Shear Strength of Deep Corrugated Steel Panels

Chingmiin Chern

James L. Jorgenson

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by

Chingmiin Chern[1] and James L. Jorgenson[2]

1. INTRODUCTION

It has been common practice for light gage corrugated steel panels to serve as both the skin covering the structure and to serve as its primary bending structural frame. A new consideration has been added and that is to use the steel panel to also carry in-plane shear forces. These forces can develop from wind load or grain load, or anything that will place a shear force in the plane of the steel panel. The purpose of this report is to evaluate the in-plane shear strength of the WEDG-COR panels.

There are two types of shear failures. A failure can result from elastic buckling in which buckled waves will appear in a diagonal pattern over the entire diaphragm. The other failure is a fastener failure which is the result of shearing or crippling of diaphragm material at the fastener locations.

A series of shear strength tests were performed on shear diaphragms of the same shape but different thicknesses. This study was to gain information on the ultimate shear

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1. Assistant Professor of Civil Engineering, North Dakota State University, Fargo, North Dakota 58102
2. Chairman and Professor of Civil Engineering, North Dakota State University, Fargo, North Dakota 58102

strength of the panel, variation of in-plane shear deflection with load, residual deflection, strength of bolts and fasteners and the slip between the panels.

A.H. Nilson[8*] laid the foundation of work on shear diaphragms in the United States. In 1955 the first Cornell University test of full scale diaphragm installations was initiated at Thurston Testing Laboratory. It was observed from test results that, (a) effect of deepening the panel section is that distortion of the panel webs near panel ends is increased, (b) depth increases eccentricity and permits relative movement between the top and bottom surface of the panel but can be overcome by the use of some shear transfer device such as closure angle, (c) rafter-spanning or purlin spanning does not affect the shear strength. Nilson recommended that shear diaphragms constructed of light-gage steel panels, with proper welding and design can resist large horizontal loads. The need for horizontal bracing system in buildings can be eliminated.

L.D. Luttrell[5,6] extended Nilson's work and investigated the effects of panel configuration, material properties, span length and, particularly, the method of fastening of diaphragms. The work was summarized as follows: (a) Frame flexibility has moderate influence on the ultimate strength of diaphragm. (b) Strength increases when number of side

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*Reference numbers, see page 414

lap fasteners are increased. (c) Pulsating load results in strength reduction. (d) Reversal loading has little effect on the strength of diaphragms if fastening arrangement is good. (e) Panel length has little effect on the shear strength but can have a strong effect on shear stiffness. Luttrell developed a semi-emirical formula for estimating the shear stiffness of standard corrugated panels.

John T. Eastley and D.E. McFarland[4] attempted to gain information concerning post-buckling behavior of shear diaphragms. They tried to explain it, with the help of large deflection theory and the Ritz Method, based on the assumption that a corrugated diaphragm could be analyzed as a thin orthotropic plate of uniform thickness with material constant of one repeated cross section of the corrugated panel. The comparison between theoretical and experimental results showed close agreement.

All the above information has been useful in selecting the method of test, however, the panel under consideration is uniquely different from all others tested which necessitates this testing program.

2. TESTING PROGRAM

2.1 Introduction

The testing program consisted of six tests on light gage corrugated diaphragms loaded by in-plane shear forces. There are three panels in a diaphragm and each panel is 2 feet and 3 inches wide in the horizontal projection. The panels were fastened with each other by using nuts and bolts of 5/16 inch in diameter with 0.79 inch washers at a pitch of 9-5/16 inches. An impact wrench was used to tighten the bolts. A strip of caulking compound was placed between the panels at the lap joint to duplicate that which occurs in actual practice. The caulking strip is used to prevent moisture from moving through the seams.

The dimensions of the shear diaphragms are listed in Table 1. The testing procedure and testing techniques will be described in detail in the following sections.

2.2 Test Set-up

To perform the tests, a specimen frame was assembled as shown in Fig. 1. The specimen frame members were channel sections C5x9 and were fastened together at four corners with washers and lubricated bolts to obtain shear load in the diaphragms. The length of the specimen frame was adjustable to accomodate for different diaphragms. The

TABLE 1 DIMENSIONS AND MODE OF FAILURE OF SHEAR DIAPHRAGMS

TEST DESIGNATION	GAGE NO.	THICKNESS (inches)	DIMENSIONS	MODE OF FAILURE
SF-1-1	20	.036	12'-4"x6'-9"	Pivot Bolt Failure
SF-1-2	20	.036	12'-4"x6'-9"	Frame Fixed-end Welding
SF-1-3	20	.036	12'-4"x6'-9"	Frame Fixed-end Welding
SF-2	24	.0239	13'-3"x6'-9"	Over-all Buckling
SF-3	18	.048	11'-8½"x6'-9"	Frame Fixed-end Welding
SF-4	22	.0299	13'-3"x6'-9"	Over-all Buckling

