LIGHT GAGE STEEL FOLDED PLATES

by

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I. INTRODUCTION

There has been widespread development and construction of plate and shell structures in the United States and throughout many areas of the world. Different forms, materials, building techniques and applications have characterized the growth of these structural forms.

From the simple beam and lintel to the arch and rigid frame, from the flat plate to the curved plate or shell, to the folded plate, each development has led to others.

This thesis is concerned with folded plates and light gage steel in a form that is readily adapted to them. By way of history, a discussion of shells should be used to introduce the topic.

The Shell Form

The shell surface is a structural form that can provide an effective solution to the problem of designing supporting roofs over long spans. Structural efficiency is obtained when applied loads are balanced primarily by tensile, compressive and shearing forces in the plane of the shell surface. The degree to which membrane stresses are dominant over flexure and normal shear gives a measure of the structural economy of the system.

In the construction of shells, reinforced concrete is easily adapted and widely used. In fact, most of the civil engineering literature on shell structures is referenced to the use of concrete. Concrete can be formed into almost any desired shape, including the complex doubly curved surfaces. Although shell roofs have many structural advantages, including beauty, strength, flexibility and economy of material, there exist two main disadvantages to discourage their use. First, the analysis is complex and relatively expensive (9)*, although engineering aids are continuously being developed in an attempt to simplify the design and reduce the complexity. (See, for example, PCA Bulletin ST77, "Design of Barrel Shell Roofs" and ASCE Separate 1057-ST5, 1957, "Hyperbolic Paraboloids and Other Shells of Double Curvature.") ASCE Manual 31 (4) is one such aid available for the analysis of cylindrical shells, one of the simplest forms of curved shell.

Second, construction costs are high due to the elaborate falsework generally required and the difficulty of placing concrete on a curved surface.

Folded Plates

The folded-plate roof structure evolved some time after the cylindrical shell. It represented an attempt to simplify design, analysis and formwork, and yet retain many of the advantageous characteristics of shells. Since the early

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*Numbers in parentheses refer to publications listed in the Bibliography, Section VII.

1950's a rapid increase in the technical literature on folded-plate structures has indicated a growing interest on the part of the engineering profession in this type of structure. Wide variations in design methods supported by different writers leave the designer with some doubts about any method he uses, so it becomes necessary that these methods be evaluated for the guidance of the profession (16, 18). The experimental and analytical work of this thesis are compared with Simpson's Method as a contribution to this effort.

Interest in folded plates first developed for folded plates of reinforced concrete as it had for concrete shells because of the ease with which concrete can be adapted. Relocation of essentially unstressed material to areas of fuller utilization reduces the volume of concrete per square foot of surface and thus makes a substantial reduction in dead load.

The folded-plate concept offers an almost unlimited range of possible cross-sectional arrangements for structures. The simplest form consists of inclined plates in a series of connected V-shapes. However, this cross-section has one disadvantage in that the area of concrete may be inadequate to resist the longitudinal compressive flexural force or to permit placement of reinforcing steel to resist longitudinal tension. (16) A more general and practical cross-section can be developed by adding horizontal plates at the top and bottom junctions of the inclined plates, forming what is called "hipped plate" construction. This form enables more convenient placing of the the reinforcing steel at the fold lines, reduces the angle change between plates and leads to better economy of steel and concrete. Other cross-sectional arrangements include tapered or triangular plates and the unsymmetrical Z-shape which is used in north-light roofs. (8, 20)

For all concrete folded plates, the slope angle is usually 45° or less in order to facilitate the placing of the concrete without top forms. (16) In general, the thickness of individual plates should be kept at the minimum as governed by the criteria for steel reinforcement protection. In turn, this will affect the width of the plate, which is generally not over 10 to 12 feet wide.

Although reinforced concrete has been used extensively in the development of folded-plates, other materials such as timber and metal have advantages to offer. Plywood is shown to be readily adaptable to large flat plate areas and has been used in some folded-plate construction. (16) The economical advantages are not yet clearly defined for metal folded plates, except perhaps in the construction of bins and bunkers. In folded plate roof structures however, sheet metal employed as shear diaphragms gives high resistance to roof loads. The ideal shear diaphragm is a thin plane sheet or membrane with a stiffening structure attached to it. If the membrane is prevented from buckling, it can resist shear forces through a diagonal tension field action. (10)

Light Gage Steel

Light-gage steel roof, wall, and floor systems may be used effectively to transfer in-plane shear forces from one part of a framed structure to another, leading to reduced loads in parts of the main load carrying frame. (1) Since the action of folded-plates involves transferring in-plane shear forces from one plate to another, light-gage steel diaphragms show favorable possibilities. Because of the large number of variable parameters, it is difficult at this stage in the state of the art to predict diaphragm behavior from a purely analytical approach; test evidence must be drawn upon in large measure. (10) Most experimental studies have been limited to diaphragms made from open fluted and standard corrugated panels. Very little data is available on cellular panel diaphragms, which appear to be most favorable for folded-plate construction.

Some of the variables that influence the action of light-gage steel diaphragms include panel configuration, length, width, diaphragm size, fastener type and arrangement, perimeter member stiffeners, type of loading, material thickness and material properties. (1, 2, 10) Some basic testing has been done at Cornell University (10) in an attempt to study trends of the influence of these variables, but much more experimental study is needed.

In lieu of expensive formwork required for concrete, the use of light-gage steel cellular panels for folded-plate structures offers favorable possibilities. These panels can form a very stiff structure when a series of them are joined together along successive fold lines in any one of a wide variety of patterns. The light weight of the panels coupled with the ease of construction are favorable aspects of this type of structural system. It was reported in 1965 that about 90 light-gage steel folded-plate structures had been built in the United States. (11)

Thesis Objectives

The purpose of this thesis is two-fold. One objective is to determine the rigidity of a V-shaped folded-plate structure made of light-gage steel cellular panels. A model scaled approximately 1 to 20 is tested under a uniformly applied load, and deflections are measured using dial gages.

A second objective is to compare experimental results with values obtained from a rational analysis.

