
E5	t8.62x0.328 *12.25x0.767	0.392	75,75,37.5, 37.5,37.5, 37.5			
H1	18.06x0.977	0.393	150,75,75			

* Bottom flange only
t Diameter and wall thickness of pipe flange
**Web depth = 50 inches

Table 1 (Continued)

(All dimensions in inches)

Girder	Center Section			End Section		
	Flanges	Web** Thick.	Stiff. Space.	Flanges	Web** Thick.	Stiff. Space.
H2	18.06x1.008	0.390	50,50,50, 25,25,25, 25,25,25			
F1	12.04x0.998	0.189	75,75	12.04x0.998	0.389	40,40 40
F2	12.00x0.998	0.190	50,50,50	12.00x0.998	0.389	40,40, 40
F3	12.13x1.011	0.174	50,50,50	12.13x1.011	0.378	40,40, 40
F4	12.07x1.008	0.192	50,50,50	12.29x1.636	0.312	120
F5	12.06x1.010	0.170	50,50,50	12.18x1.646	0.312	120
F6	12.13x0.628	0.182	50,50,50	12.13x0.628	0.312	90
F7	12.15x0.638	0.182	50,50,50	12.15x0.638	0.312	90
F8	12.00x0.708 *18.00x1.003	0.203	50,50,60, 50,50			
F9	12.00x0.708 *18.00x1.003	0.195	50,50,60, 50,50			

* Bottom flange only
**Web depth = 50 inches

Table 2 Characteristic Loads of Test Girders

Girder	α	β	P_{cr} (kips)	P_u (kips)
G1	1.50	185	70.1	81
	0.75	185	41.9	72
G2	1.50	185	74.1	135
	0.75	185	74.1	144
G3	1.50	185	82.1	130
	0.75	185	82.1	136
G4	1.50	388	15.3	118
	0.75	388	15.3	125
G5	1.50	388	17.0	110
	0.75	388	17.0	124
G6	1.50	259	27.4	116
	0.75	259	51.9	150
	0.50	259	97.6	177
G7	1.00	255	37.6	140
E1	3.00	131	332	555
	1.50	131	402	580
	1.00	131	506	684
E2	3.00	99	570	755
	1.50	99	584	757
E4	1.50	128	445	595
	0.75	128	513	634
	0.50	128	517	645
E5	0.36	128	314	350
	0.75	128	322	360

Girder	α	β	P_{cr} (kips)	P_u (kips)
G8	3.00	254	41.5	170
	1.50	254	56.4	200
	1.00	254	57.3	259
G9	3.00	382	12.9	96
	1.50	382	16.8	150
H1	3.00	127	377	1260
	1.50	127	464	1538
H2	1.00	128	594	1834
	0.50	128	1614	2250
F1	1.50	265	25.7	106
F2	1.00	263	34.3	131
F3	1.00	287	26.2	120
	0.80	132	298	240
F4	1.00	260	35.4	127
	2.40	160	98	169
F5	1.00	294	24.6	111
	2.40	160	98	169
F6	1.00	275	43.8	144
	1.80	160	94.5	162
F7	1.00	275	44.4	139
	1.80	160	95.0	158
F8	1.20	246	68.7	179
	1.00	246	36.2	173
	1.00	246	27.3	179
F9	1.20	256	63.1	178
	1.00	256	32.4	165
	1.00	256	24.7	123

Table 3 Example of Web Deflection Data

Girder G7; Station x = 0 inches; Readings in inches

Y(in.)	Ref.	Load 1 (0^k)		Load 2 (27^k)		Load 3 (54^k)	
		Read.	Diff.	Read.	Diff.	Read.	Diff.
+21	0.532	0.560	+0.028	0.562	+0.030	0.568	+0.036
+15	0.554	0.590	+0.036	0.594	+0.040	0.611	+0.057
+9	0.590	0.580	-0.010	0.587	-0.003	0.504	-0.086
0	0.516	0.438	-0.078	0.448	-0.068	0.436	-0.080
-9	0.571	0.480	-0.091	0.488	-0.083	0.461	-0.110
-15	0.511	0.448	-0.063	0.452	-0.059	0.435	-0.076
-21	0.512	0.494	-0.018	0.495	-0.017	0.490	-0.022

Table 4 Maximum Initial Lateral Deflections of Test Girders

Girder	α	β	w_i max (in)	$\frac{w_{i\ max}}{\text{Web depth}} \times 10^5$	$\frac{w_{i\ max}}{t}$
G1	1.50	185	0.141	71	0.467
	0.75	185	0.054	27	0.196
	0.75	185	0.033	17	0.122
G2	1.50	185	0.157	79	0.581
	1.50	99	0.067	34	0.132
	1.50	99	0.076	38	0.150
	0.75	185	0.080	40	0.296
	0.75	185	0.067	34	0.248
G3	1.50	185	0.160	80	0.593
	1.50	102	0.115	58	0.080
	1.50	102	0.234	117	0.181
	0.75	185	0.097	49	0.359
	0.75	185	0.101	51	0.374
G4	1.50	388	0.278	139	2.155
	1.50	128	0.044	22	0.122
	1.50	128	0.076	38	0.194
	0.75	388	0.160	80	1.240
	0.75	388	0.108	54	0.837
G5	1.50	388	0.456	228	3.535
	1.50	128	0.144	72	0.367
	1.50	128	0.063	32	0.161
	0.75	388	0.243	122	1.884
	0.75	388	0.204	102	1.581
G6	1.50	259	0.448	224	2.321
	1.50	259	0.221	111	1.145
G7	1.00	255	0.358	179	1.826
	1.00	255	0.133	67	0.678
	1.00	255	0.309	155	1.576

Table 4 (Continued)

Girder	α	β	w_i max (in)	$\frac{w_i \text{ max}}{\text{Web Depth}} \times 10^5$	$\frac{w_i \text{ max}}{t}$
G7	0.80	131	0.021	11	0.055
	0.80	131	0.092	46	0.241
G8	3.00	254	0.297	149	1.507
	1.50	254	0.122	61	0.619
G9	3.00	382	0.474	237	3.618
	1.50	382	0.455	228	3.473
	1.50	382	0.450	225	3.435
E1	3.00	131	0.320	160	0.838
	1.50	131	0.073	37	0.191
	1.50	131	0.098	49	0.257
E2	3.00	99	0.041	21	0.081
	1.50	99	0.101	51	0.199
E4	1.50	128	0.112	52	0.286
	0.75	128	0.067	34	0.171
	0.75	128	0.102	51	0.260
	0.75	128	0.055	28	0.140
E5	1.50	128	0.169	85	0.431
	0.75	128	0.020	10	0.051
H1	3.00	127	0.261	131	0.664
	1.50	127	0.199	100	0.506
	1.50	127	0.105	53	0.181
H2	1.00	128	0.134	67	0.344
	1.00	128	0.195	98	0.500
	1.00	128	0.036	18	0.092
	0.50	128	0.105	53	0.269
	0.50	128	0.057	28	0.146
	0.50	128	0.049	25	0.125
	0.50	128	0.067	34	0.172
	0.50	128	0.032	16	0.082
	0.50	128	0.184	92	0.472

Table 4 (Continued)

Girder	α	β	w_i max (in)	$\frac{w_i \text{ max}}{\text{Web Depth}} \times 10^5$	$\frac{w_i \text{ max}}{t}$
F1	1.50	264	0.608	304	3.217
	1.50	264	0.493	247	2.609
	0.80	129	0.134	67	0.344
	0.80	129	0.108	54	0.277
	0.80	129	0.123	62	0.316
	0.80	129	0.149	75	0.383
	0.80	129	0.066	33	0.169
	0.80	129	0.103	52	0.264
F2	1.00	263	0.206	103	1.084
	1.00	263	0.191	96	1.005
	1.00	263	0.053	27	0.394
	0.80	129	0.037	19	0.095
	0.80	129	0.022	11	0.057
	0.80	129	0.016	8	0.041
	0.80	129	0.030	15	0.021
	0.80	129	0.058	29	0.149
	0.80	129	0.040	20	0.103
F3	1.00	288	0.255	128	1.465
	1.00	288	0.150	75	0.860
	1.00	288	0.135	68	0.776
	0.80	132	0.185	93	0.489
	0.80	132	0.129	65	0.341
	0.80	132	0.085	43	0.224
	0.80	132	0.101	51	0.267
	0.80	132	0.042	21	0.111
	0.80	132	0.050	25	0.133

Table 4 (Continued)

Girder	α	β	$w_{i\ max}$ (in)	$\frac{w_{i\ max}}{\text{Web Depth}} \times 10^5$	$\frac{w_{i\ max}}{t}$
F4	2.40	160	0.171	86	0.548
	2.40	160	0.102	51	0.327
	1.00	260	0.208	104	1.083
	1.00	260	0.161	81	0.838
	1.00	260	0.142	71	0.739
F5	2.40	160	0.185	93	0.593
	2.40	160	0.033	17	0.106
	1.00	294	0.131	66	0.771
	1.00	294	0.101	51	0.594
	1.00	294	0.171	86	1.006
F6	1.80	160	0.197	99	0.631
	1.80	160	0.149	75	0.478
	1.00	274	0.253	127	1.390
	1.00	274	0.184	92	1.011
	1.00	274	0.279	140	1.533
F7	1.80	160	0.104	52	0.333
	1.80	160	0.108	54	0.346
	1.00	275	0.362	181	1.989
	1.00	275	0.191	96	1.049
	1.00	275	0.280	140	1.538
F8	2.40	246	0.111	56	0.547
	1.00	246	0.159	80	0.784
	1.00	246	0.170	85	0.836
	1.00	246	0.059	30	0.291
	1.00	246	0.082	41	0.404
F9	2.40	256	0.200	100	1.025
	1.00	256	0.113	57	0.580
	1.00	256	0.153	77	0.785
	1.00	256	0.059	30	0.302
	1.00	256	0.128	64	0.656