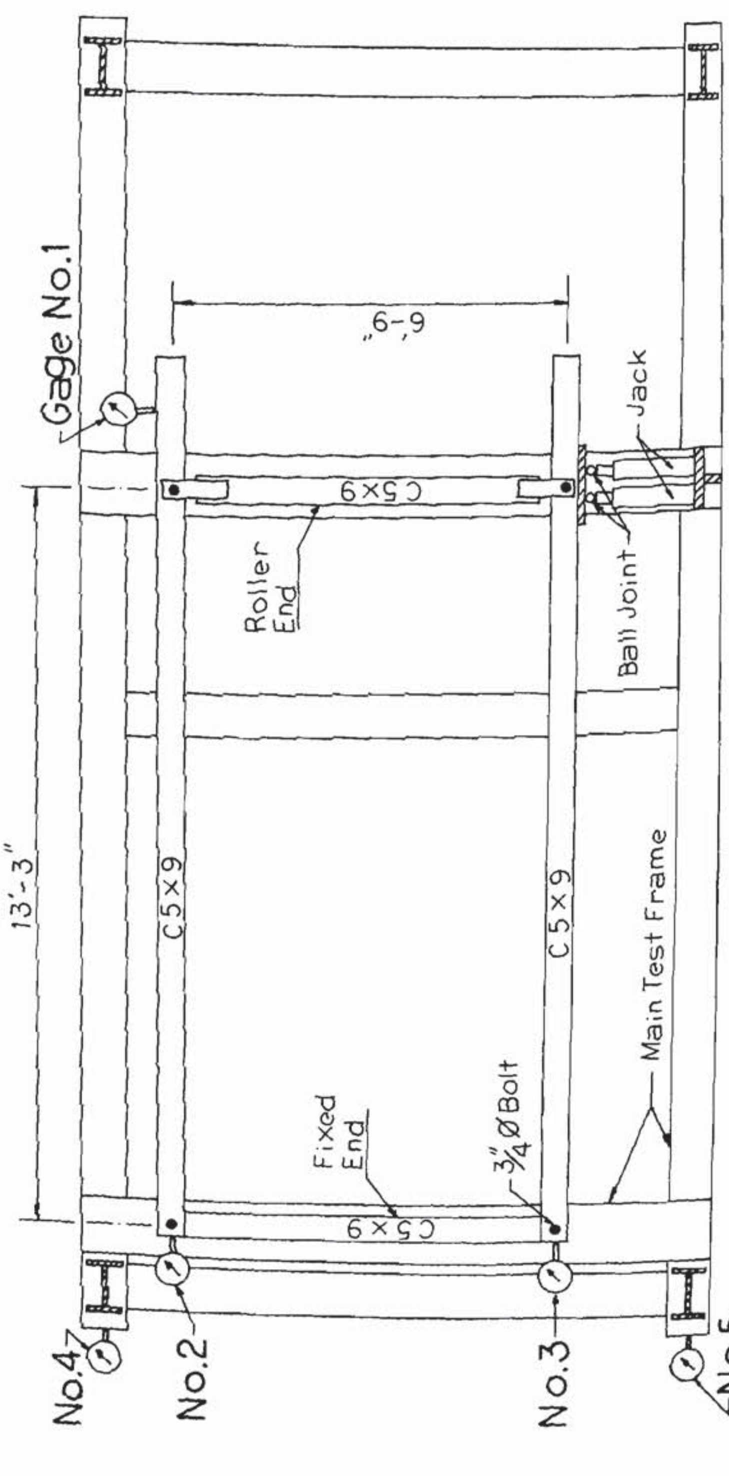

FIG. 1 SPECIMEN FRAME AND IN-PLANE DEFLECTION MEASUREMENTS

individual panels were fastened to each other and to the specimen frame with 5/16 inch bolts and washers at a pitch of 9-5/16 inches. One end of the specimen frame was fixed, while the other end on the applied loading side was placed on rollers to allow the frame to move freely. The loading was applied from a set of hydraulic jacks to the specimen frame at its roller end.

In order to transfer shear load from the specimen frame to the diaphragm, a special type of diaphragm end connections consisting of base plates and end pans* was used, as shown in Fig. 5.

2.3 Instrumentation

2.3.1 In-Plane Deflection

To measure in-plane shear deflections of the diaphragm under loads, a set of five Ames dial gages with graduations of one-thousandth of an inch was used, shown in Fig. 1. Dial gage No. 1 was used to measure the in-plane deflection of the diaphragm in the line of applied load. Gage Nos. 2 and 3 were to check the distortion of the specimen frame, introduced by the stresses produced and by the frame arm movement. Gage Nos. 4 and 5 were used to detect possible errors caused by the distortion of the main test frame on which the specimen frame was attached to.

*Base plates and pans were supplied by WEDG-COR, Inc., Jamestown, North Dakota

2.3.2 Slip Measurement

The slip between the adjacent panels of shear diaphragms was measured by a set of six dial gages mounted on the top side of the diaphragm on the joints of two panels. The measuring set-up is shown in Fig. 2. The dial gages were mounted on the edge of one panel, while wooden block were glued on the edge of the adjacent panel.

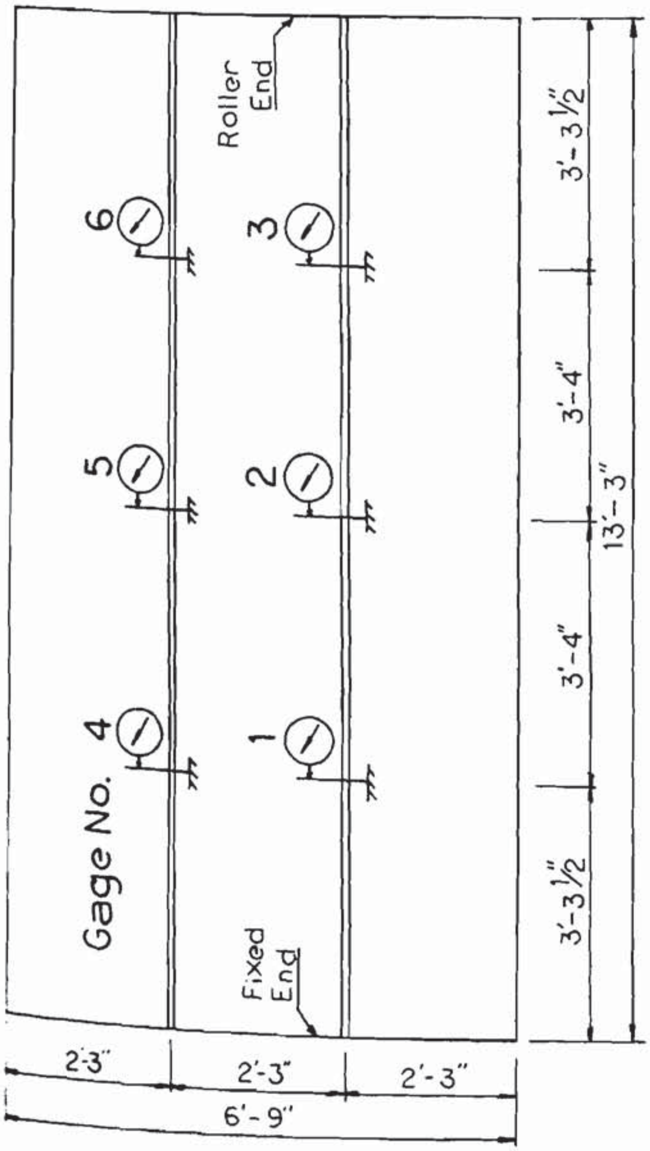

FIG. 2 DIAL GAGE LOCATIONS FOR SLIP MEASUREMENTS

3. TESTING PROCEDURE AND RESULTS

3.1 Introduction

This chapter deals with different techniques used in loading procedures to study the behavior of shear diaphragms during the course of testing and the interpretation of test results. Two factors concerning the deformations of the specimen frame and the main test frame were applied to adjust the test results. They are as follows:

(a) Frame arms correction: It was noted during the testing that the frame arms of the specimen frame as well as the main test frame were moved under loading. The effect of this movement was considered in correcting the dial gage reading for the in-plane deflections.

(b) Frame stresses correction: When an axial load is applied to the frame members of the specimen frame, stresses are produced in it which cause a change in length. This correction was applied to the readings of dial gages attached to the diaphragm to measure the slip. Elongation in the specimen frame arms was calculated, considering the axial load produced at that point due to shear load.