II. REVIEW OF LITERATURE

Early History

The first known application of folded plates was in large coal bunkers erected in Germany in 1925 and the first papers on the corresponding design theory were published in Germany by G. Ehlers and H. Craemer (5, 6, 7) in 1930. The folded-plate structure was widely used in Europe and Russia before it was introduced into the United States. (21)

First Publication in the United States

The first technical publication on folded plates in the United States was written by Winter and Pei (21) in 1947. Since the early 1950's, there have been numerous papers published dealing with the analysis, design and construction of folded plates. Included among these are the well known papers by Simpson and Parme. (19, 13)

Few papers have been written about light-gage steel folded plates. The AISI has been the prime mover in promoting research in this area for many years and sponsored studies are currently being conducted at Cornell, Arizona, West Virginia and other universities.

Experimental Testing at Cornell University

In 1961 Arthur H. Nilson, Professor of Civil Engineering at Cornell University, published an experimental study (12) in which a full-sized, light-gage steel folded plate unit, forty-six and one-half feet long, was fabricated and tested in the structural laboratory. The cross-section of the test structure was trapezoidal.

The test structure was full size and difficult to load with distributed surface design loads. Vertical loads were applied by jacks along the fold lines to simulate end reactions from uniformly loaded transverse slab segments.

The observed vertical deflections of a lower fold line coincided very closely with the predicted values. Deflection contributions from flexure, shear, and seam slip were about 85%, 11%, and 4% of the total deflection, respectively. Proportionate contributions for other cases depend largely on the ratio of span length to width of the inclined plate and on the configuration of the structure.

Nilson analyzed the test structure by considering the plates as separated along the fold lines and calculating the in-plane deflection of each plate due to flexure, shear, and seam slip. The plates were considered to be deep beams with each flange area equal to one-half of the cross-sectional area of the connecting fold line members. The total deflection was determined by the geometry of small angles.

Extensive study has also been made of shear diaphragm action and some theoretical techniques have been developed for the proper evaluation of the action and load capacity of light-gage folded-plate steel welded diaphragms (11).

III. DEFLECTION ANALYSIS OF LIGHT GAGE STEEL FOLDED PLATES

The action of light gage steel folded plates differs from the action of reinforced concrete folded plates in that the fold lines of the steel structure provide no continuity of transverse bending moment. The plates may rotate with respect to each other with relatively insignificant resistance.

In order to analyze them, the action of folded-plate structures when subjected to surface loading can be considered in two parts. First, with the plates acting as flat slabs supported along the fold lines and subjected to the normal component of loading, this is called "slab action." Second, with the plates acting as deep beams supported at each end and subjected to the in-plane component of loading (plus the resolved components of fold line forces), this is called "beam action." When these separate analyses are completed, compatibility at the fold lines must be established.

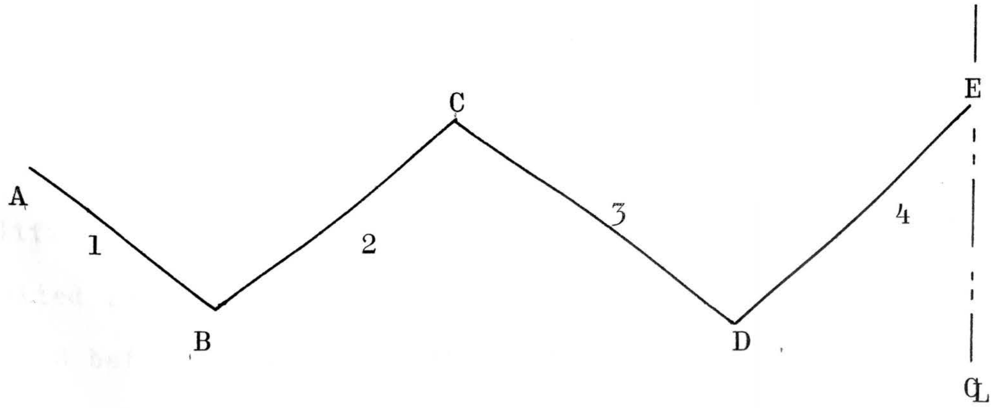
There may be several ways in which the plates of a light gage steel structure could be treated for the purpose of analysis. Methods presented in the literature (12, 16, 19, 22) suggest that the plates may be divided arbitrarily at the fold lines. Usually this means along some plane of symmetry wherein the fold line member (the connecting angle in the light gage steel structure) is divided in half and each half acts as a flange of the deep beam to which it is attached. To assure continuity and compatibility along the edges of adjoining plates, the longitudinal shearing stresses and the longitudinal axial strains at the edges of separation of each half of the fold line member must be the same. If continuity does not exist, these longitudinal stresses may be corrected by a relaxation process (19). Table I shows the longitudinal stresses in the test model at mid span before and after relaxation.

In lieu of correcting these longitudinal stresses in a stepwise manner after each application of adjusted loading, a modified method is used to determine directly the longitudinal stresses that will be compatible along the separated edges. When each plate is separated longitudinally along its fold lines, the fold line members are proportioned so that the plates are considered to be deep beams with flange areas equal to one-half of the cross-sectional area of the fold line members. The moment of inertia of each plate acting as a deep beam is calculated and the strains induced in the extreme edge fibers of the plates by the in-plane load on the structure are determined. The differences in edge strains are then re-evaluated. The cross-sectional area of the fold line member connecting the adjacent plates is reapportioned so that the common edge stresses of the

Table I. Longitudinal Stresses in the Test Model at Mid Span

Plate	Fold Line	Longitudinal Edge Stresses (psi) Before Relaxation	Longitudinal Edge Stresses (psi) After Relaxation	Longitudinal Edge Stresses (psi) Using Effective I
1	A	-5,100	-4,900	-4,900
	B	+5,100	+4,800	+4,700
2	B	+3,800	+4,800	+4,700
	C	-6,900	-8,900	-9,000
3	C	-11,000	-8,900	-9,000
	D	+11,000	+10,600	+10,700
4	D	+11,000	+10,600	+10,700
	E	-11,000	-10,800	-10,900

+ Tensile Stresses
− Compressive Stresses



Longitudinal Edge Stresses

Structure Uniformly Loaded with 10 psf

two plates become equal. This new division of flange areas generally results in shifting the neutral axis of the plates and changing the moments of inertia. New values for moments of inertia can be referred to as effective moments of inertia. The process of reapportioning the cross-sectional area of the fold line members is continued until the effective moment of inertia of each plate in the structure converges to a value which gives compatibility of longitudinal strains between every pair of adjacent plates. The convergence is rapid; in the test structure, convergence occurred after two cycles of adjustment. Calculated values of longitudinal stress for the test model are also shown in Table I for comparison.