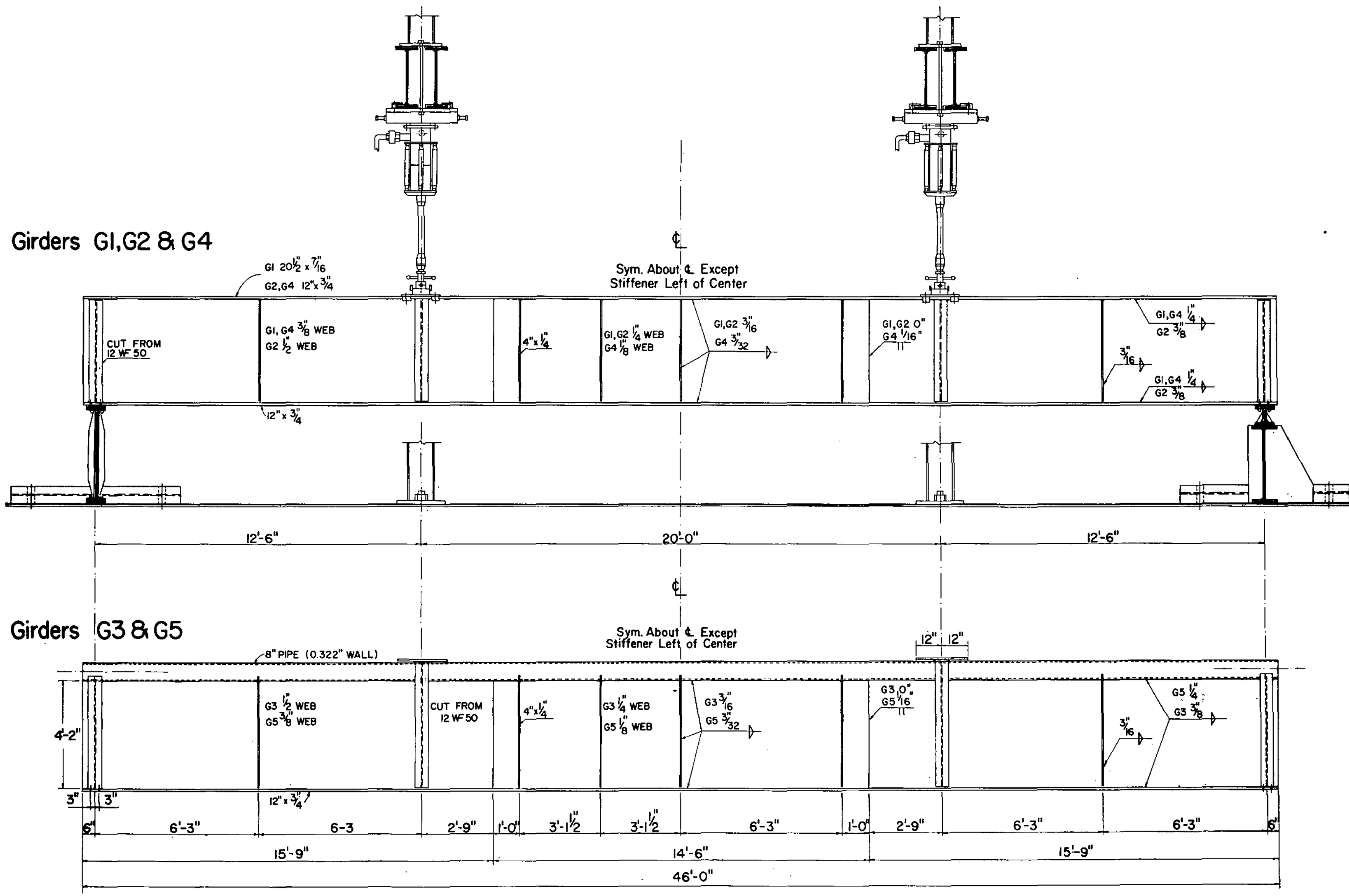


Fig. 1 Specimens and Loading Condition, Girders G1-G5

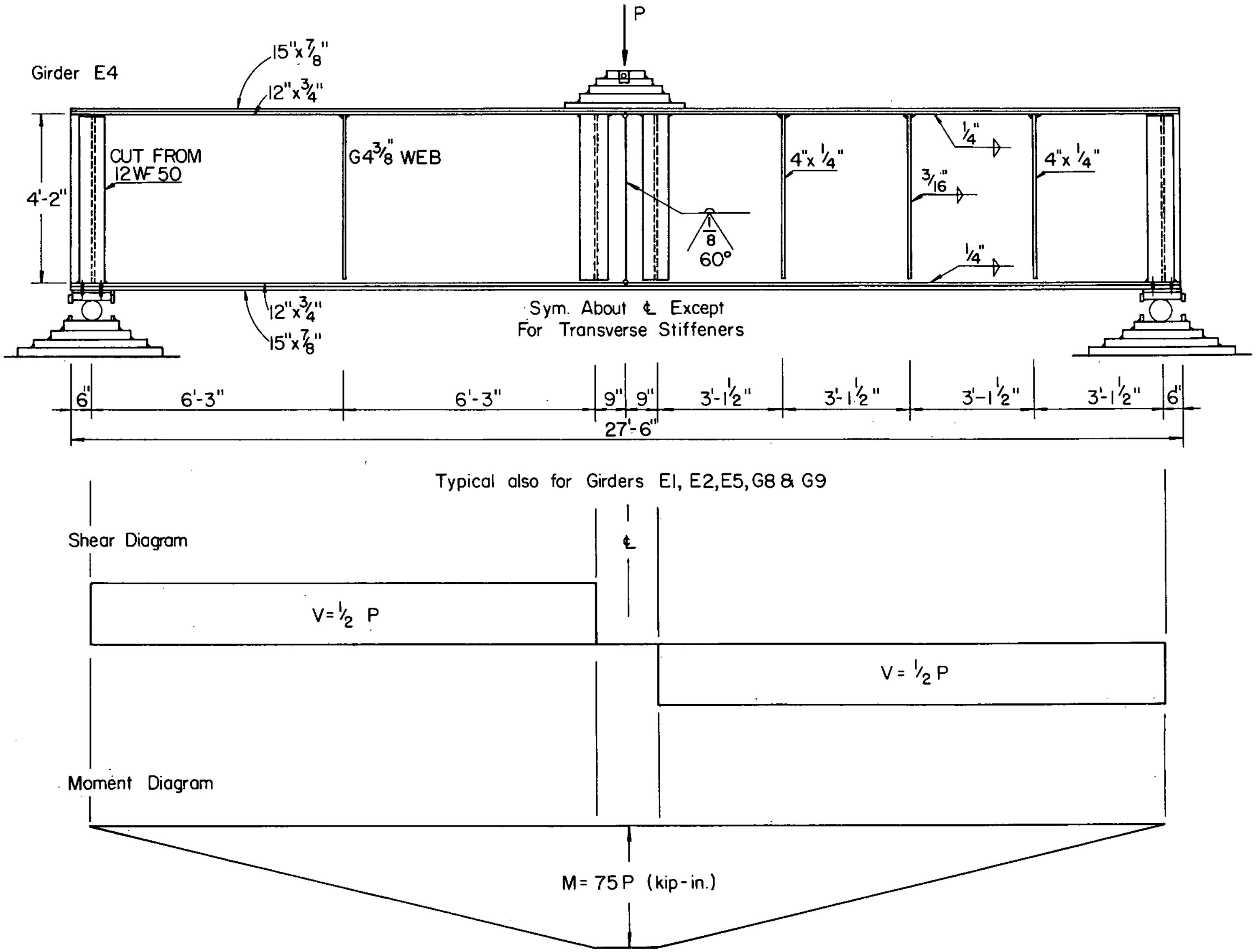


Fig. 2 Specimens and Loading Condition,
Girders E1-E5, G8-G9

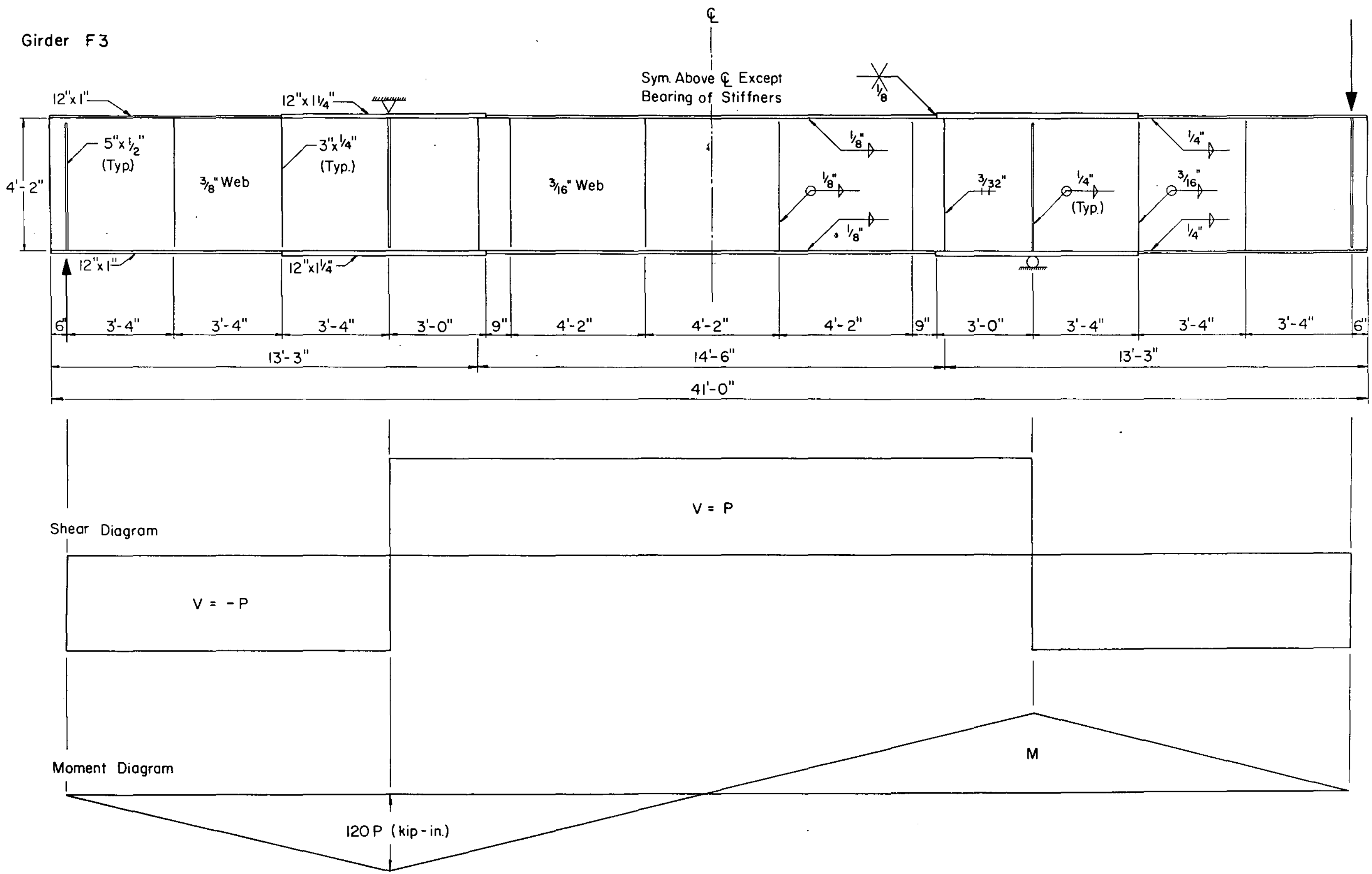


Fig. 3 Specimens and Loading Condition,
Girders G6 & G7, F1-F5

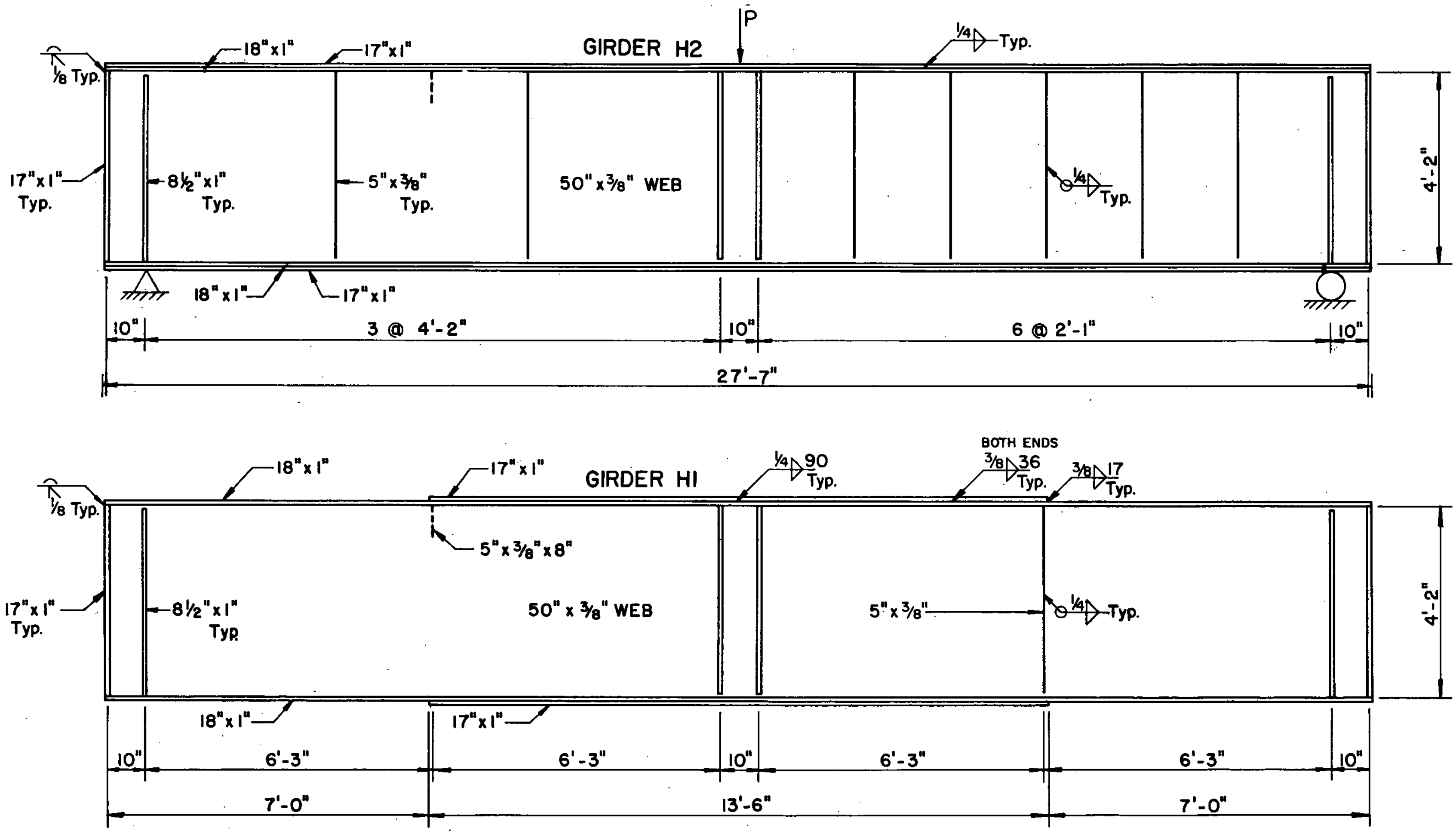


Fig. 4 Specimens and Loading Condition,
Girders H1 & H2

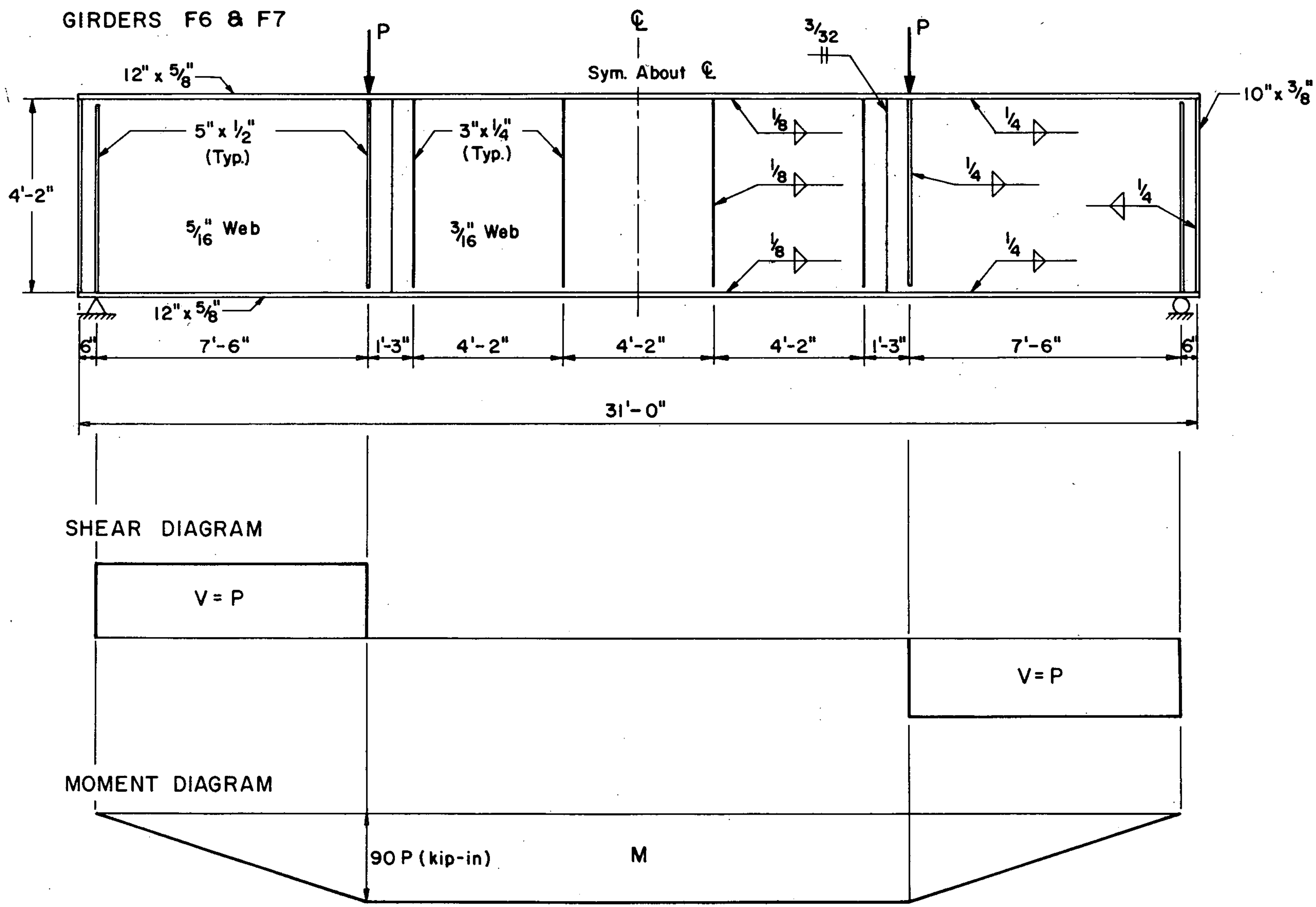