After the above two adjustments on the dial gage readings the results were plotted, respectively, for the relationships of the applied shear load with respect to in-plane deflection, seam slip, shearing strain and residual deflection of the diaphragms.

3.2 Procedure and Results

Two types of loading procedures were used during the course of testing: (a) Procedure No. 1--All the dial gage readings were recorded at zero load. Then, the loading was gradually increased to the next loading value and a set of all readings was noted. Loading was increased at a certain increment until failure occurred. The main objective of this type of loading system was to find out the ultimate shear strength of the diaphragm. (b) Procedure No. 2--The procedure of this type of loading was that the load was applied from zero to a certain value and then unloaded to zero. The readings on all the dial gages were noted at every loading cycle. The same procedure was repeated for the next loading value until the diaphragm failed. This loading technique was used to measure the residual deflection under loads.

3.2.1 Tests SF-1-1, SF-1-2, SF-1-3 (20 Gage)

The loading procedure used in this test was of type No. 1 and the loading process was shown in Fig. 3.

A ripple formation was noticed on the panel webs of the diaphragm at a load of 39.2 lbs/in. The ripples were getting deeper and deeper with the increase of loads and disappeared while unloading at a load of 32.4 lbs/in.

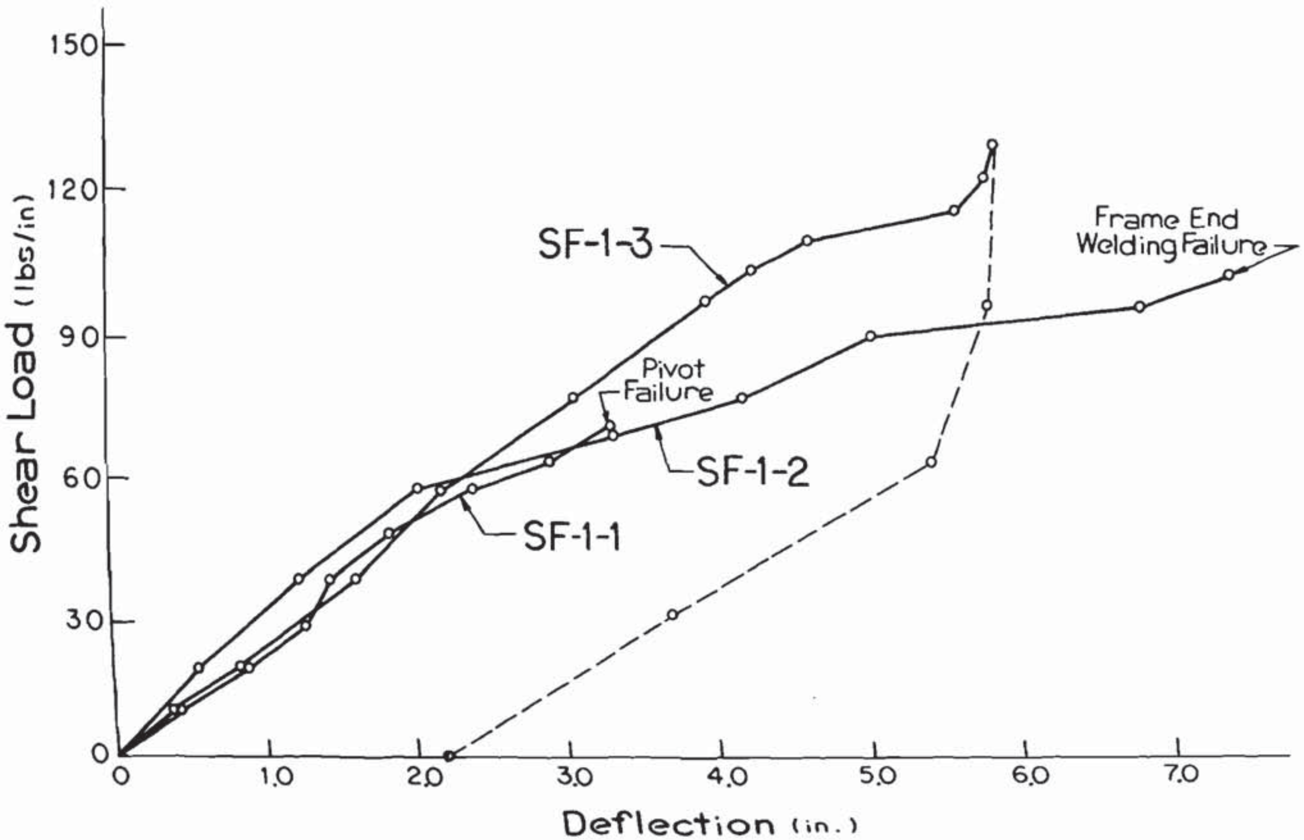

FIG. 3 SHEAR LOAD VS. DEFLECTION CURVES FOR SHEAR TEST SF-1-1, SF-1-2 AND SF-1-3

One of the pivot bolts on the fixed end side of the specimen frame was sheared off at 78.4 lbs/in. The experiment was terminated. The performance curve of this test is denoted by SF-1-1 in Fig. 3.

After replacing the pivot bolts, the experiment again started. The loading increments used is shown in Fig. 3 for test SF-1-2. The experiment was terminated due to welding failure at the connection of the specimen frame to the main test frame at the fixed-end side. The highest applied shear load was 103.7 lbs/in. There was no significant difference in behavior of the diaphragm than it was before.

The loading diagram for test SF-1-3 is also shown in Fig. 3. Loading again had to be terminated at 129.6 lbs/in due to welding failure at the fixed-end connection. In this experiment, the permanent in-plane deflection was noted after unloading to zero. The following items should be noted in interpreting these test results: (a) Due to weldings failure at the fixed-end connection, it was impossible in these three tests to attain the failure load of the diaphragm. (b) Variation of in-plane deflection due to applied loads is shown in Fig. 3 for tests SF-1-1, SF-1-2 and SF-1-3. Load-deflection curves are almost linear for all tests up to 60.0 lbs/in of applied load. The curves for tests SF-1-2 and SF-1-3 show similarity in behavior. The ripples on the webs started forming at the load of 40.0 lbs/in for this type of diaphragms. (c) A permanent in-plane deflection of about 2.2 inches was observed after it was loaded to 129.6 lbs/in and then unloaded to zero.