After an effective moment of inertia has been determined for each plate, compatibility along the fold lines is assured for any other proportional values of loading applied on the structure.

Certain limitations may have to be imposed on this modified procedure, particularly when large differences in applied loading exist on adjacent plates. Further study is needed before a broader application of this method can be used.

With continuity assured between adjacent plates, the deflections of each plate acting as a deep beam in flexure can be calculated. The total deflection is composed of contributions due to flexure, shear and seam slip. Since the cellular panels of the test model are continuous for the full length of the structure, seam slip transverse across the panels cannot occur. The shear along the fold line is small compared to the transverse shear; thus, the amount of seam slip developed along the fold lines is small and has been neglected. In the analysis of this test model, only deflections due to flexure and shear are considered to contribute to the total deflection.

The deflection due to flexure of a deep beam simply supported and subjected to uniform loading is

$$\Delta_f = \frac{wx(L^3 - 2x^2L + x^3)}{24\ E\ I'}$$

The moment of inertia, I', is the effective value that assures compatibility between adjoining plates.

The deflection due to shear in the web of a deep beam simply supported and under uniform loading is

$$\Delta_s = \frac{a\ M}{A_W G}$$

The shape factor, a, has been established from experimental tests to be equal to about 1.3 for light gage steel diaphragms (12). The moment, M, is the bending moment at the section in question, and the area of the web, A_W, includes both the corrugated and flat plates.

After calculating the total deflection for each plate, the plates are rotated to a new position and the structure is joined together in its new position to give the total deflected structure. Geometry of small angle changes is used to determine the total deflections of the structure.

IV. PROGRAM OF EXPERIMENT

Model Fabrication

In order to make up the 6" x 67" plate elements of the test model, light gage .002 inch stainless steel foil was corrugated into the hat section shape shown in Figure 1a and spot welded to a flat steel plate of the same thickness to form the cellular panel assemblage shown in Figure 1b. The spot welds were placed between every third hat corrugation with seven welding spots spaced one inch apart parallel to the corrugation of the plate. Six cellular panel assemblages, each 6" x 67", were fastened together along their common longitudinal edges with galvanized steel angles, .15" x .15" x .018", to form a V-shaped roof as shown in Figure 2. The angles were fastened to the panels by spot welding between every hat section along the longitudinal length of the plates. The spacing of these welds was about one inch, center to center.

Special attention had to be given to the welding process. Spot welding is probably the most important means of shop fabrication of light gage steel. A spot welder as shown in Figure 3 was used to fabricate this test model. Extreme precaution had to be exercised in order to obtain adequate welding bond without burning the material. Experience gained from building this model showed that the

a. Corrugated Hat Section
Actual Size

b. Corrugated Cellular Panel Section
Actual Size

Figure 1. Light Gage Steel Foil Configuration.

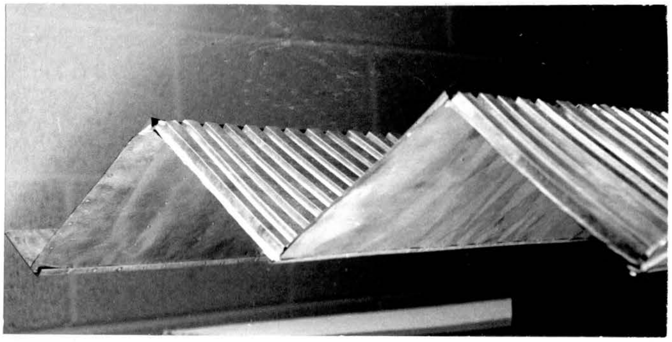


Figure 2. Fabrication Detail of Test Model.

Figure 3. Electric Spot Welder.

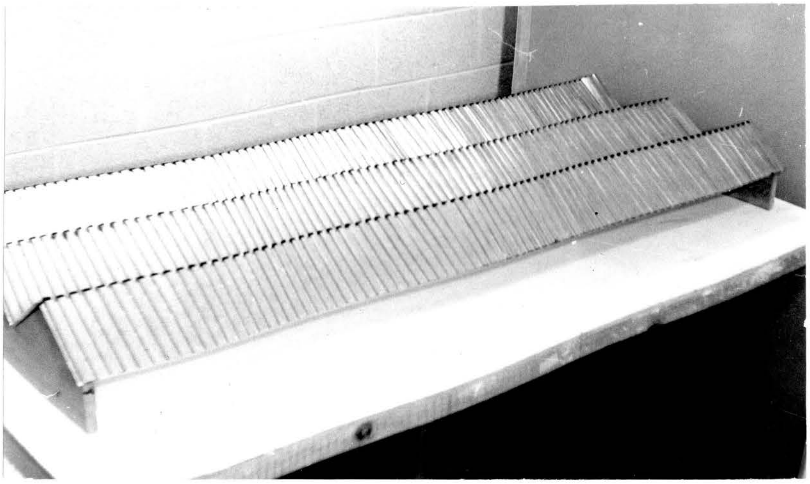
following fundamentals are essential for good weld bondage.

First, the kind of metal in the electrodes of the welder must be compatible with the material being welded. It was found that pure copper electrodes relatively free of any alloy material was best suited for welding the light gage stainless steel foil. Alloyed copper electrodes tended to fuse to the stainless steel.

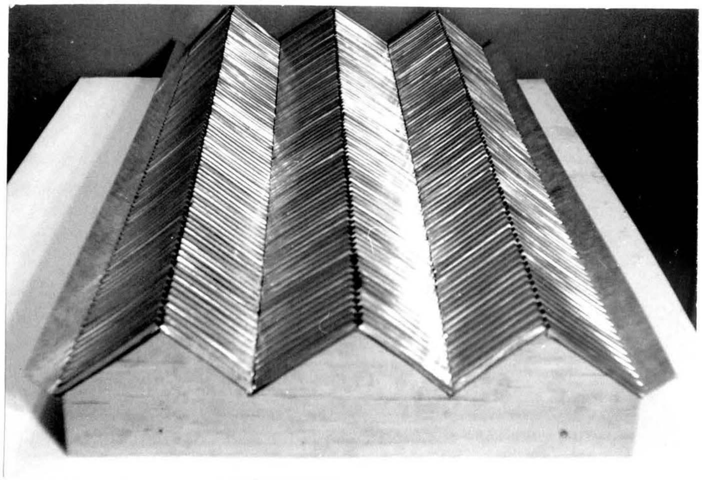
Second, the points of the electrodes should be chosen to provide proper contact area. Points with contact areas too large disperse the current over more area than desired. This often results in a poor weld. If the contact area is too small, holes are burned through the material, also giving a poor weld. The thicknesses of the light-gage steel will govern the proper contact area.