Fig. 5 Specimens and Loading Condition,
Girders F6 & F7

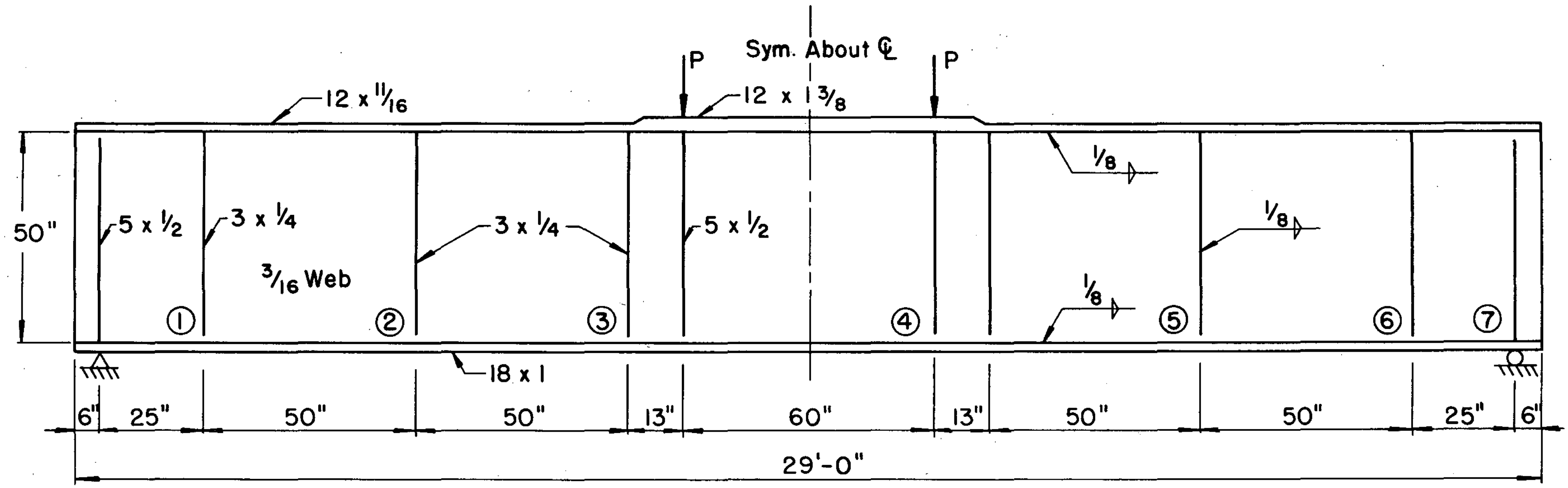


Fig. 6 Specimens and Loading Condition, Girders F8 and F9

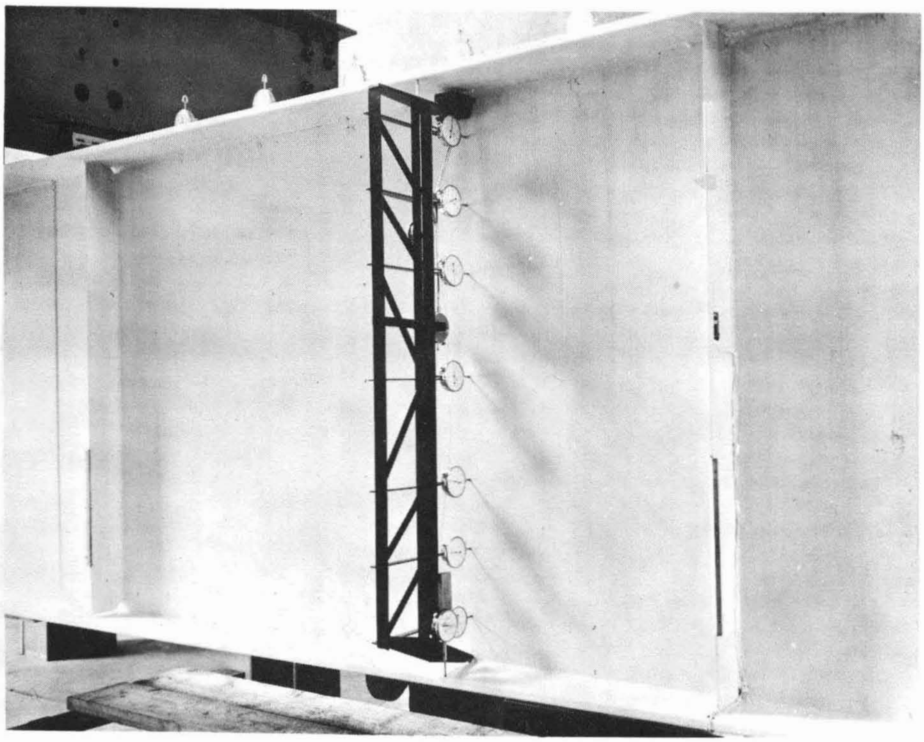


Fig. 7 Dial Gage Rig for Web Deflection Measurements

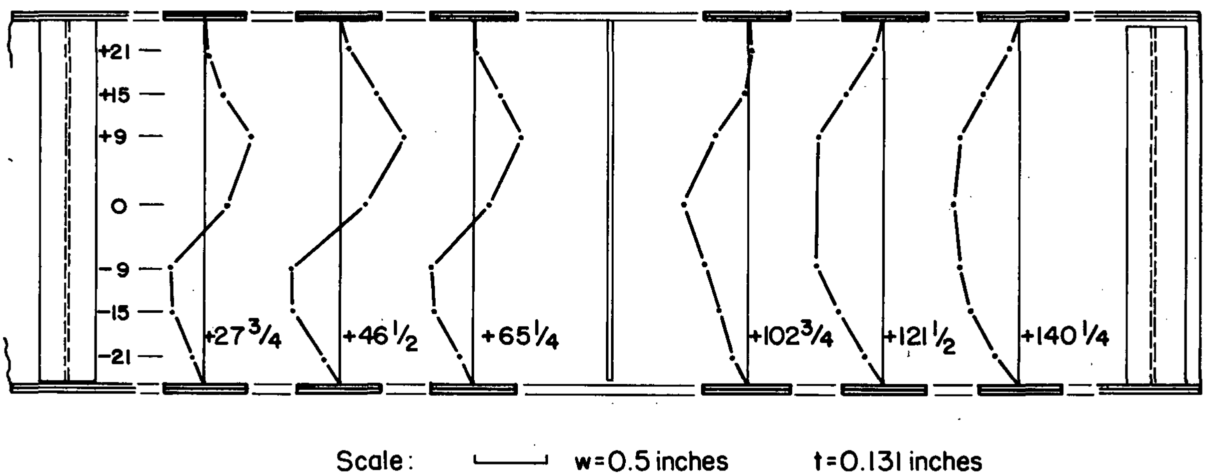


Fig. 8 Initial Web Deflection Shapes, Single and Double Curvature (Girder G9)

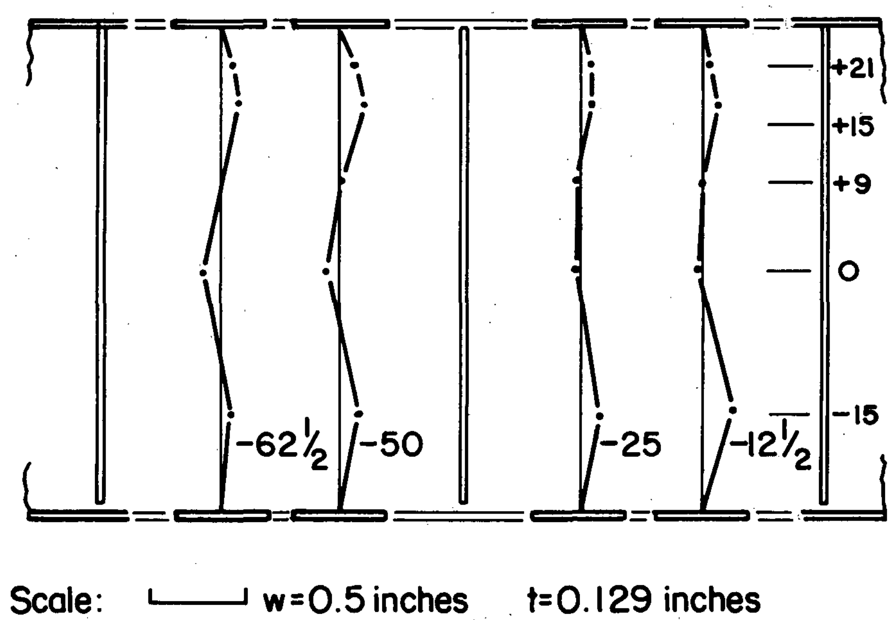


Fig. 9 Initial Web Deflection Shapes, Triple Curvature (Girder G4)