3.2.2 Test SF-2 (24 Gage)

The loading procedure used in this test was a combination of the type Nos. 1 and 2. The loading pattern is shown in Fig. 4. The panel which is adjacent to the specimen frame at the hydraulic jack side, buckled at the load of 51.8 lbs/in. When the load was reduced, the panel returned to its original shape. The diaphragm was reloaded and it buckled again at the same load. The diaphragm after failure load is shown in Fig. 5. Longitudinal profiles of the buckled shape is shown in Fig. 6. The following items were noted during the course of testings: (a) The failure load of the diaphragm is 51.8 lbs/in. (5.7 kips jack load). (b) In-plane load-deflection behavior is shown in Fig. 4. The ripples started forming at 25.9 lbs/in. (c) The loading system was such that residual deflections resulting from each loading cycle could be recorded. For every 14.0 lbs/in of shear load, an average residual deflection of about 0.35 inch was observed. After buckling, the diaphragm was unloaded to zero and again reloaded to failure, the buckling loads of the diaphragm are about the same. It was interesting to note that after unloading to zero, the residual deflection was about the same as it was before.

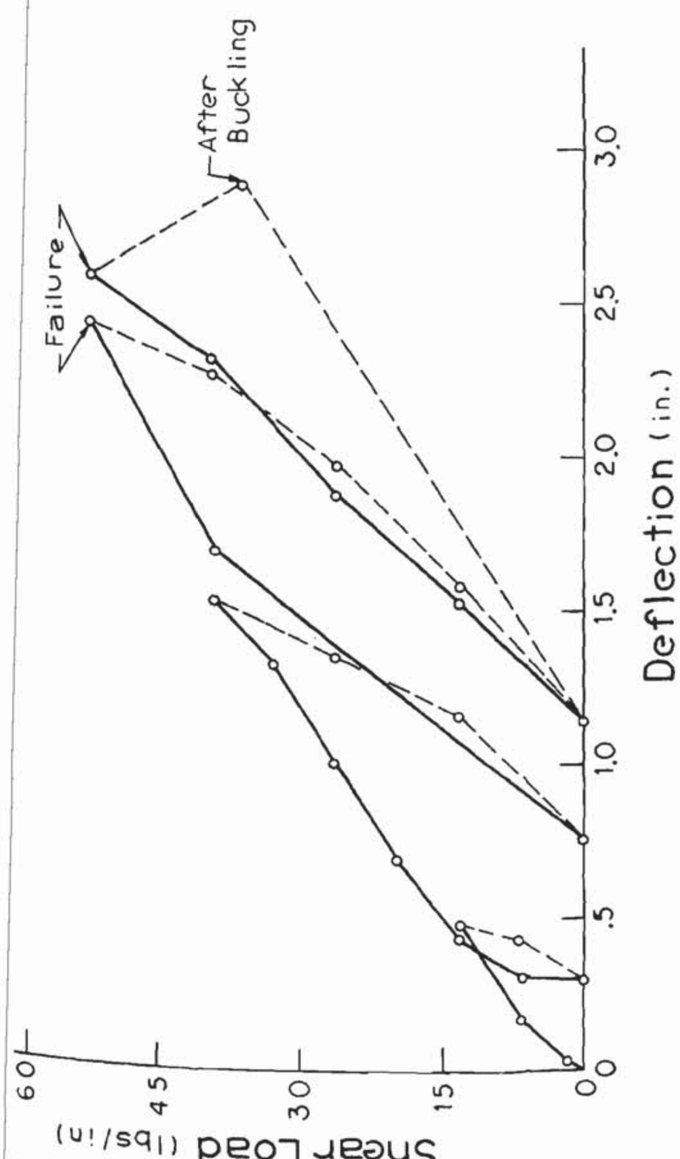

FIG. 4 LOAD VS. DEFLECTION CURVE OF TEST SF-2

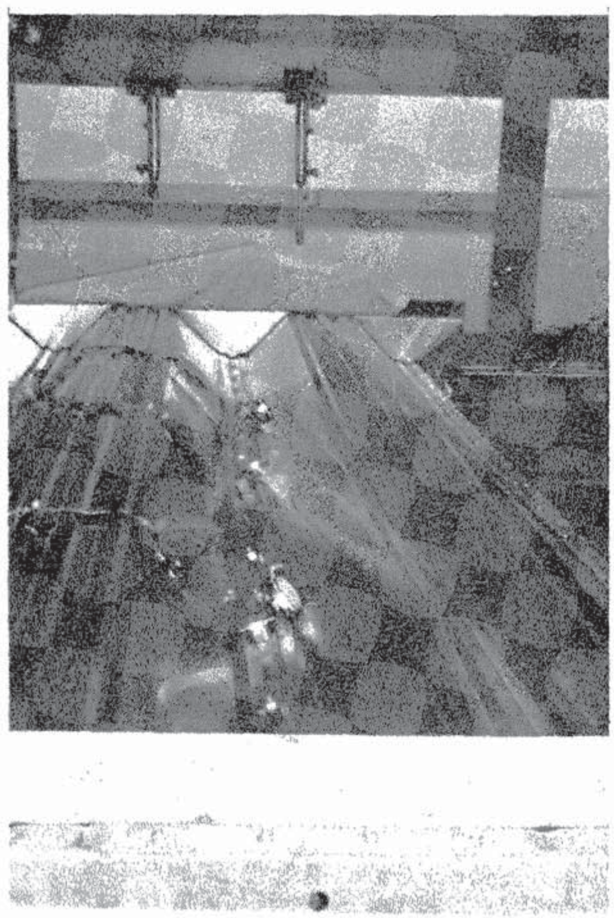

FIG. 5 SHEAR DIAPHRAGM SF-2 AFTER FAILURE LOAD