Third, proper regulation of the voltage must be maintained in order to provide the proper amount of current flow. If the voltage is too high, the current flow will disintegrate the metal foil. Voltage too low will not allow proper fusing of the metal. Experience will dictate the proper voltage level.

Edge plates as shown in Figures 4a and 4b were welded along the free edges to provide stiffness and to prevent rotation and large deflections in the outside plates. The edge plates were flat galvanized steel plates folded into angles 0.375" x 2.0" x .037".



a. Longitudinal View



b. End View

Figure 4. Test Model in an Upright Position.

The model was simply supported on two solid wooden diaphragms spaced 67" apart. The overall dimensions of the model were 32.0" wide by 67.0" long by 3.6" high, Figures 4a and 4b.

A plastic bag (made with vinyl 4 mils thick) was fabricated to extend over the entire surface of the model. The plastic bag was placed on a firm table and the model was anchored by the supports to the table in an inverted position over the plastic bag, Figure 5. By inflating the plastic bag, the model was loaded with a uniform upward pressure while it was held down by the end supports.

Model Loading

The manner in which the model was loaded did not produce the exact equivalent of gravity loading. The applied pressure was normal to the surfaces and did not have the in-plane force components that gravity loading would have produced. However, the plastic bag was convenient, simple, dependable and quickly inflated; and the resulting forces could be resolved in the same manner as gravity loads to determine deflections.

Instrumentation

Pressure Equipment. A schematic diagram of the instrumentation used to measure the applied loads on the model is shown in Figure 7. A small auxiliary plastic bag,

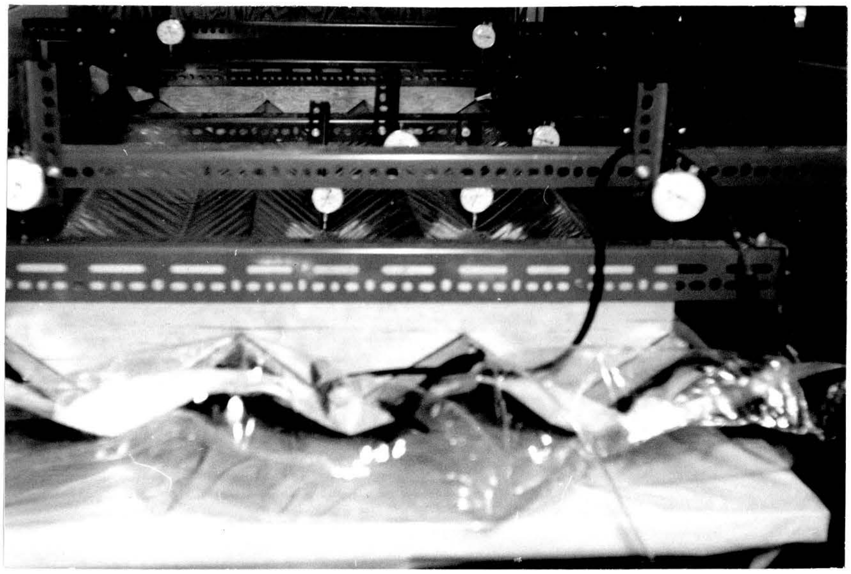


Figure 5. Inverted Model Over Pressure Bag.

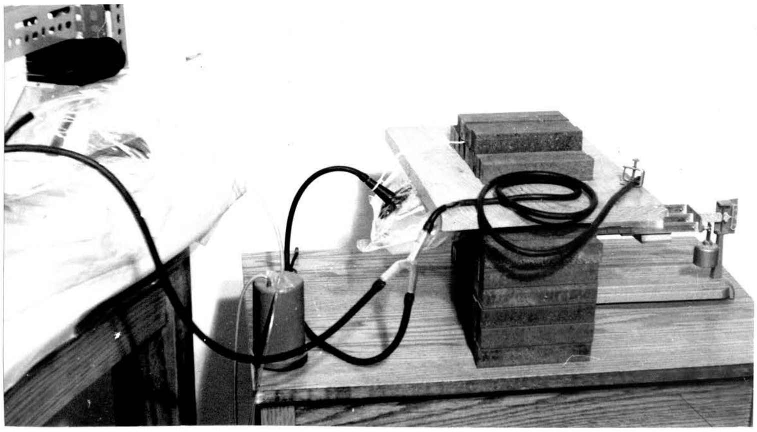


Figure 6. Instrumentation of Pressure Equipment.