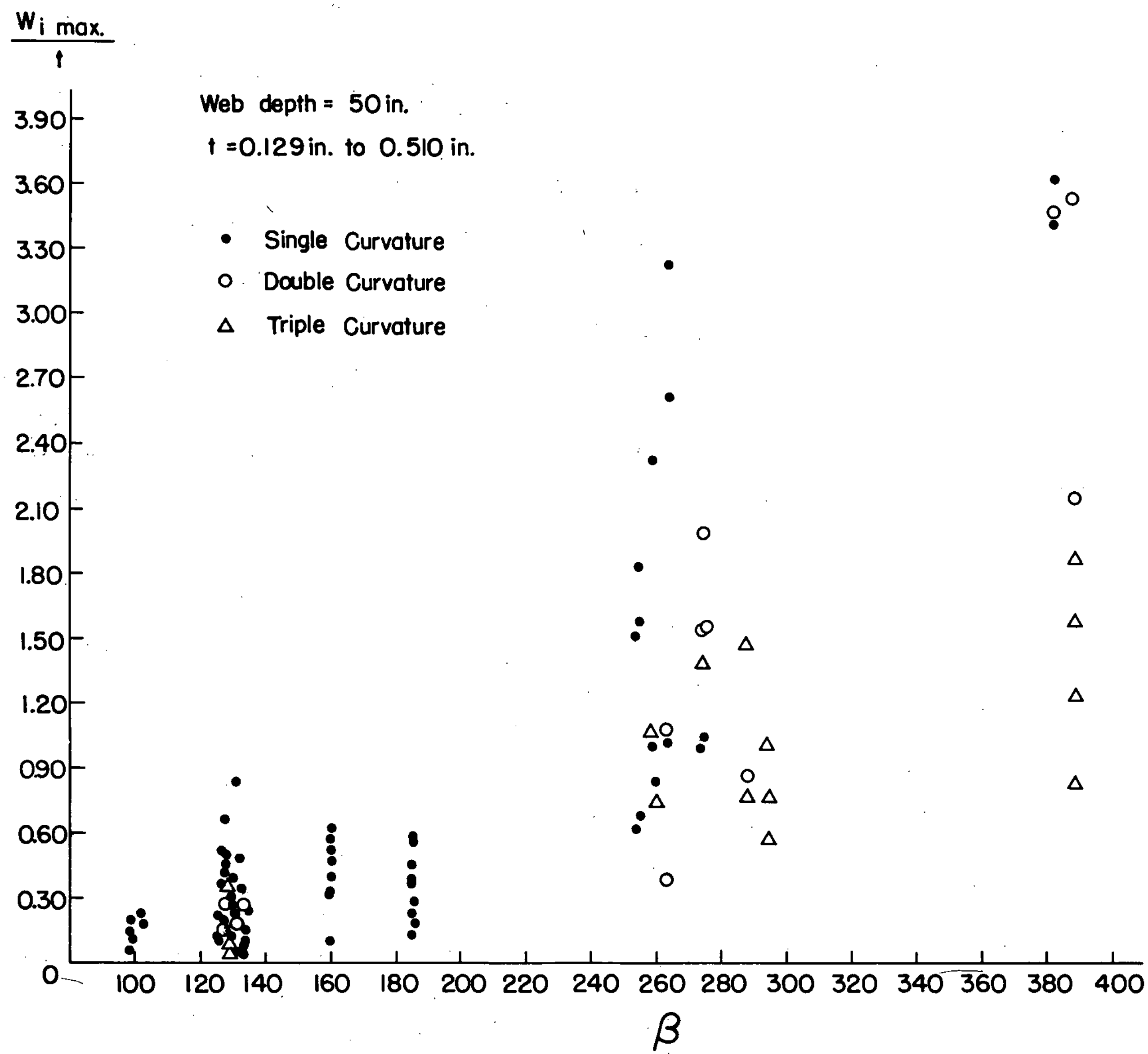


Fig. 10 Maximum Initial Deflection Versus Web Slenderness Ratio

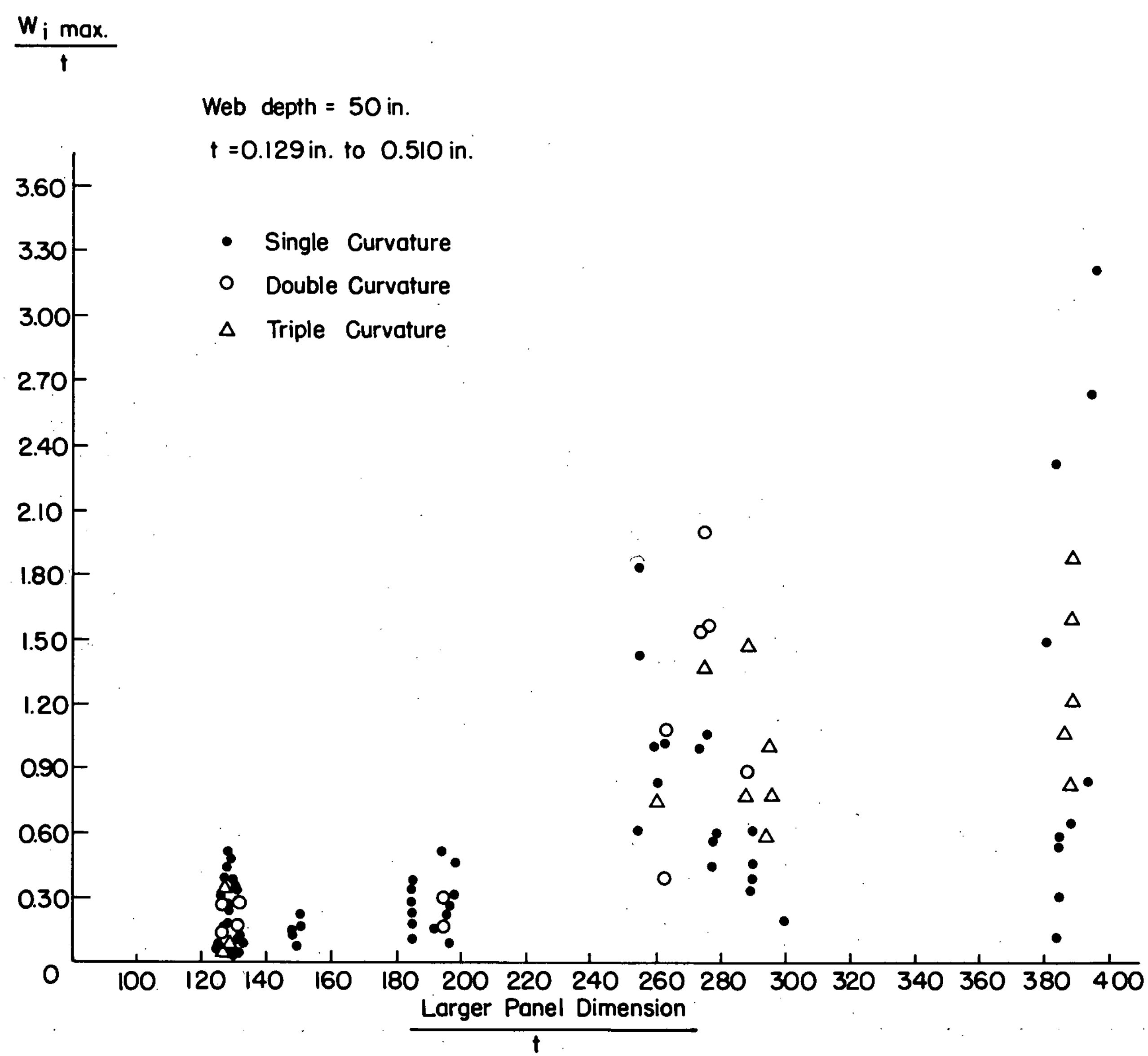


Fig. 11 Maximum Initial Deflection Versus Largest Panel Dimension

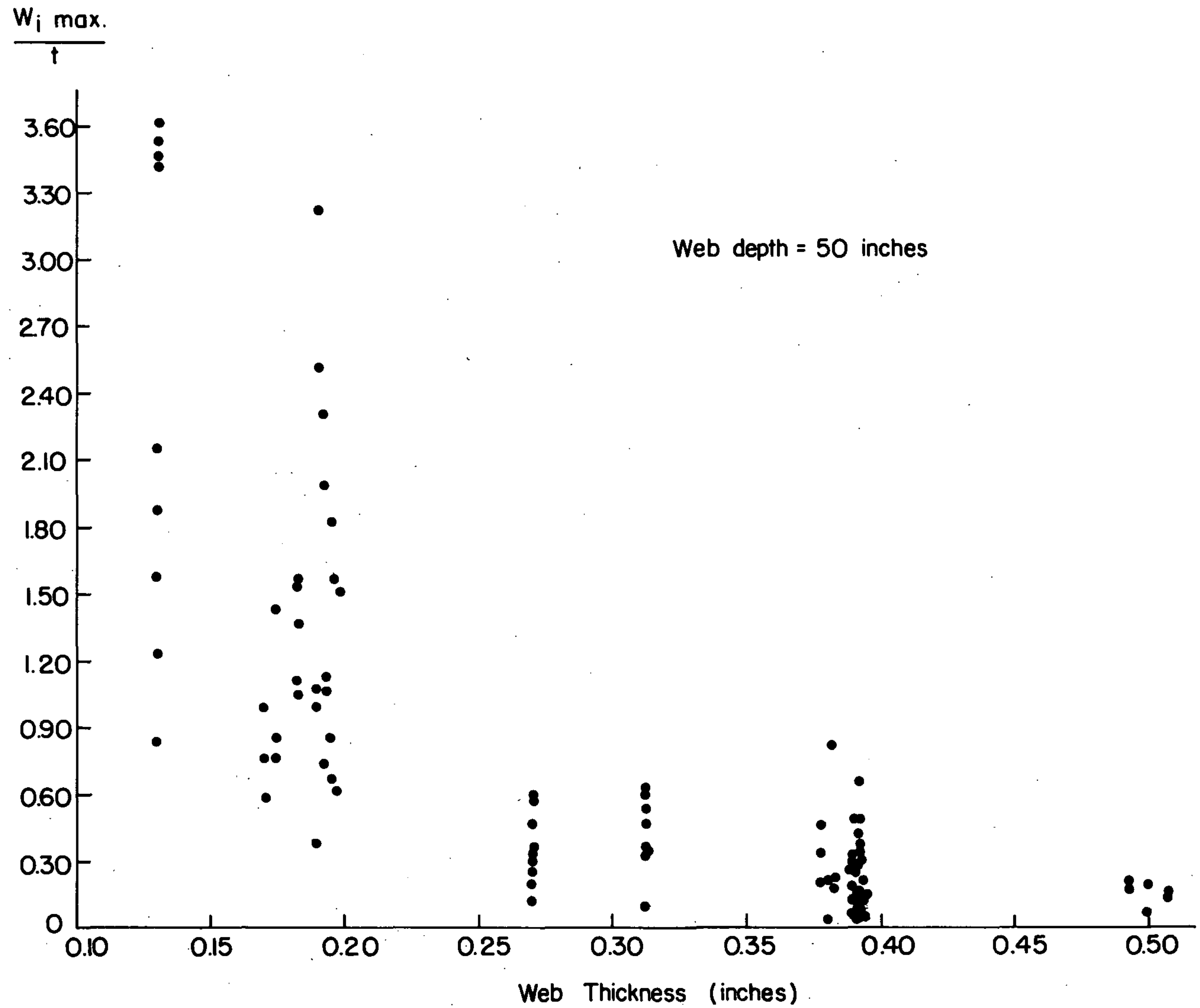


Fig. 12 Maximum Initial Deflection Versus Web Thickness

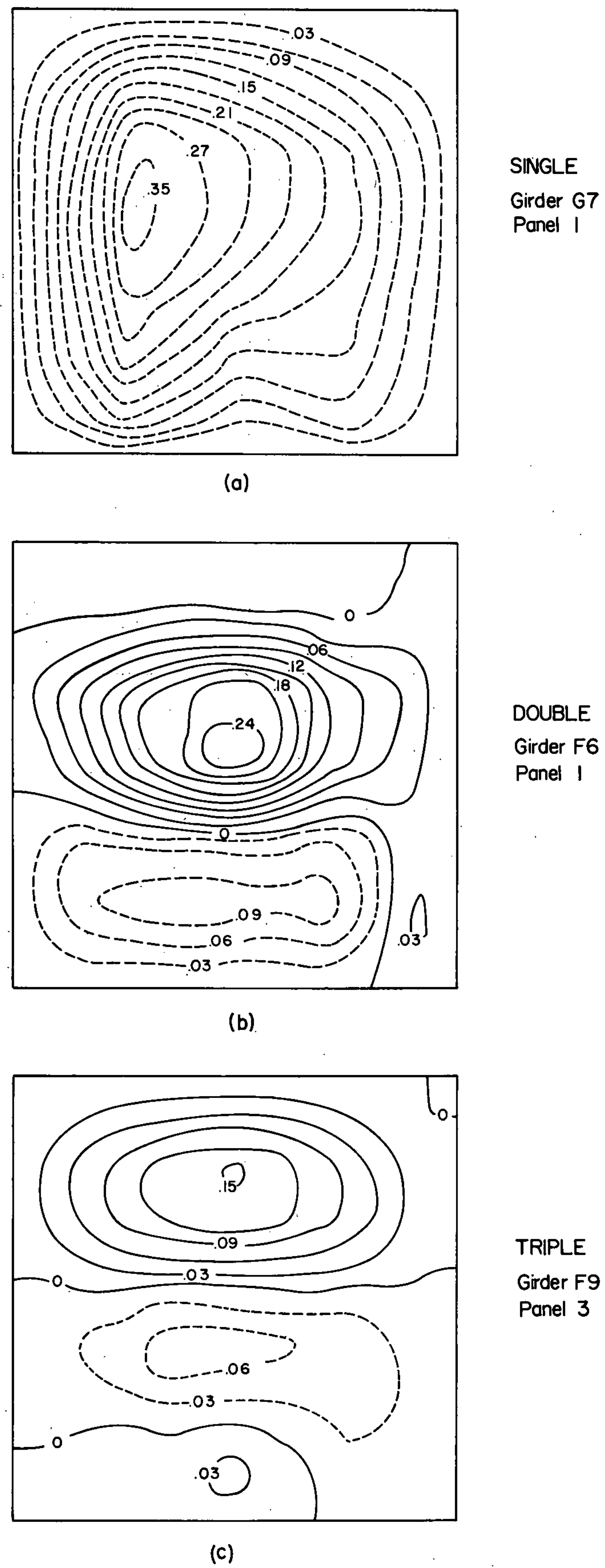


Fig. 13 Initial Web Deflection Contours