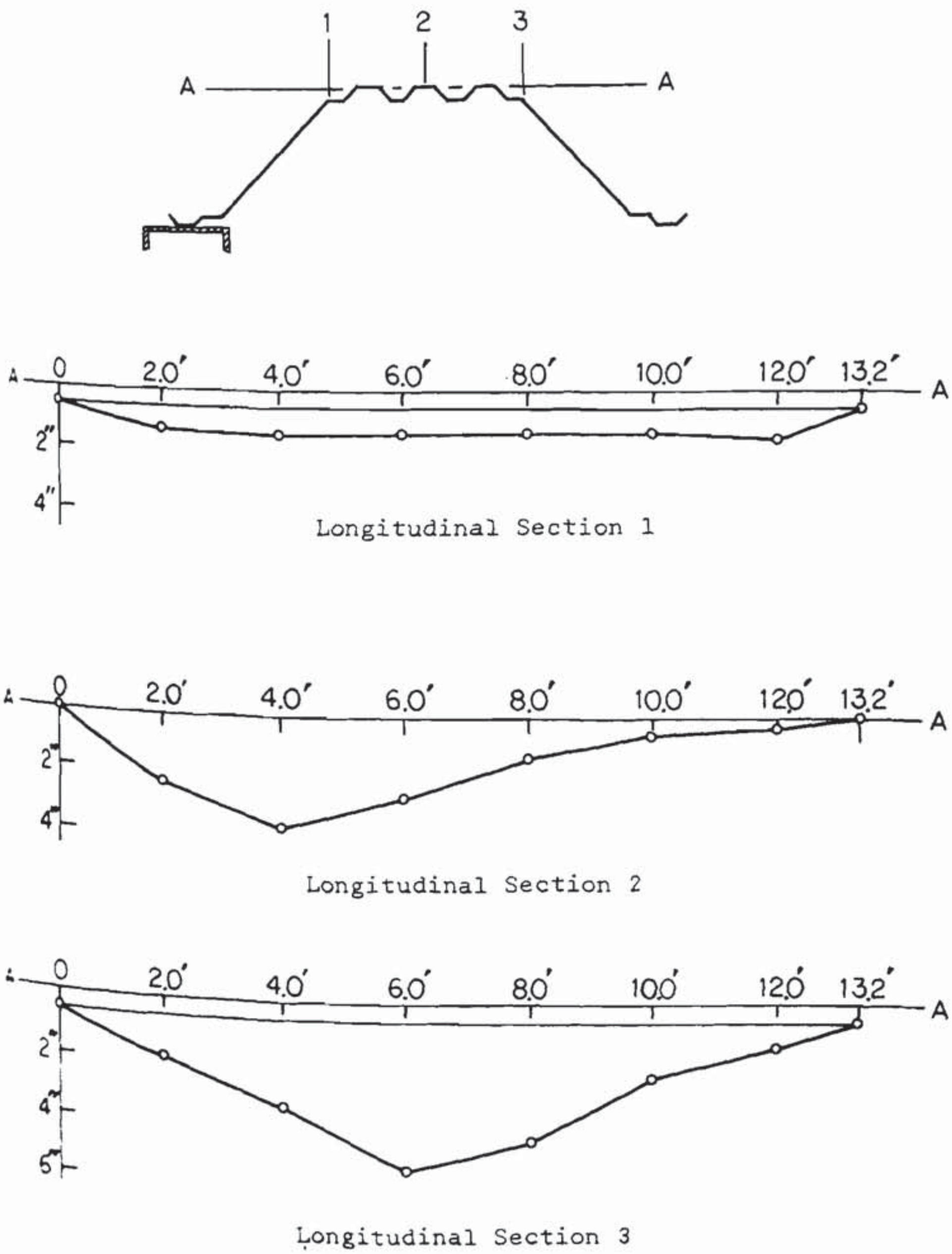

FIG. 6 PROFILES OF BUCKLED SHAPE OF TEST SF-2

(d) Load-slip results are shown in Fig. 7. A considerable amount of slip occurred at the location of dial gage Nos. 4,5 and 6 as these were compared to the slip at gage Nos. 1,2 and 3 (dial gage locations are shown in Fig. 2). Significant readings of slip at gage Nos. 4,5 and 6 were noted at the load of 25.9 lbs/in while the slip at gage Nos. 1,2 and 3 started at the load of 45.4 lbs/in. (e) Shearing strains obtained from slip and from in-plane deflection are shown in Fig. 8. Both curves show similarity in behavior. The average shearing strain per unit shear load (lb/in) is 0.000126.

3.2.3 Test SF-3 (18 Gage)

Type No. 2 loading procedure was used up to the load of 90.7 lbs/in and type No. 1 loading procedure afterward until the welding failure at the fixed-end connection occurred at 111.2 lbs/in. The loading curve is shown in Fig. 9. The results were obtained as follows: (a) Due to welding failure at the frame fixed-end connection, no failure load of the diaphragm was obtained. (b) Load-deflection relationship is plotted in Fig. 9. It is observed that the deflection is increasing at a steady rate and that the performance curve is linear. The ripples on the webs of the panels started appearing at the load of 78.4 lbs/in. (c) Shear load-slip behaviors are shown in Fig. 10. Slip started occurring at all dial