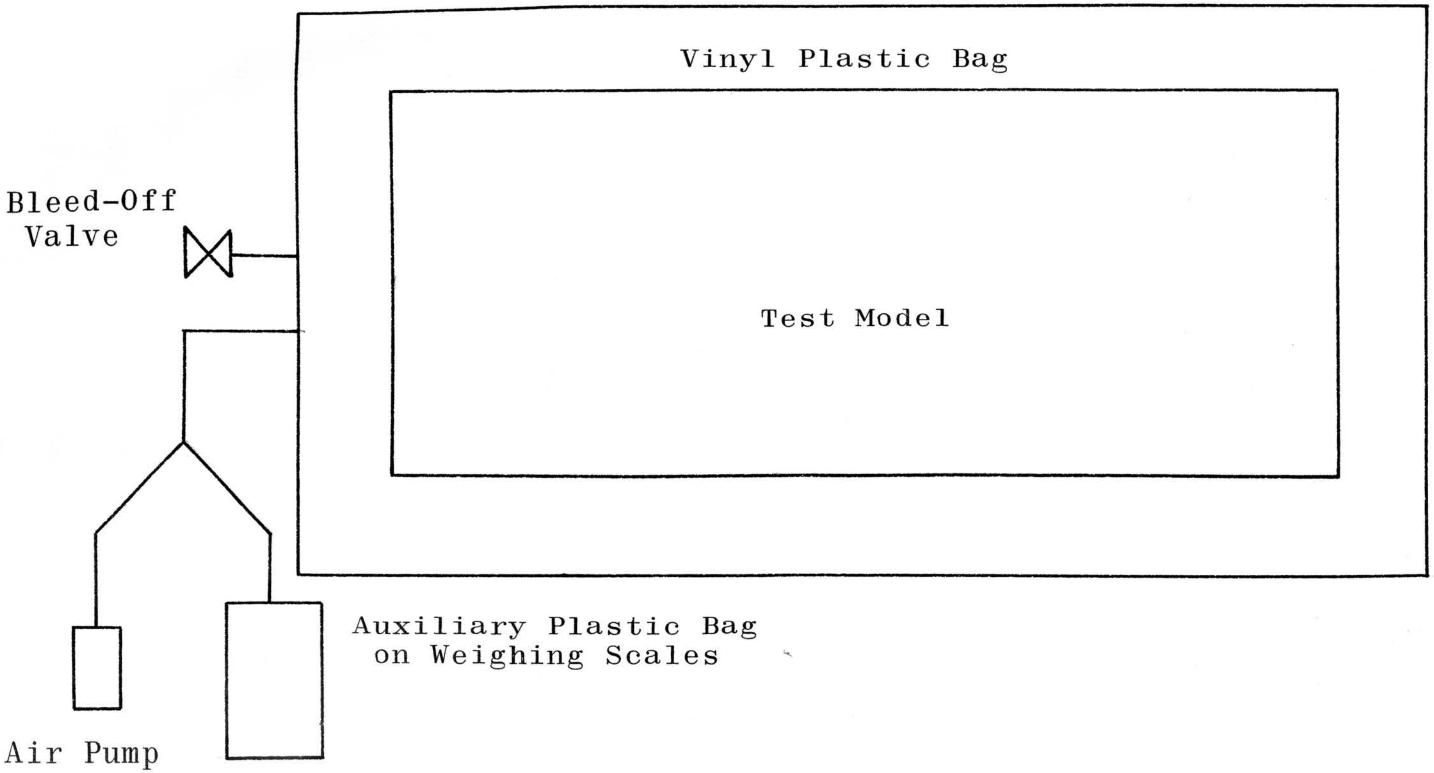


Figure 7. Schematic Diagram of Pressure Measuring Equipment.

connected by a rubber tube to the main bag, was placed between a 1600 gram balance below it and an anchored rigid surface above it. As the main plastic bag was inflated, the auxiliary bag also filled and became tightly confined between the scale pan and the rigid surface. The pressure in the bag was determined by dividing the load reading on the scales by the contact area between the bag and the scales, Figures 6 and 8.

After the initial inflation by pump, the pressure in the plastic bag was supplied by a small electric powered aquarium air pump. The pump ran continuously throughout the testing period and the pressure in the bag was controlled with a bleed-off valve, Figures 6 and 7.

Deflection Gages. Dial gages calibrated to .001 in. were used to measure displacements. Several gages were mounted on an independent isolated frame to measure vertical movements of the model and any movement at the four corners of the model's supports. The displacements at the corners were used to correct the measured deflections and reference them to the end supports.

Four gages were placed along the mid-span center line of the model as shown in Figure 9. After a series of loading cycles were made and the mid-span deflections measured, the gages were relocated at the quarter span. One gage was kept in position at the center line so that the second set of displacements could be referenced to the first set.

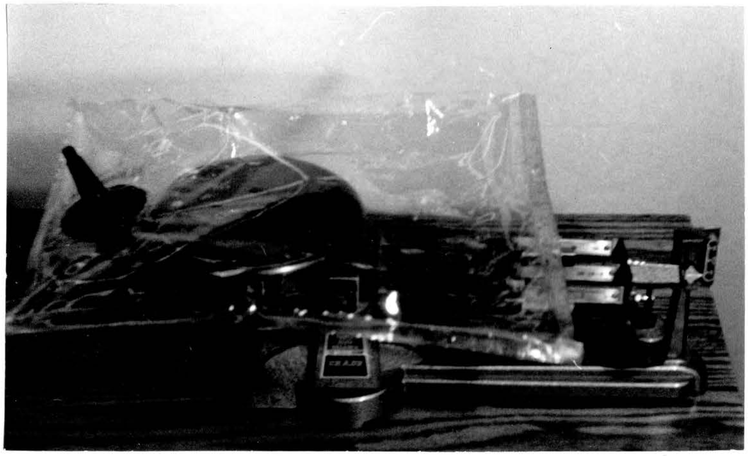


Figure 8. Auxiliary Bag on Scales.

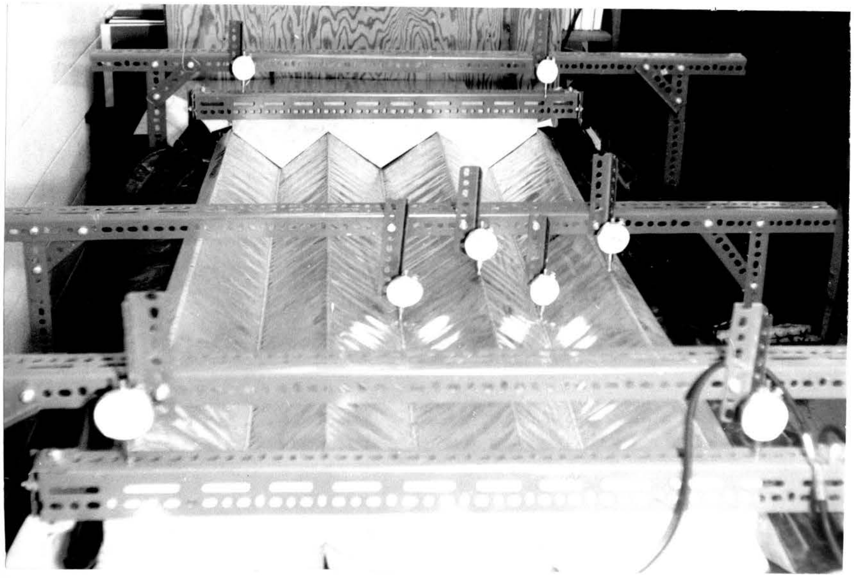


Figure 9. Dial Gage Arrangement.