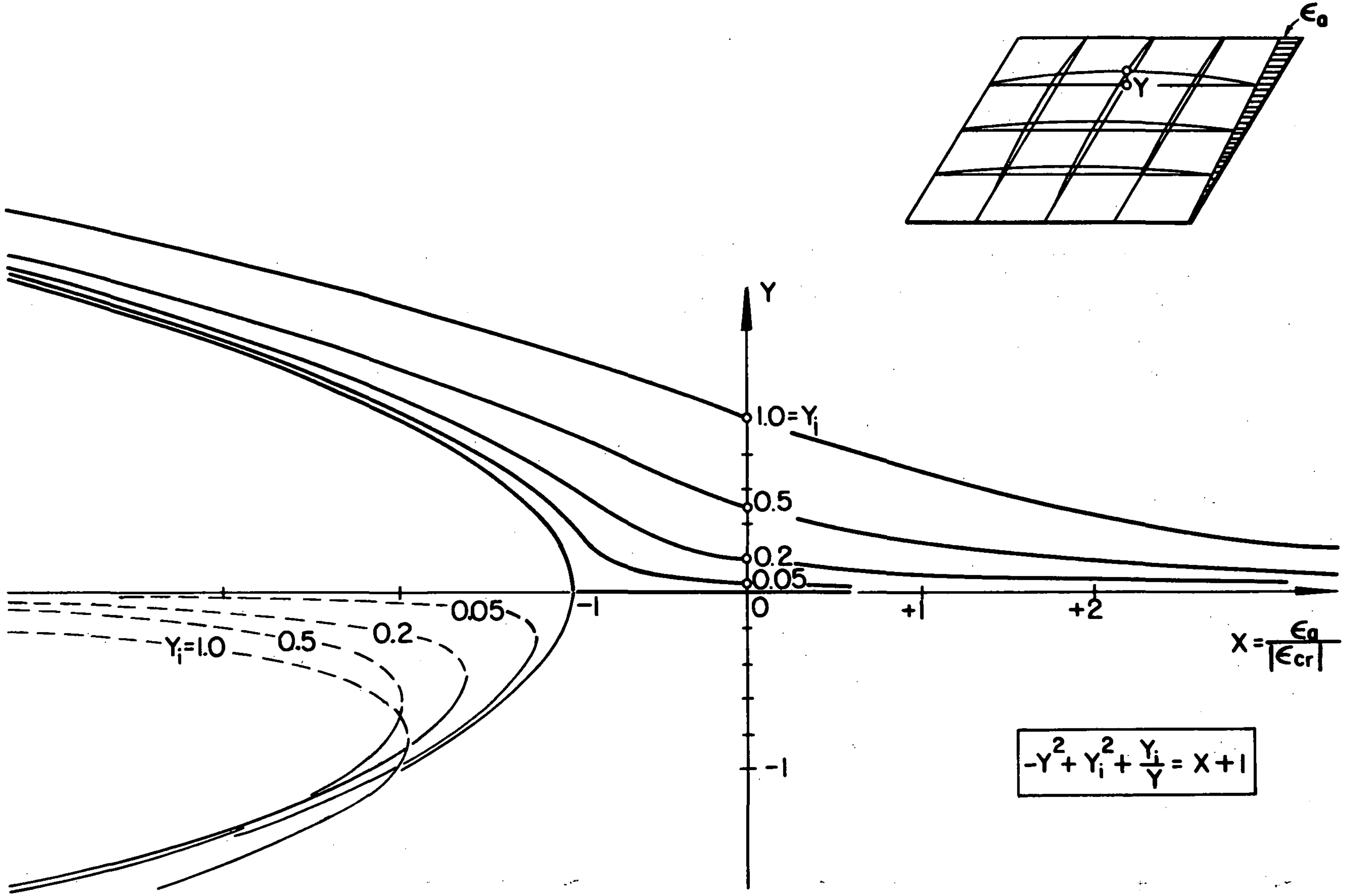


Fig. 14 Lateral Deflection Versus Applied Strain From Ref. 12

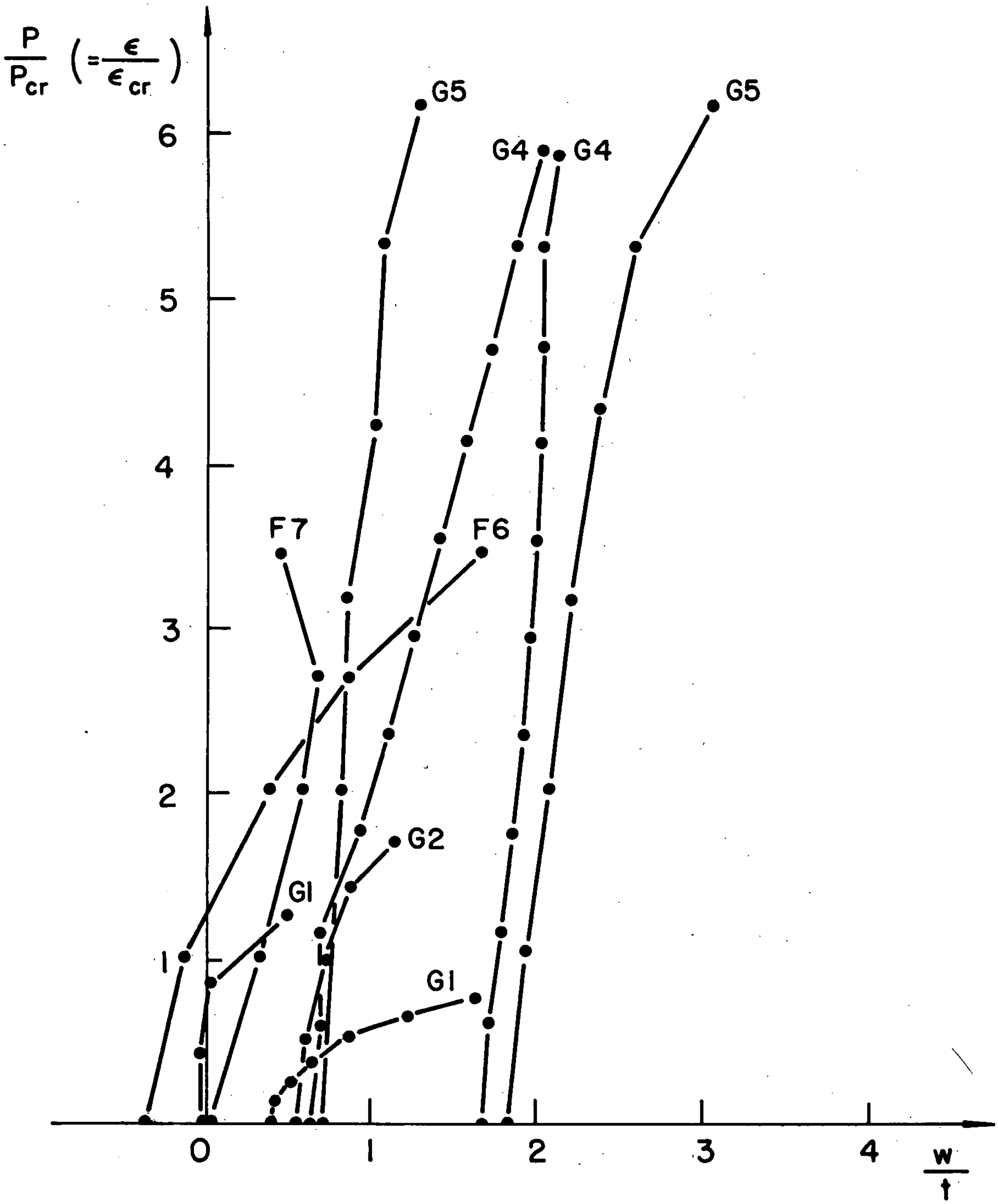


Fig. 15 Load-Deflection Curves for Panels in Bending

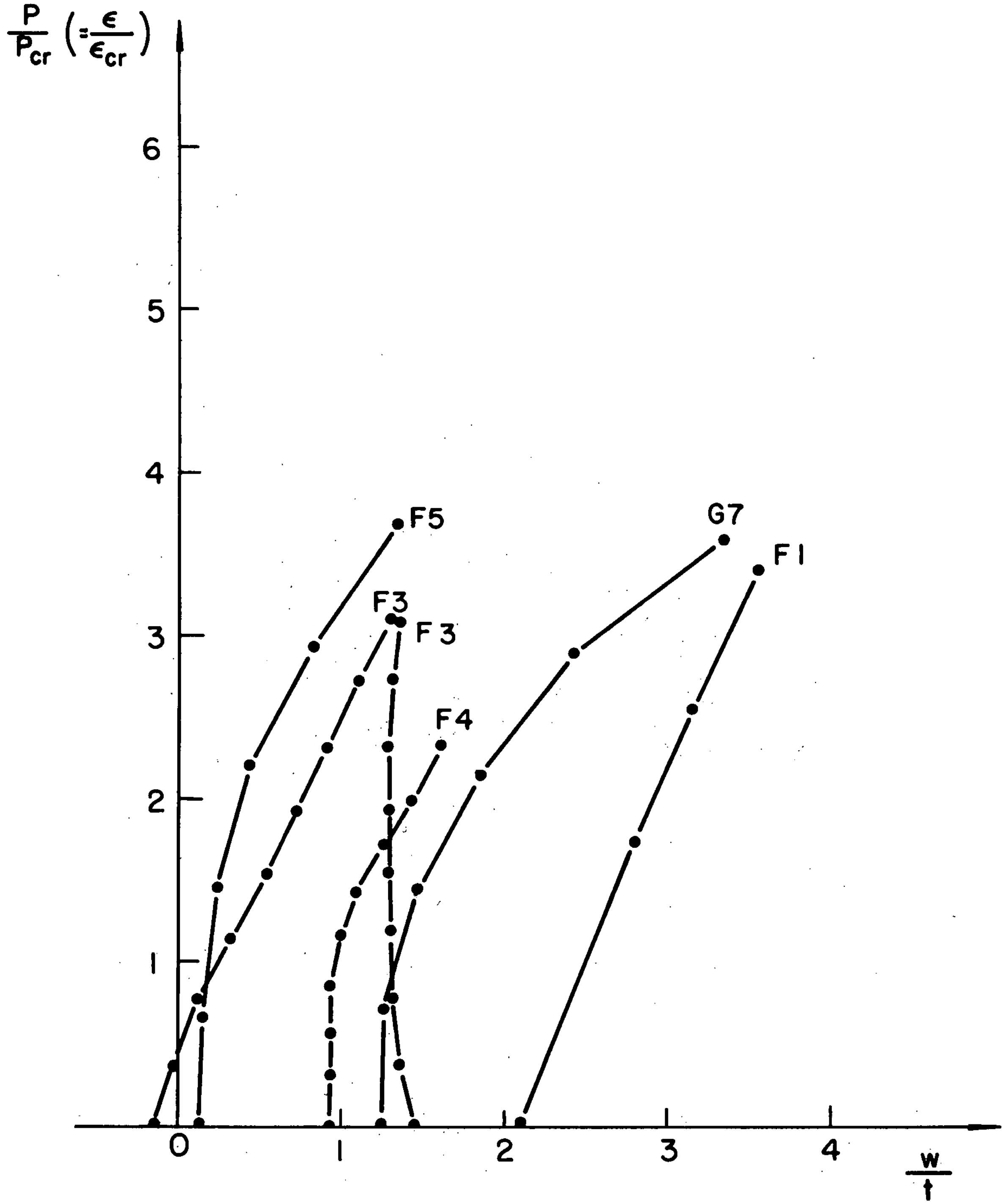


Fig. 16 Load-Deflection Curves for Panels in Shear

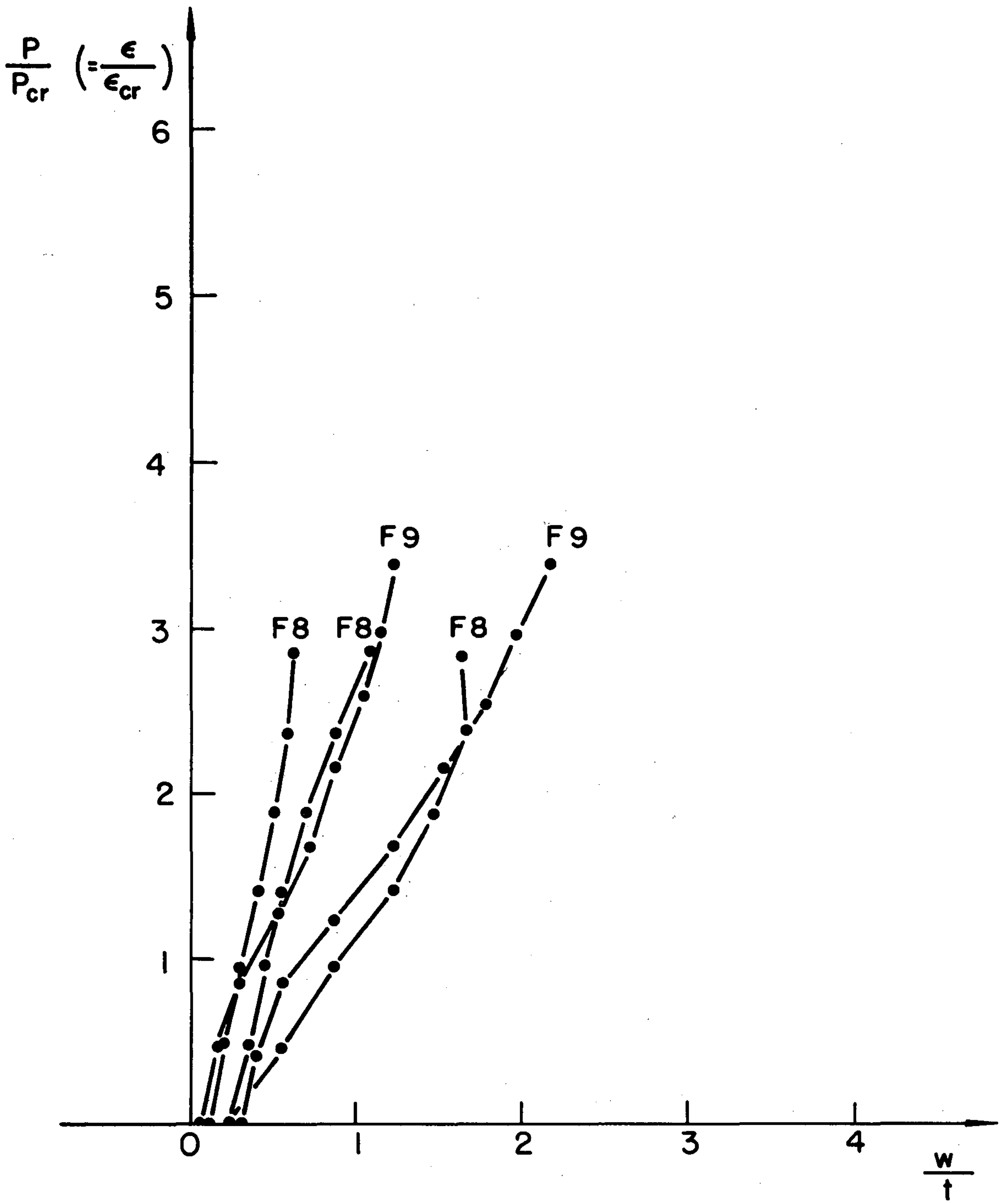


Fig. 17 Load-Deflection Curves for Panels Subjected to Combined Bending and High Shear