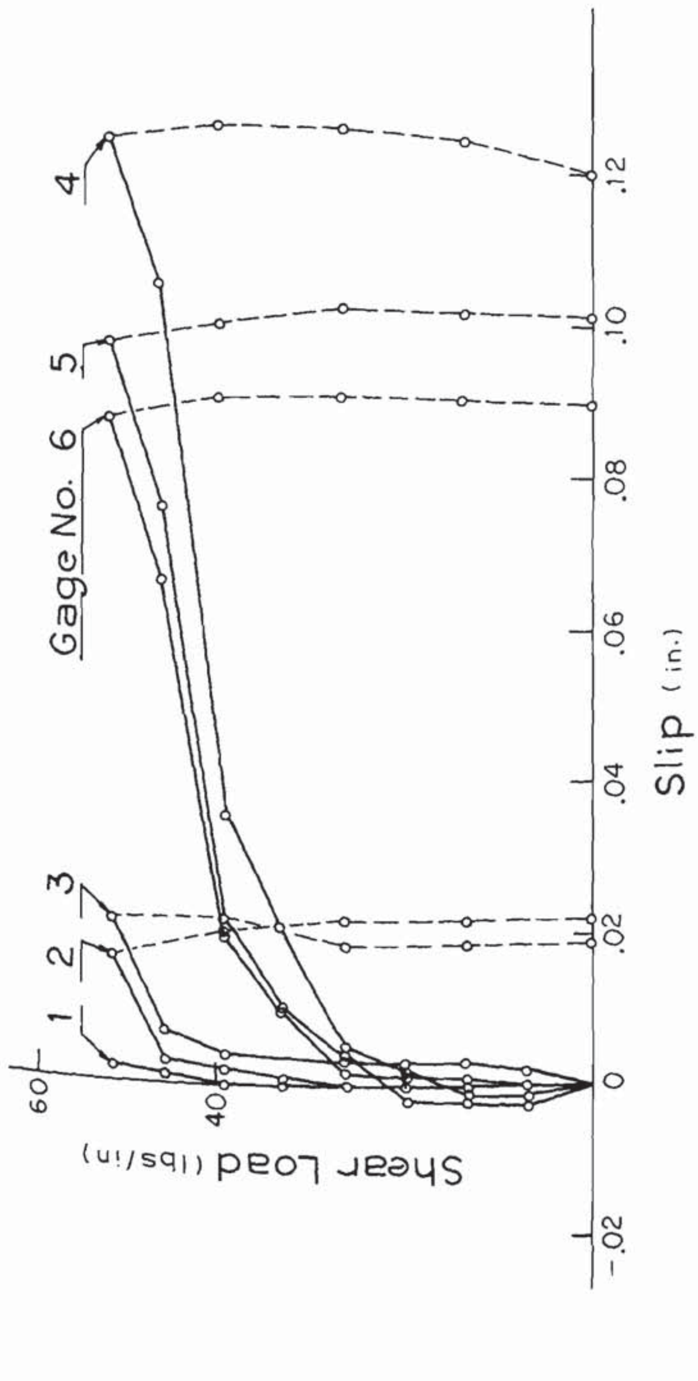

FIG. 7 SHEAR LOAD VS. SLIP FOR TEST SF-2

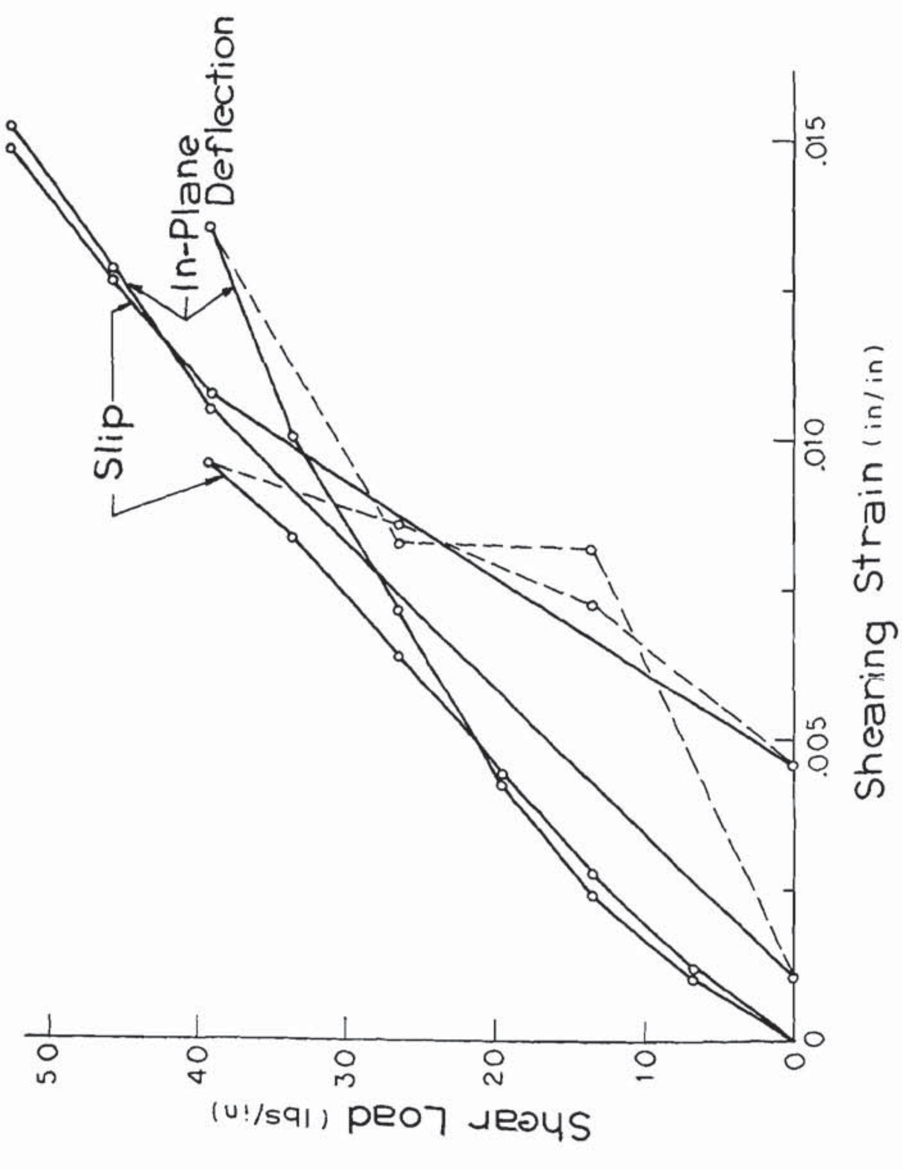

FIG. 8 SHEAR LOAD VS. SHEARING STRAIN CURVE FOR TEST SF-2

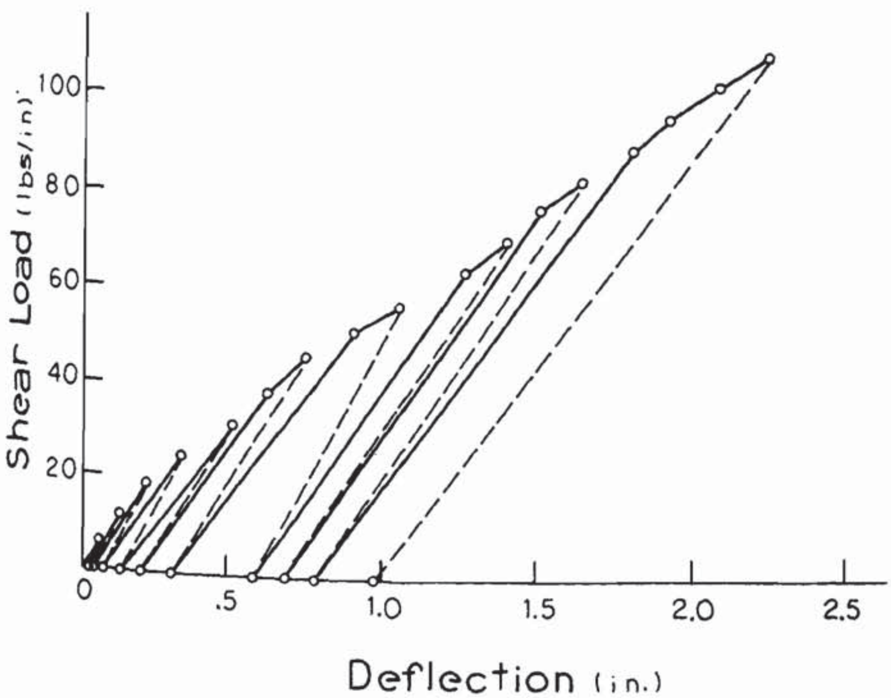

FIG. 9 SHEAR LOAD VS. DEFLECTION CURVE FOR TEST SF-3

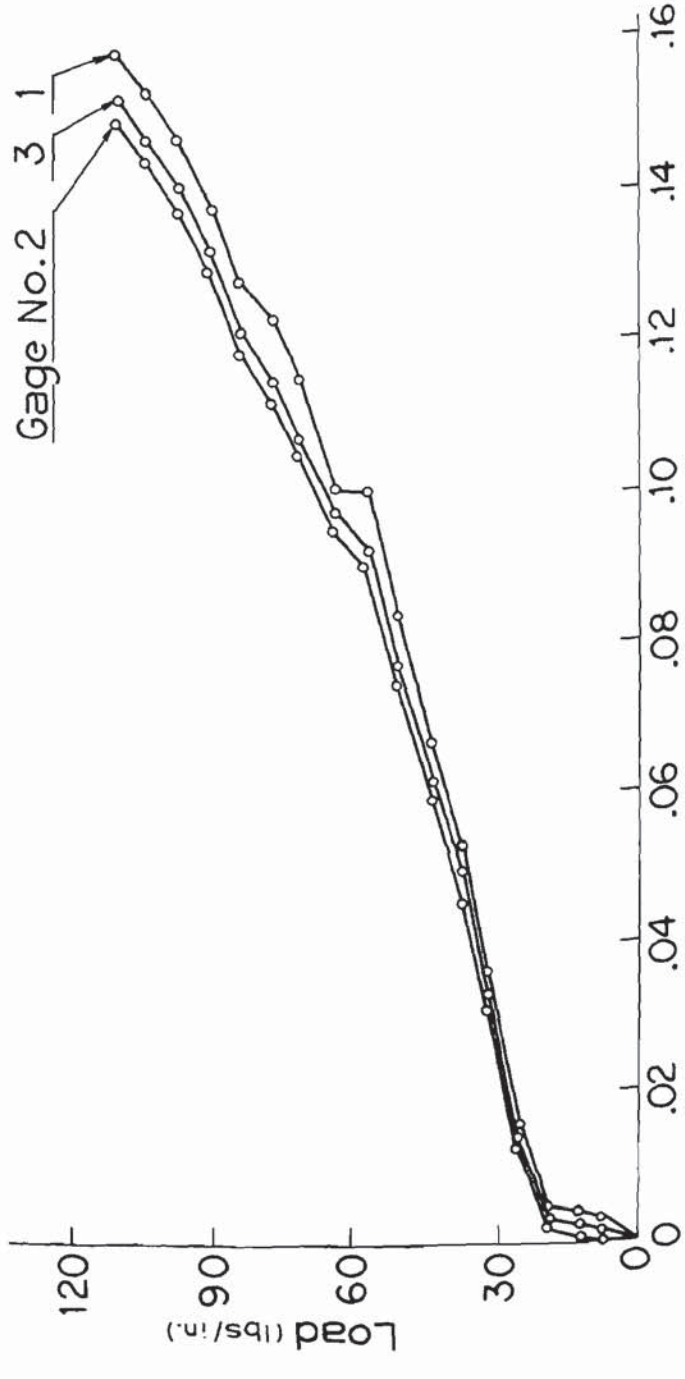

FIG. 10 SHEAR LOAD VS. SLIP (TOP GAGES) CURVE FOR TEST SF-3

gage locations at the load of 19.6 lbs/in and increased at a very fast rate up to 58.8 lbs/in of loading. Slip increase rate is less between loads of 58.8 and 78.4 lbs/in, but the slip increment is about constant. (d) Residual deflection was increased at a constant rate for every loading increment. A maximum deflection of 0.98 inch (Fig. 9) was observed in the diaphragm after unloading from the load of 111.2 lbs/in. (e) Relationships of shearing strain calculated from in-plane deflection and slip are shown in Fig. 11. Both curves are identical. The average shearing strain per unit load (lb/in) is 0.000424.

3.2.4 Test SF-4 (22 Gage)

Loading procedure for test SF-4 was similar to that for test SF-3. The load-deflection behaviors of these two tests were about the same. The diaphragm buckled at a load of 97.2 lbs/in. The test results are as follows: (a) Ultimate strength of the diaphragm is 97.2 lbs/in (10.6 kips jack load). (b) Load-deflection curve for test SF-4 is almost linear with respect to shear load as shown in Fig. 12. The ripples started forming on the panel webs of the diaphragm after a load of 51.8 lbs/in. (c) It is seen from Fig. 12 that the residual deflection of the diaphragm increases with the increases in shear load. (d) Figure 14 shows the shear load-slip relationship at one of the lap joints of the diaphragm. (e) Shearing strains obtained from in-plane