Test Procedure

An initial setting of the scales was made to give an effective pressure of 3 psf (less dead weight) over the surface of the model. The weight of the auxiliary bag was accounted for in the initial load. The pressure was then increased by 1 psf increments to 10 psf and decreased in like manner to 3 psf again. Dial gage readings were recorded at each level of load. The time required for each cycle of loading was about four hours. Since the pressure instrumentation lacked the sensitivity of the dial gages, extreme assiduity was exercised to obtain an equilibrium condition after applying each load increment.

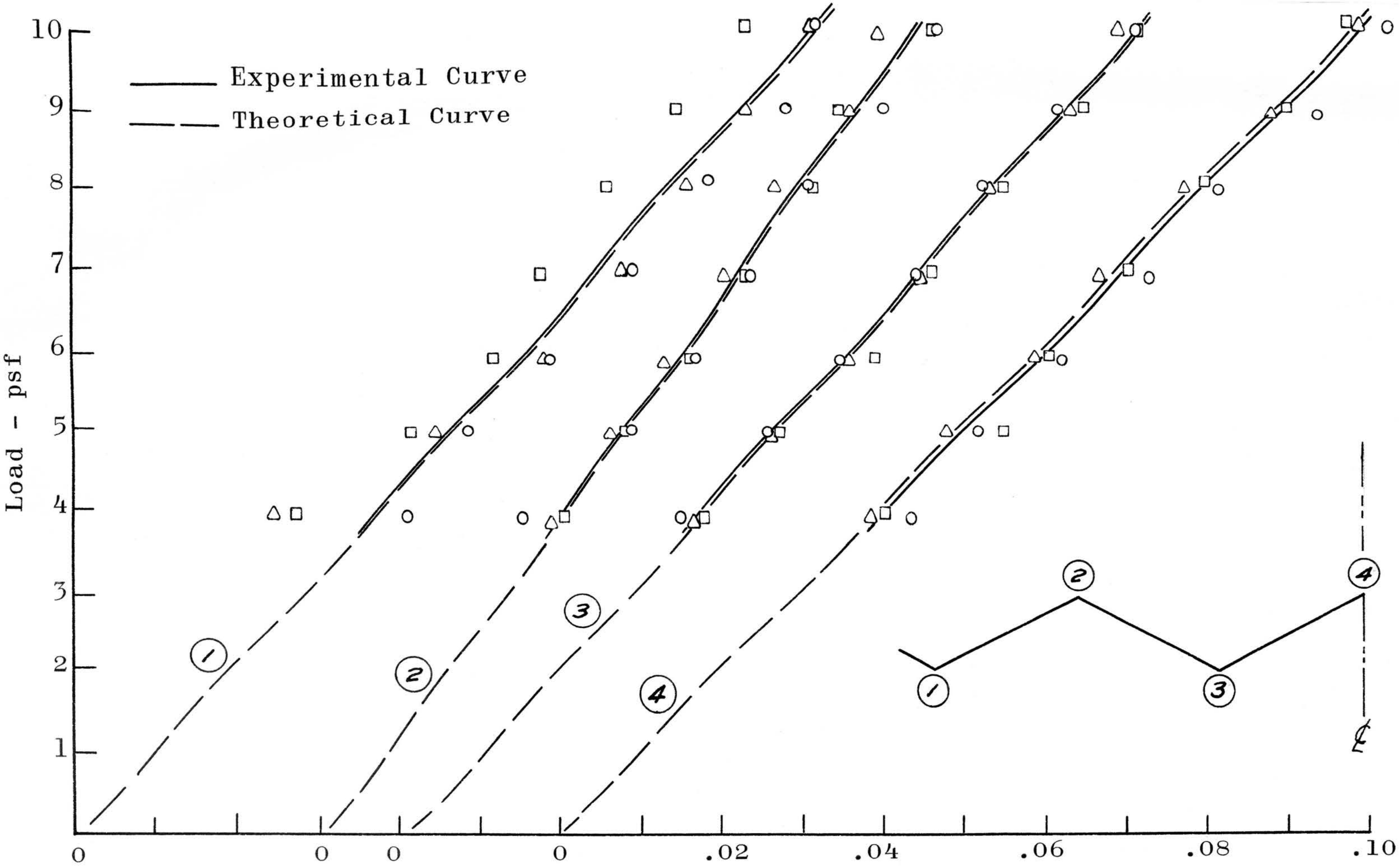
The results of the tests are presented in Section V.

V. DISCUSSION OF TEST RESULTS

The measured deflections of the test model agree closely with the calculated values obtained by the analysis outlined in Section III. The results of these tests, compared with the theoretical analysis, are shown in Figures 10 and 11. Both flexure and shear in the planes of the deep-beam diaphragms were considered in calculating the total deflection of the test model; the contributions of each were about 95% and 5% respectively. Torsion, seam slip and normal longitudinal bending and shear were neglected.

After minor adjustments, the model was loaded and unloaded through a couple of cycles using a four foot sloping water manometer to measure loading pressure. Since it was desirable to measure the pressure in one psf increments, it was found that the manometer lacked the sensitivity and precision necessary to be consistent with the dial gage readings. It became necessary to devise a better scheme for measuring pressure, so a weighing system was invented using an auxiliary plastic bag and another trial run was made.

At this point most of the defects appeared to have been worked out of the system, so three test runs were made and the data recorded for mid-span deflections (Points 1, 2, 3 and 4). The results are plotted in Figure 10. The individual loading cycles can be identified by the different symbols. The next loading cycle was made with the gages



Deflection, in.

Figure 10. Load-Deflection Curves at Mid Span.