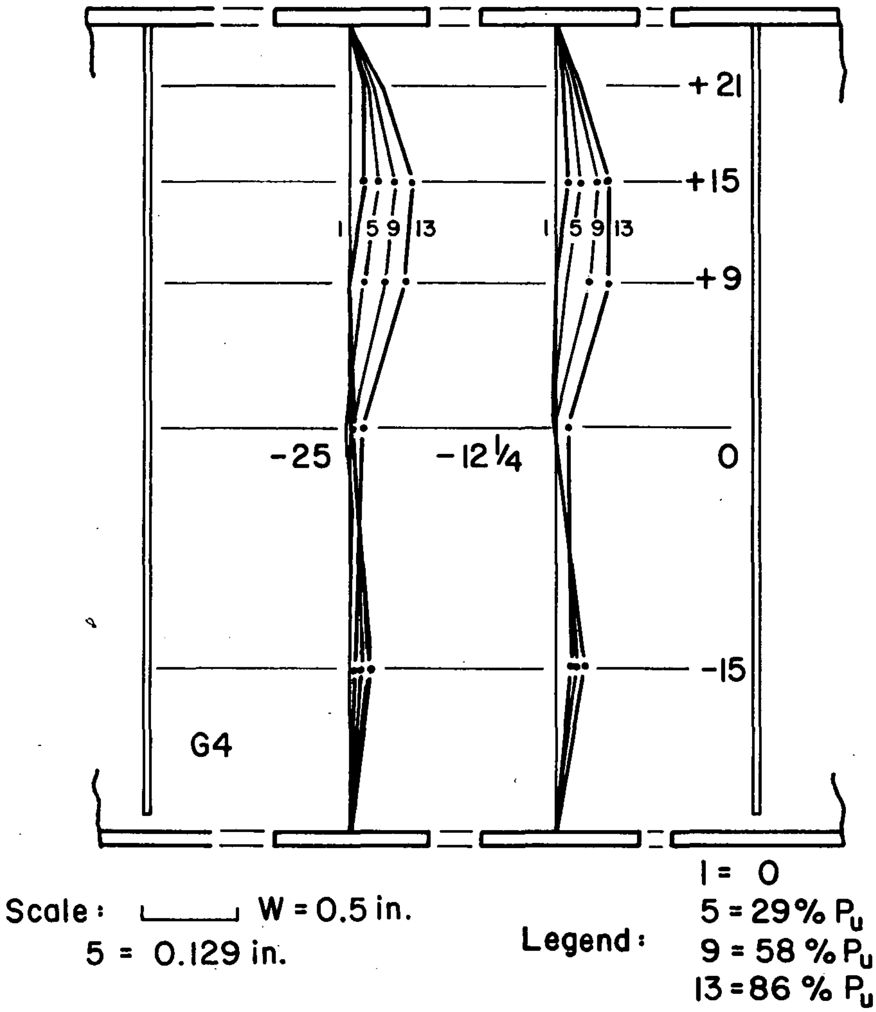


Fig. 18 Sequence of Web Deflection Growth, Girder G4, Panel 2

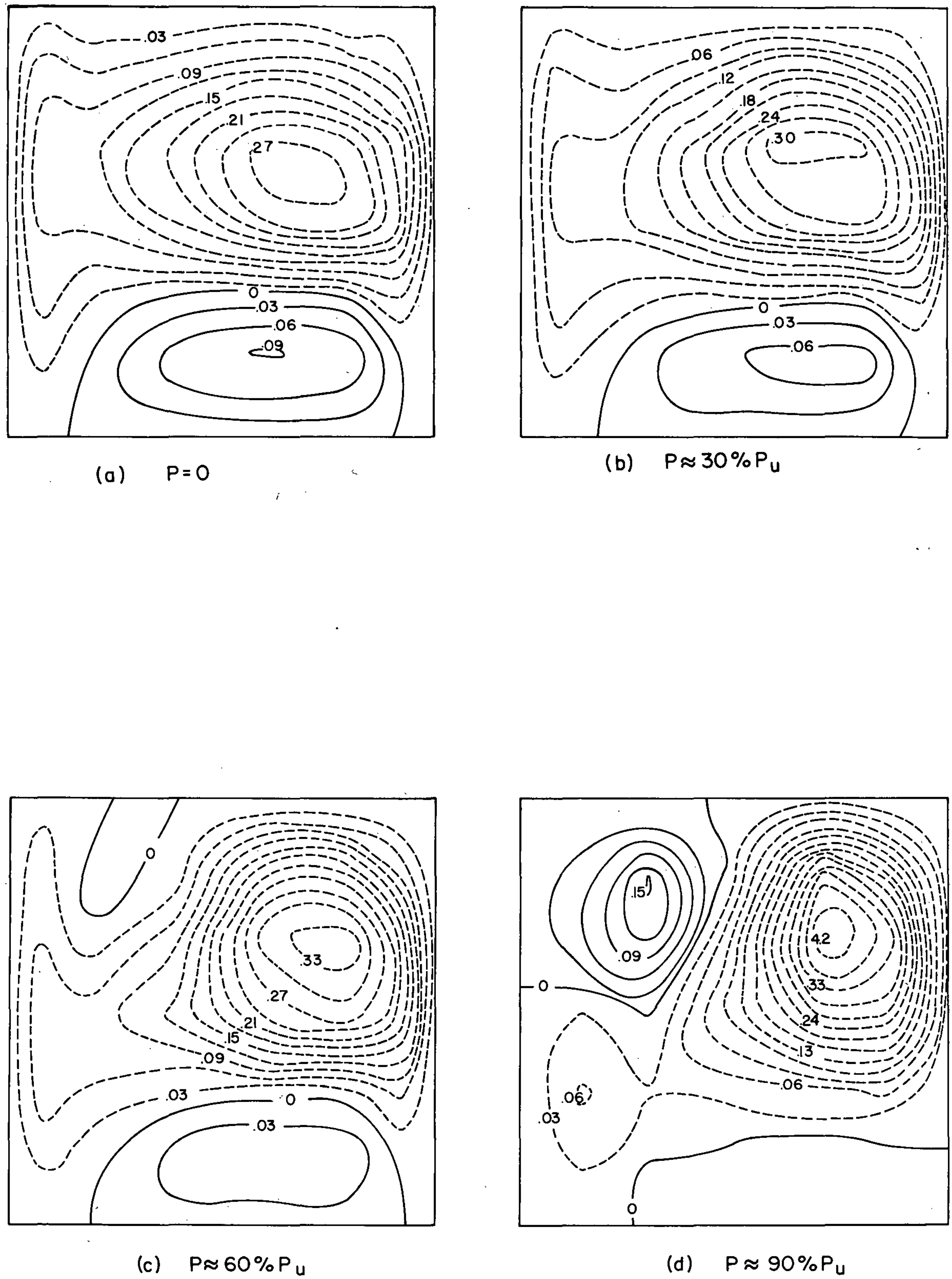


Fig. 19 Gradual Change of Deflection Contours,
Girder F7, Panel 3

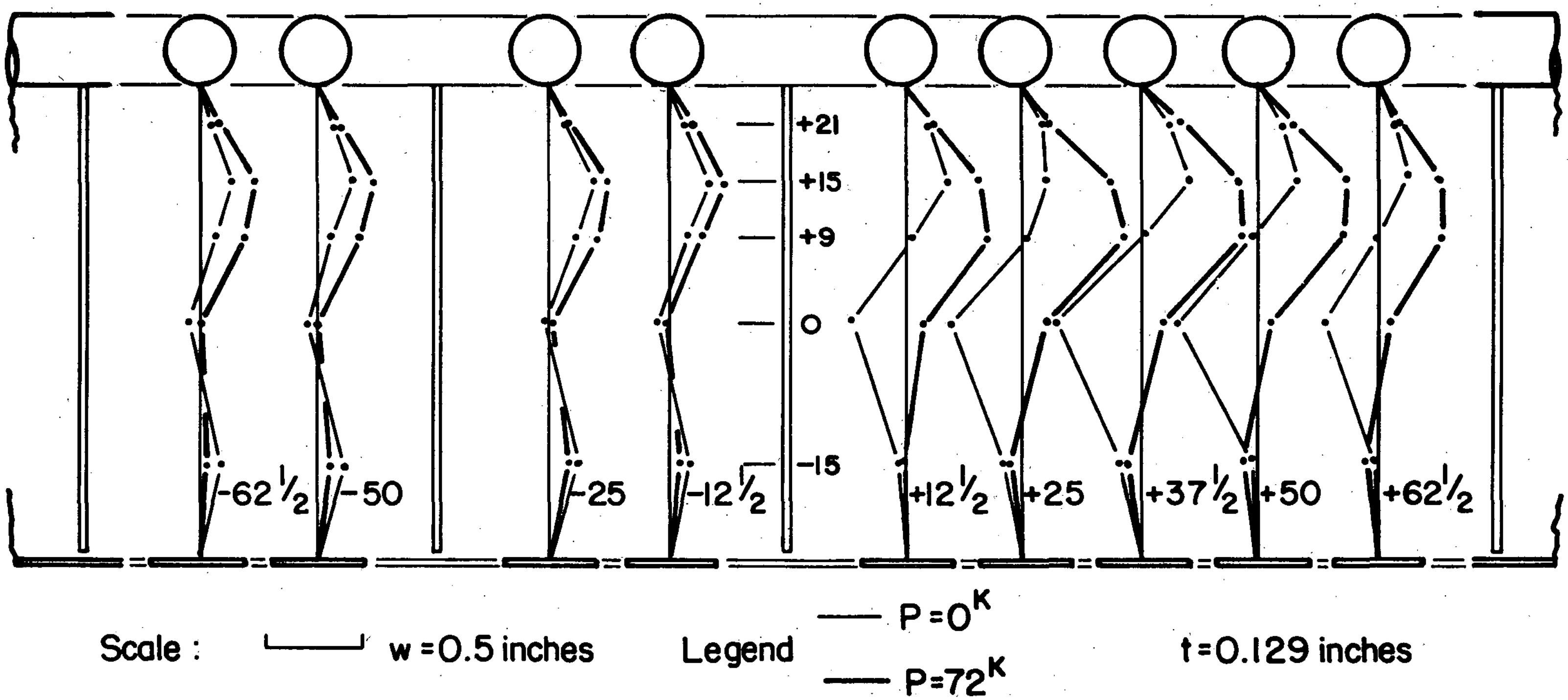


Fig. 20 Deflected Cross-Sectional Shapes Under Bending, Girder G5

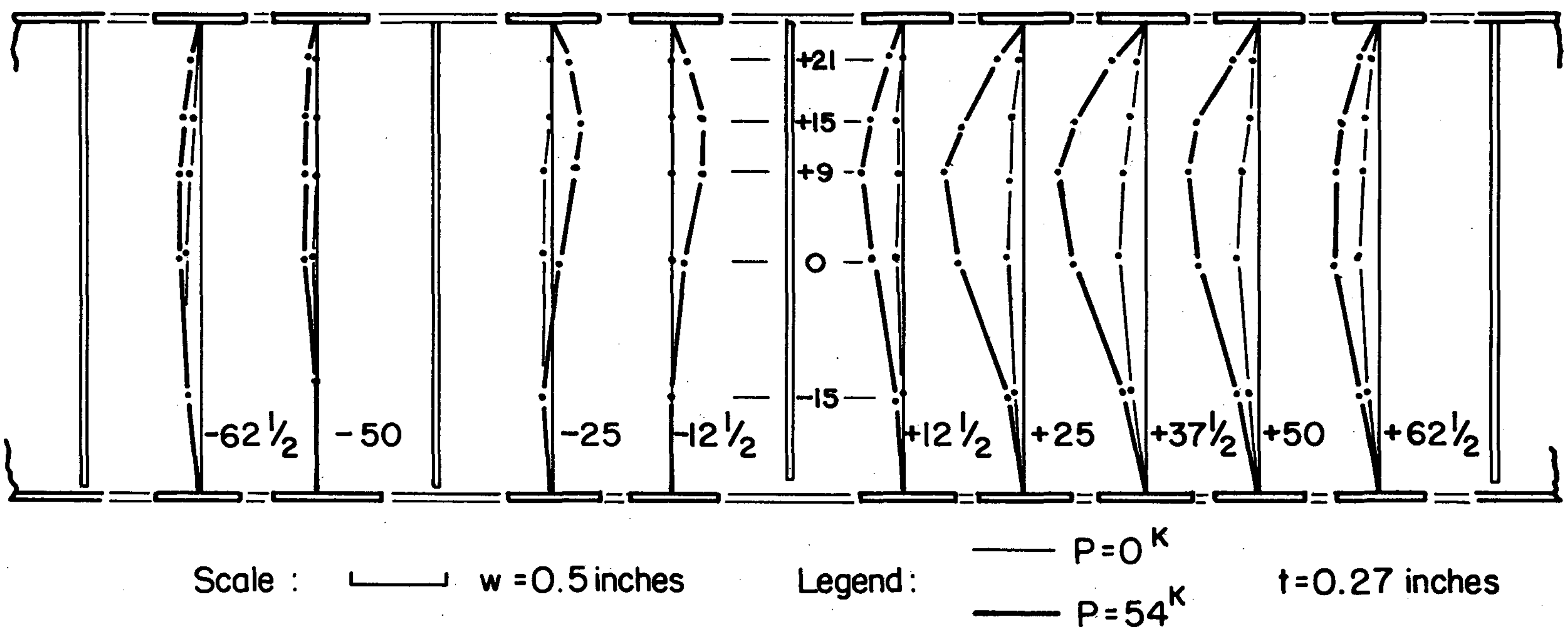


Fig. 21 Deflected Cross-Sectional Shapes Under Bending, Girder G1