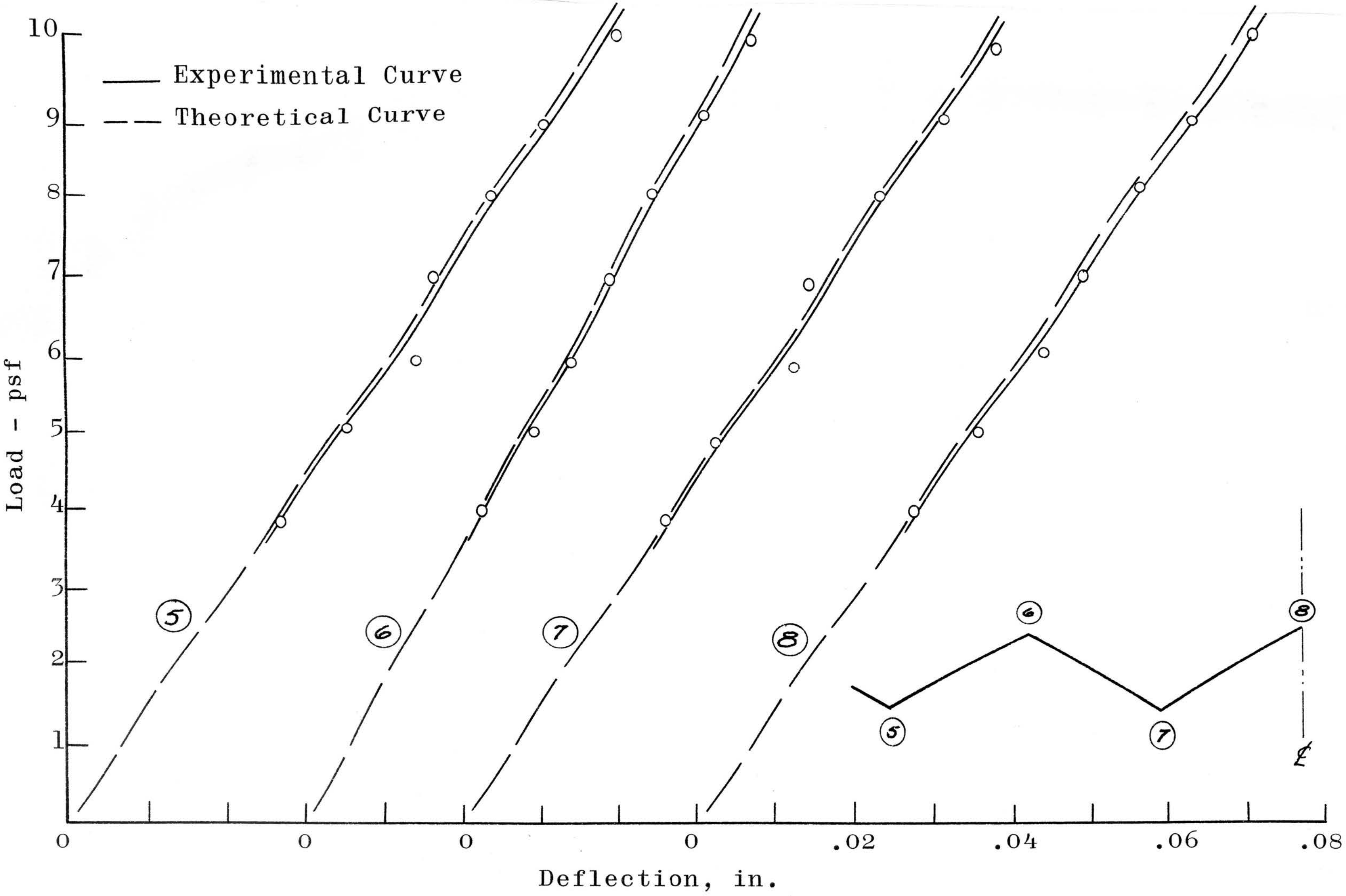


Figure 11. Load-Deflection Curves at Quarter Span.

located at the quarter-span and the data was recorded and plotted in Figure 11 (Points 5, 6, 7 and 8).

In every test cycle, the data for loading and unloading agreed very closely; average values were plotted. A straight line curve was fitted approximately to each set of data and extended to the margin as shown, along with an analytical prediction. The figures show that the theoretical predictions agree very closely with the experimental data. The largest variation occurred at the edge (Fold Line 1 in Figure 10). This variation could be due to the neglect of torsion in the analysis or due to the boundary conditions of the pressure bag, since the pressure bag was only slightly wider than the test model. In subsequent testing programs, if a pressure bag is used, it is suggested that it be made to extend some distance beyond the outer edges of the model.

This experiment was carried out within the elastic range of the materials. The test model was designed to carry a working load of 20 psf under which the longitudinal stress at the center fold line would not exceed 20,000 psi. The structure was intentionally designed to be flexible so that the model would deflect with sensitivity to the lighter loads. Little is known about how the diaphragm material acts under yield loads and less is known about the action of a folded plate structure made of such diaphragm segments. It was expected that the light gage steel foil model would perform in a similar manner to a prototype, but there was no assurance of that before the tests. With concern that several test runs might induce some fatigue, it was decided not to overload the model beyond about 50 percent of its allowable working loads. In addition, the strength and reliability of the welds were not assured before testing. The model was not tested to failure; the applied loads never exceeded 10 psf. The model performed well under about eight repeated cycles of loading with only slight local buckling around the welded points along the fold lines. Surface irregularities were developed during fabrication, probably due to uneven heating from the spot welder. They appeared to increase slightly in magnitude during the first loading cycle, but they did not appear to change during subsequent loading cycles. No quantitative measurements were made. This apparent buckling could contribute to the diaphragm action known as "seam slip" although it would be a small contribution compared to that caused by shearing or tearing of the spot welds. An analytical evaluation of the effect of seam slip along the fold lines on the total deflection would be similar to the evaluation of shear strains when balancing edge forces between plates. However, because the magnitude of these deformations were hardly perceptible after the initial loading cycle, they were not considered in the analysis. All welding points remained intact and no breaks or cracks appeared.

The only unusual reactions observed during testing were occasional sudden "jumps" of the deflection dial during loading as though the apparatus had been jarred slightly. These were accompanied by a sound like the "snap-through" of a flat warped surface. Some of these produced deflection offsets on the plotted curves but apparently did not affect the load-deflection ratios. Actually there was only one offset during the fifth loading cycle that was large enough to show an irregularity; this was removed by adjusting the axis when the data were plotted. The other offsets were very small and no adjustments were made in plotting. This phenomenon can not be quantitatively explained except as representing points of unstable stress concentrations within the system. When subjected to additional stress, there could have been a very rapid relaxing of stress at some other point and a redistribution of stress within the structure, thus causing a sudden change in deflection.

The maximum deflection of the test model occurred along the center "fold line." At mid span, the deflection under the uniform load of 10 psf was .095 inches giving a Δ/L ratio of 1/700.