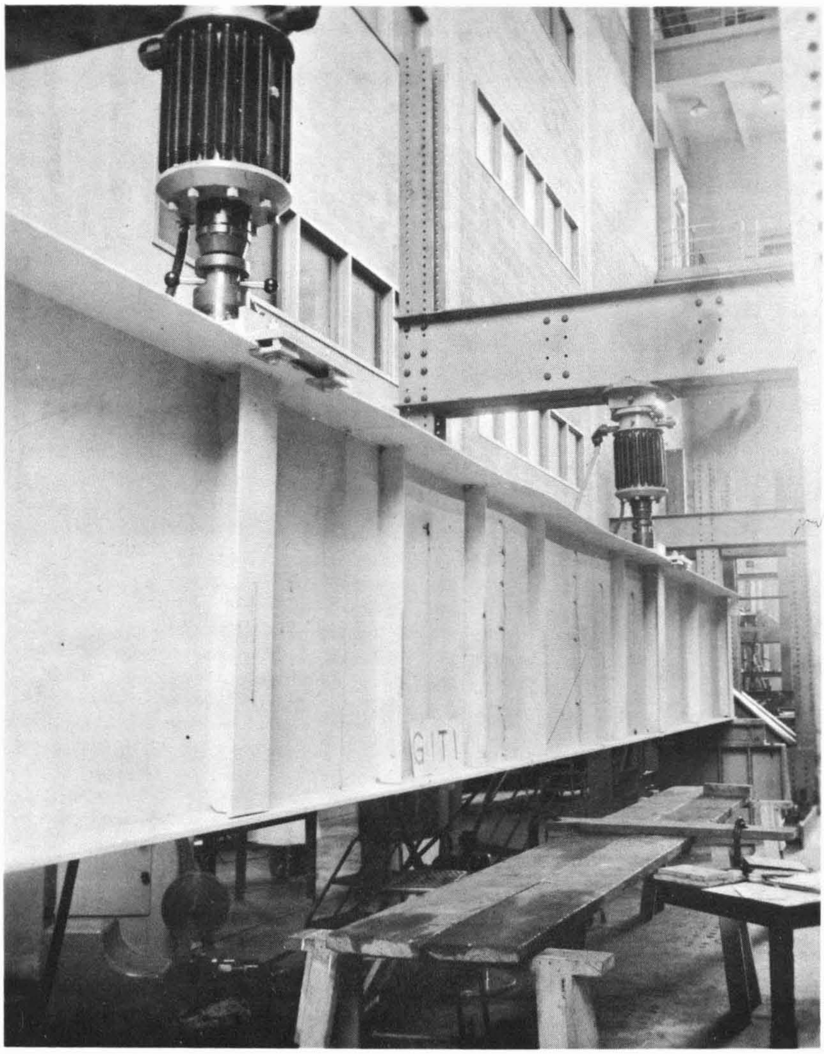
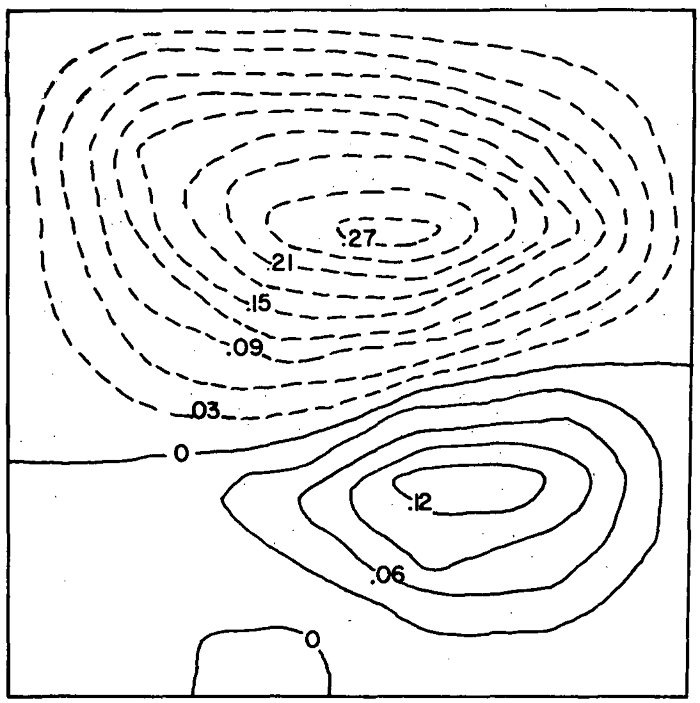


Fig. 22 Overall View of Girder G1



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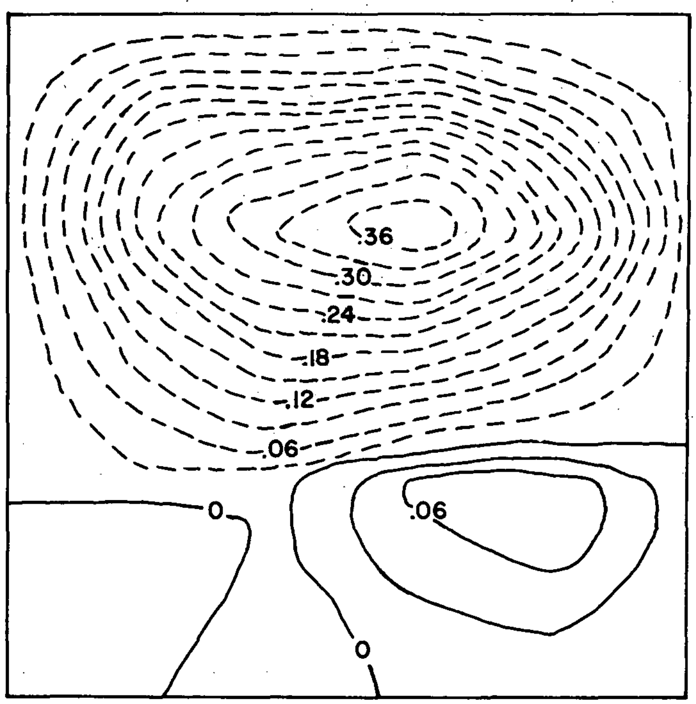
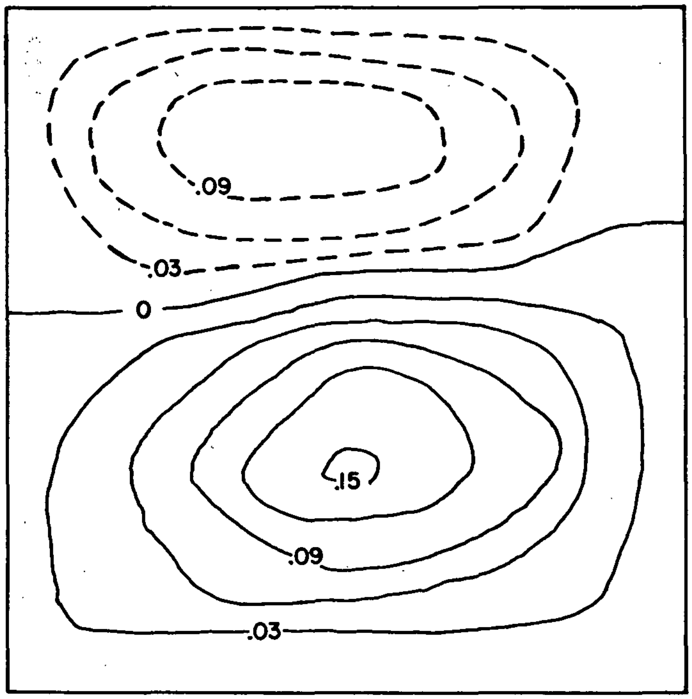


(b)

Fig. 23 Web Deflection Contours, Girder F6, Panel 3



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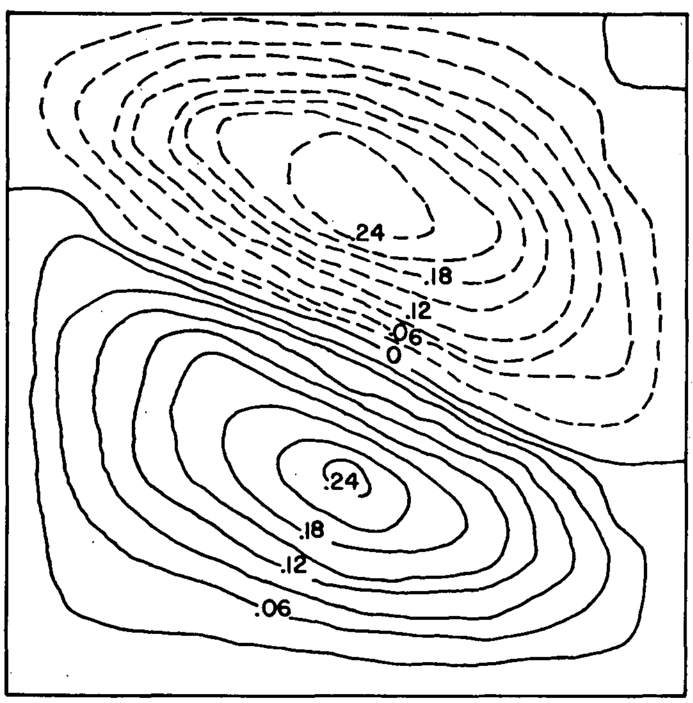


(b)

Fig. 24 Web Deflection Contours, Girder F8, Panel 2

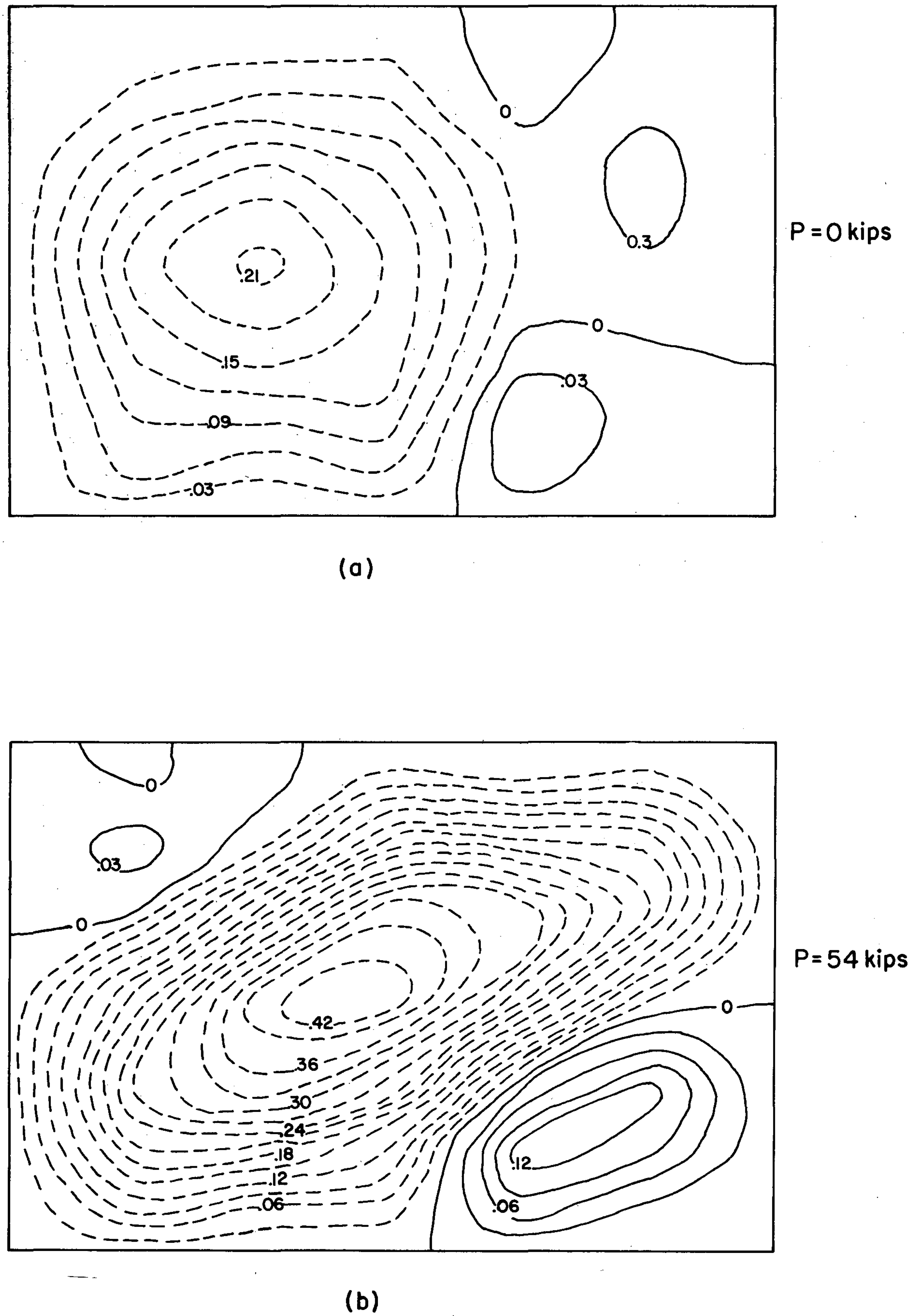


Fig. 25 Web Deflection Contours, Girder G6, Panel 1

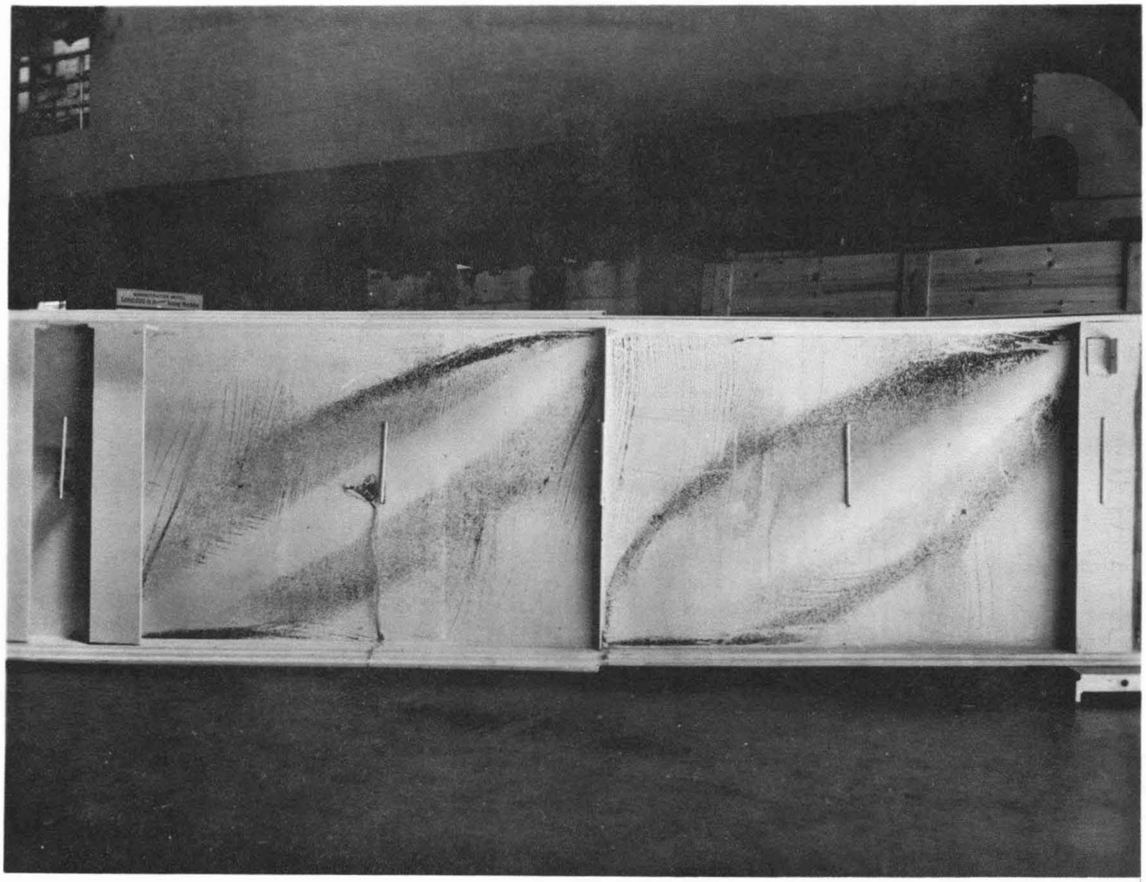
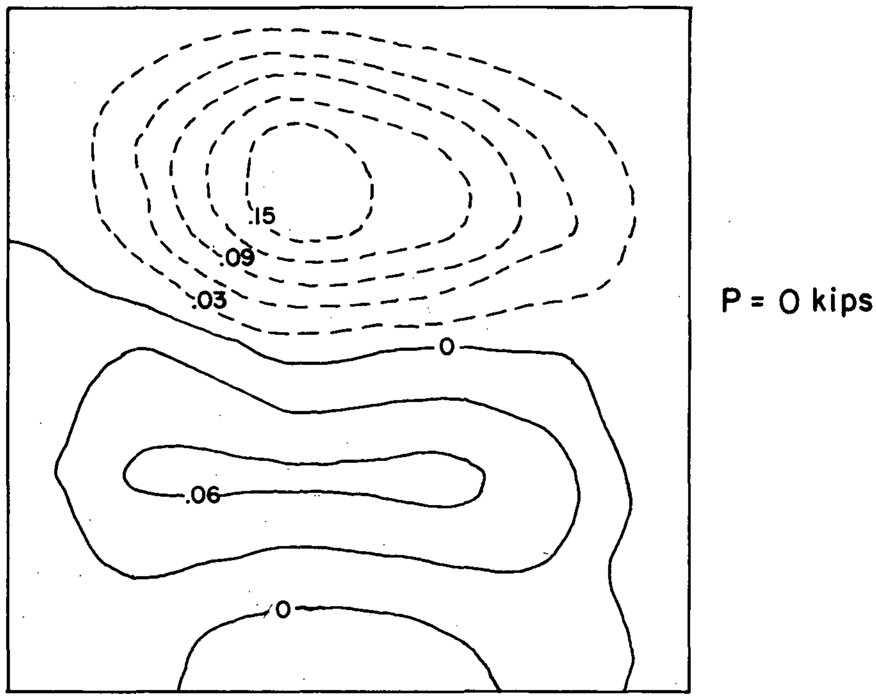


Fig. 26 Shear Deflection Patterns, Girder E1



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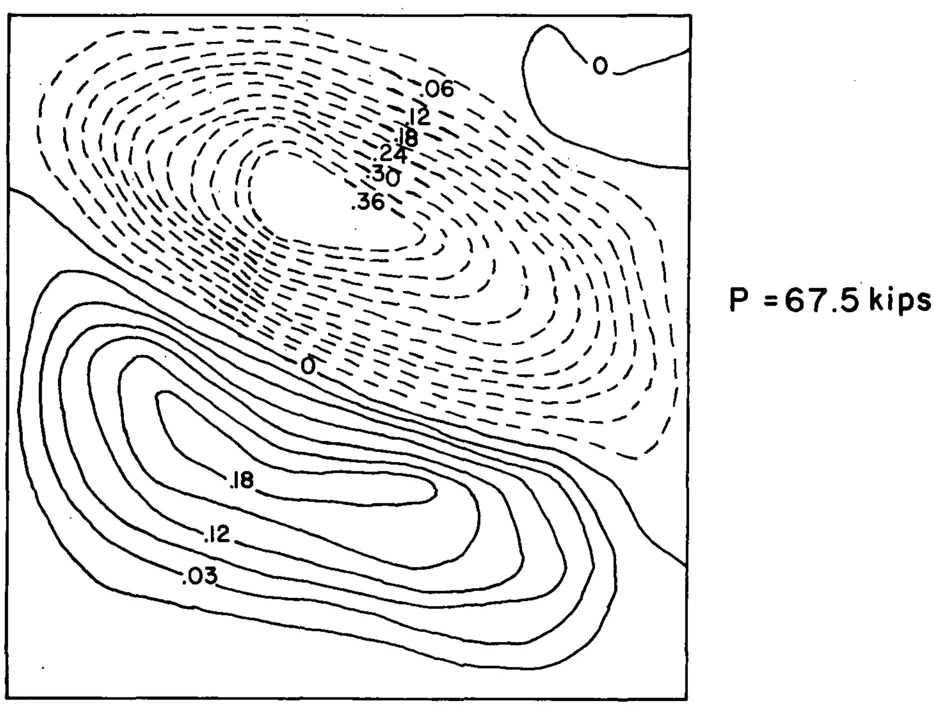
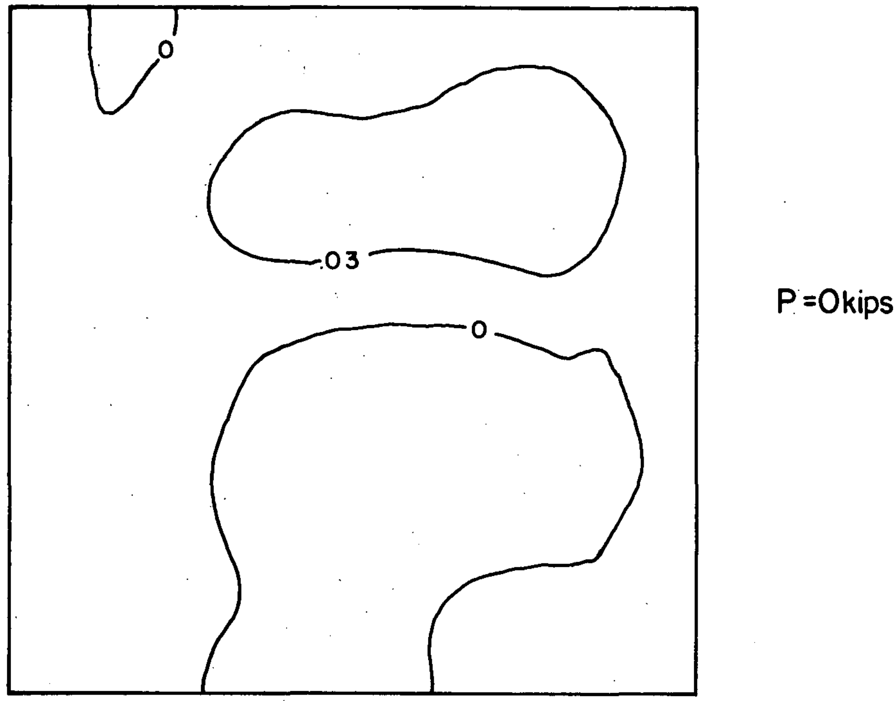


(b)

Fig. 27 Web Deflection Contours, Girder F8, Panel 3



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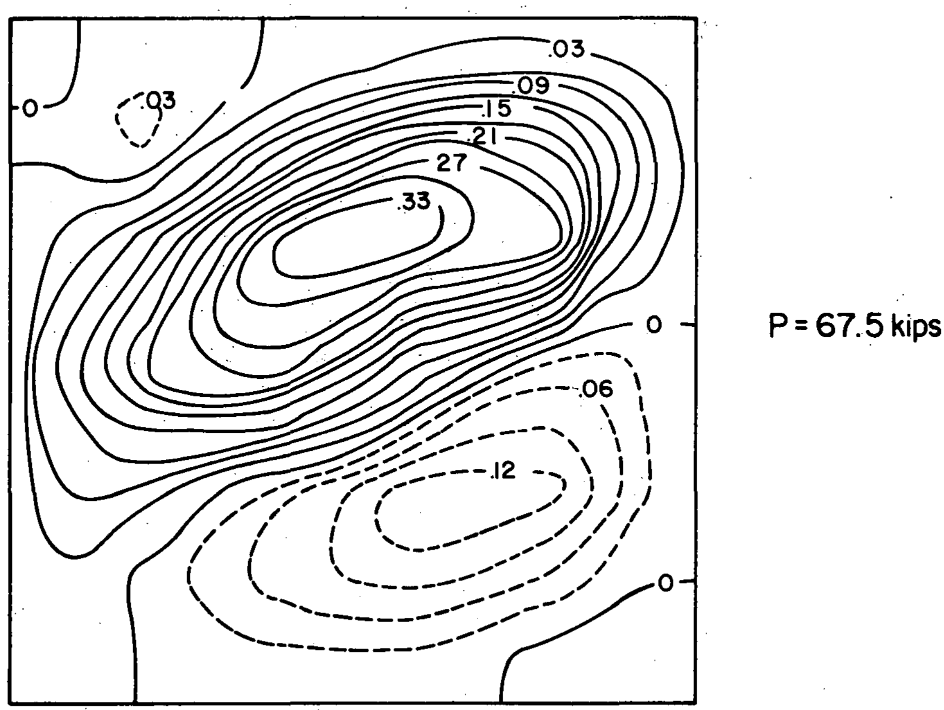

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Fig. 28 Web Deflection Contours, Girder F8, Panel 5

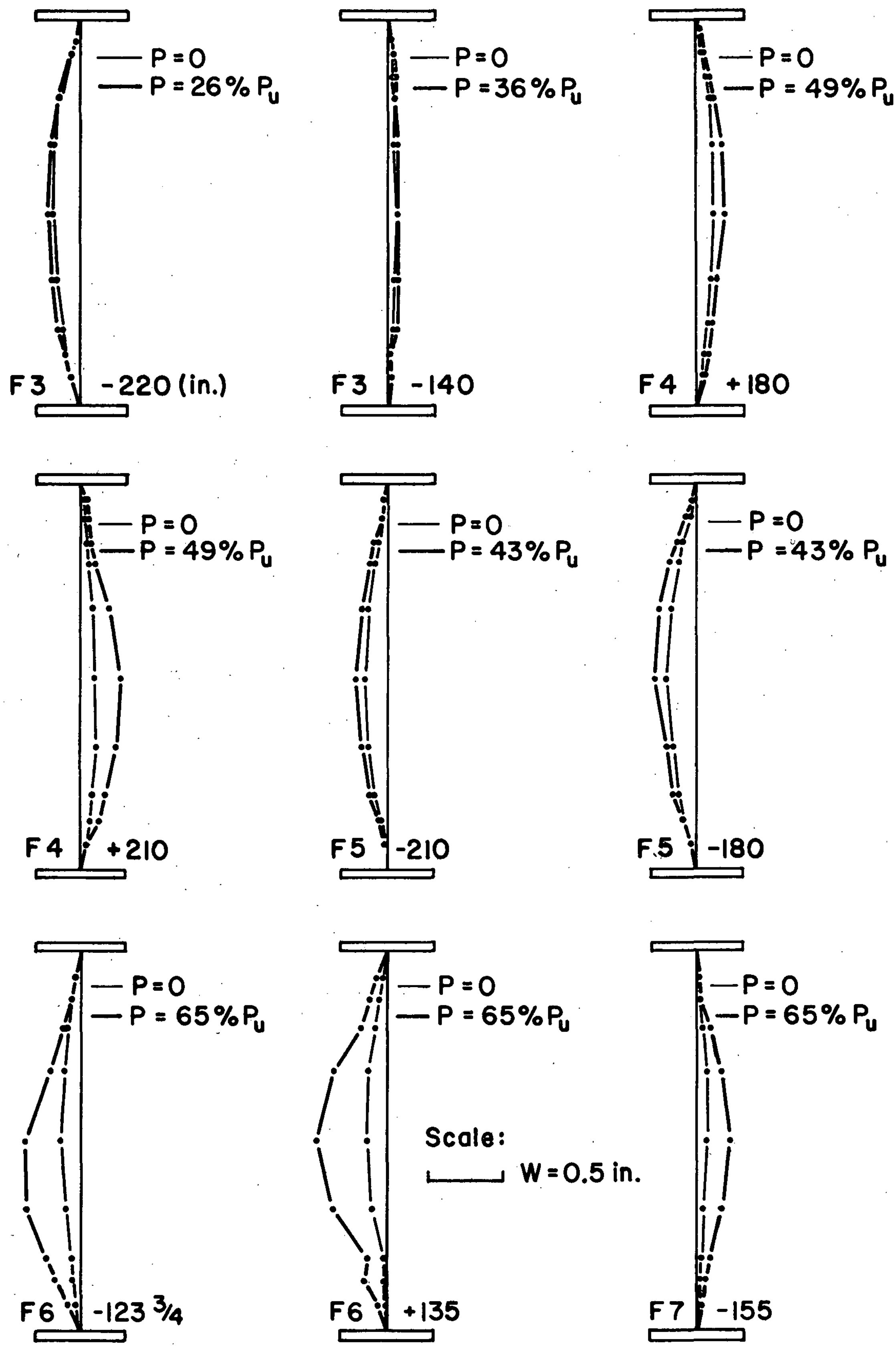

Fig. 29 Initial and Deflected Cross-Sectional Shapes of End Panels

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