VI. CONCLUSION

About 40 percent of all steel produced in the United States is light-gage, cold formed steel (11). Most of the design and analysis of light-gage steel structures is based on empirical formulas developed from experimental or in-service testing. During the past 20 years, the use and development of light-gage steel construction in the United States have been accelerated by the issuance of the "Light Gage Cold-Formed Steel Design Manual." (3) This manual is based primarily on a long-time research project sponsored by AISI at Cornell University (1). Much research is still needed in order to fully understand the action of light-gage steel structures subjected to various loading conditions. Load-deflection testing of light-gage folded plate structures is only part of the total research needed in this area. Nevertheless, it provides a very significant contribution to the establishment of a fuller understanding of light-gage steel structures.

The use of small-scale test models fabricated from light-gage steel foil offers a reasonably convenient method for studying folded plate structures, although the fabrication of the model is tedious and exacting. Variations in shape and form of structure might also be tested in the same manner as the model tested for this thesis.

The test model was a V-shaped folded plate structure made of light gage steel cellular panels. It was approximately one-twentieth scale model size and tested under uniform pressure loading to determine stiffness and compare deflections with analytical predictions.

The results of the tests agreed closely with the calculated values of the theoretical analyses. Both flexure and shear in the planes of the deep-beam diaphragms were considered in calculating the total deflection of the test model; the contributions of each were about 95 per cent and 5 per cent, respectively. Torsion, seam slip and normal longitudinal bending and shear were neglected.

The tests were carried out within the elastic range with loads up to 50 per cent of design working loads. The test model appeared to perform in a similar manner to a prototype; there was no sign of fatigue and no evidence of weld failure. The model performed well under about eight repeated cycles of loading with only slight local buckling around the welded points along the fold lines. Surface irregularities were developed during fabrication, probably due to uneven heating from the spot welder. They appeared to increase slightly in magnitude during the first loading cycle, but they did not appear to change during subsequent loading cycles. No quantitative measurements were made.

A few sudden jumps of the deflection dials accompanied by sounds like the snap through of a flat warped surface were noticed during testing, but apparently had no effect on the results. The maximum deflection of the test model occurred along the center "folded line." At mid span, the deflection under the uniform load of 10 psf was .095 inches giving a Δ/L ratio of 1/700.

VII. BIBLIOGRAPHY

1. AISI Committee on Building Research and Technology, "Design of Light Gage Steel Diaphragms," First Edition, 1967.

2. AISI Committee on Building Technology, "Sectional Properties of Corrugated Steel Sheets," 1964.

3. American Iron and Steel Institute, Light Gage Cold-Formed Steel Design Manual, Third Edition, New York, 1962.

4. ASCE Manual No. 31, "Design of Cylindrical Concrete Shell Roofs," October, 1951.

5. Craemer, H., "Design of Prismatic Shells," ACI Journal, February, 1953, Proc. V. 49, pp. 549-563.

6. Craemer, H., "Theorie der Faltwerke," Beton und Eisen, V. 29, 1930.

7. Ehlers, G., "Ein neues Konstruktion prinzip," Bauingenieur, V. 9, 1930.

8. Ketchum, M. S., "Design and Construction of a Folded Plate Roof Structure," ACI Journal, Feb., 1955, Proc. V. 51, pp. 449-455.

9. Kirkland, W. G., "Shell Structures of Light Gage Steel Roof Panels," Southern Building Magazine, March, 1963.

10. Luttrell, L. D., "Strength and Behavior of Light-Gage Steel Shear Diaphragms," Cornell Engineering Research Bulletin, No. 67-1, July, 1967.

11. Luttrell, L. D., Lecture Notes, AISI Conference at West Virginia University, 1966.

12. Nilson, A. H., "Folded Plate Structures of Light Gage Steel," Journal of the Structural Division, ASCE, V. 87, No. ST 7, Proc. Paper 2970, October, 1961, pp. 215-237.

13. Parme, A., "Direct Solution of Folded Plate Roofs," PCA Bulletin, No. 3, 1960.

14. Pion, R., "Light-Gage Steel Folded Plates," Interim Report, Structural Conference, West Virginia University, 1966.

15. Progress Report of the Committee on Research of the Structural Division, "Survey of Current Structural Research," Journal of the Structural Division, ASCE, V. 91, No. ST 1, Proc. Paper 4233, February, 1965, pp. 28 and 46.

16. Report of the Task Committee on Folded Plate Construction, Committee on Masonry and Reinforced Concrete, "Phase I Report on Folded Plate Construction," Journal of the Structural Division, ASCE, V. 89, No. ST 6, Proc. Paper 3741, December, 1963, pp. 365-406.

17. Report by the Committee on Research, Structural Division, "Research Needs in Structural Engineering for the Decade 1966-1975," Journal of the Structural Division, ASCE, V. 92, No. ST 5, Proc. Paper 4946, October, 1966, pp. 287-311.

18. Scordelis, A. C., Croy, E. L., Stubbs, I. R., "Experimental and Analytical Study of a Folded Plate," Journal of the Structural Division, ASCE, V. 87, No. ST 8, Proc. Paper 3023, December, 1961, pp. 139-159.

19. Simpson, H., "Design of Folded Plate Roofs," Journal of the Structural Division, ASCE, V. 84, No. ST 1, Proc. Paper 1508, January, 1958, pp. 1-21.

20. Whitney, C. S., Anderson, B. G., Birnhaum, H., "Reinforced Concrete Folded Plate Construction," Journal of the Structural Division, ASCE, Vol. 85, No. ST 8, Proc. Paper 2219, October, 1959, pp. 15-43.

21. Winter, G. and Pei, M., "Hipped Plate Construction," ACI Journal, January, 1947, Proc. Vol. 43, pp. 505-531.

22. Yu, Wei-Wen, "Design of Light Gage Cold-Formed Steel Structures," Engineering Experiment Station, West Virginia University, 1965.

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LIGHT GAGE STEEL FOLDED PLATES

by

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Abstract

A light gage steel folded plate model structure was fabricated and tested under a uniform pressure to determine the relative stiffness of this type of structure. Deflections at mid and quarter spans were measured and compared with values determined by a rational method of analysis.

A different approach to the analysis was introduced in which values of equivalent moment of inertia were determined for each plate cross-section so that compatability along adjoining longitudinal edges would be assured. The experimental and theoretical results were in good agreement.