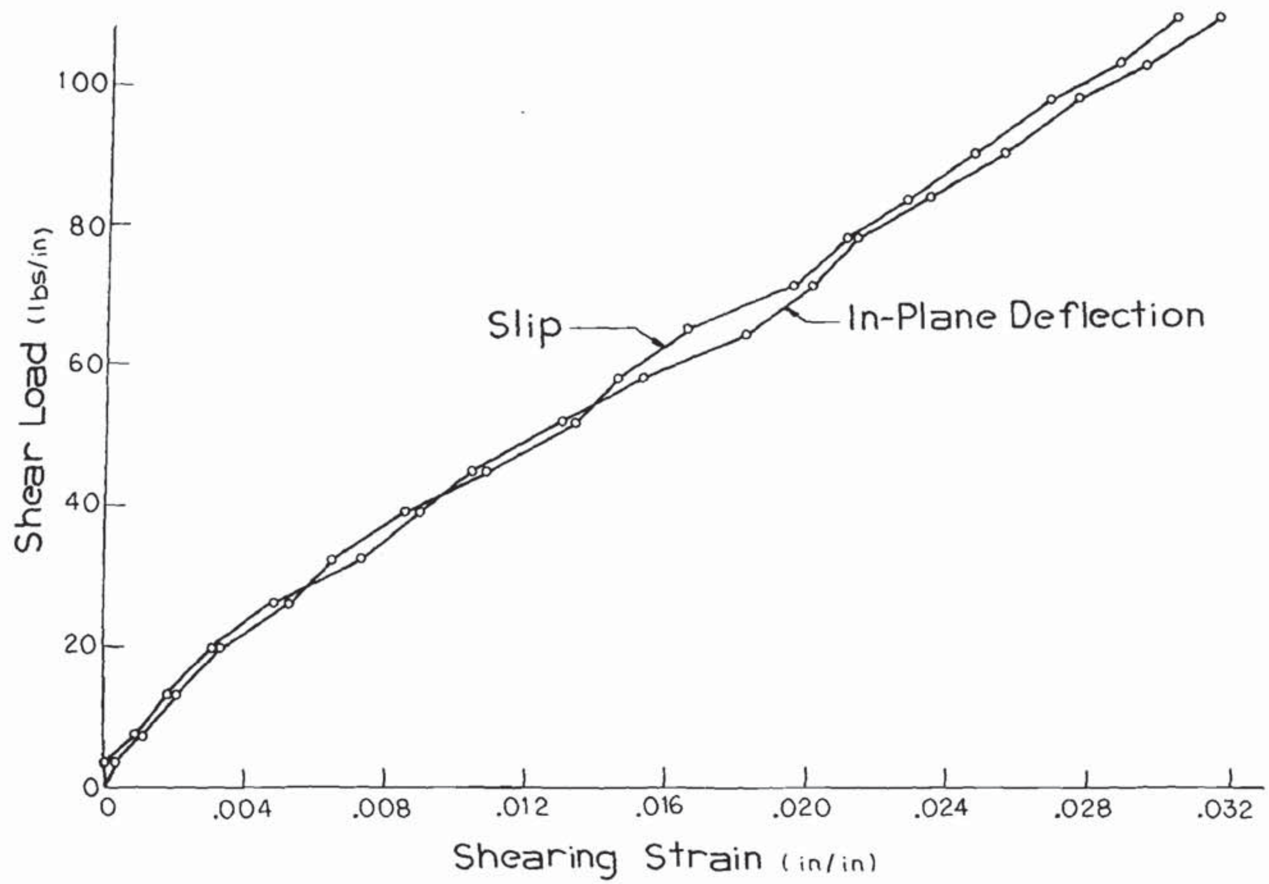

FIG. 11 SHEARING STRAIN VS. SHEAR LOAD CURVE FOR TEST SF-3

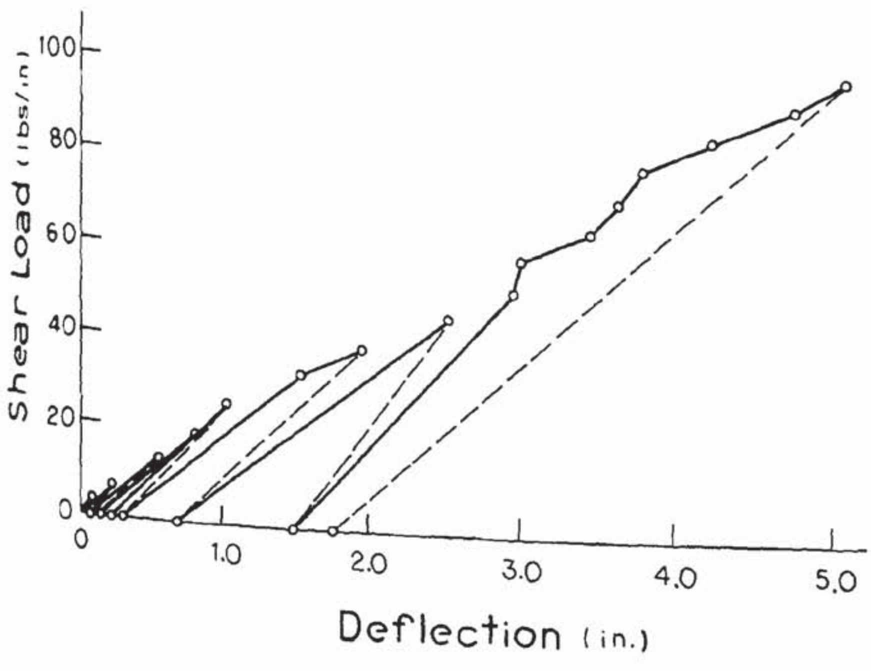

FIG. 12 SHEAR LOAD VS. DEFLECTION CURVE FOR TEST SF-4

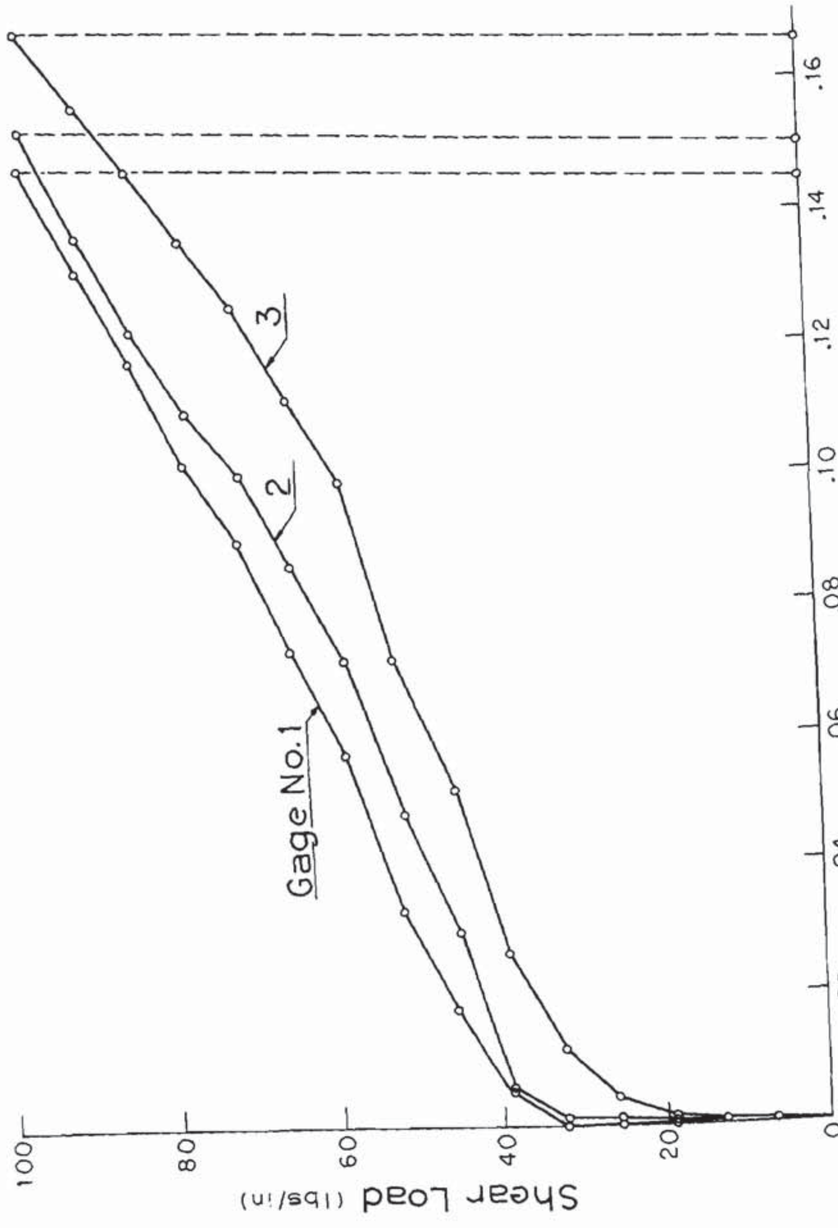

FIG. 13 SHEAR LOAD VS. SLIP (TOP GAGES) CURVES FOR TEST SF-4

deflection and from seam slip indicate the similarity in behavior as shown in Fig. 14. The average shear strain per unit load (lb/in) is 0.00047.

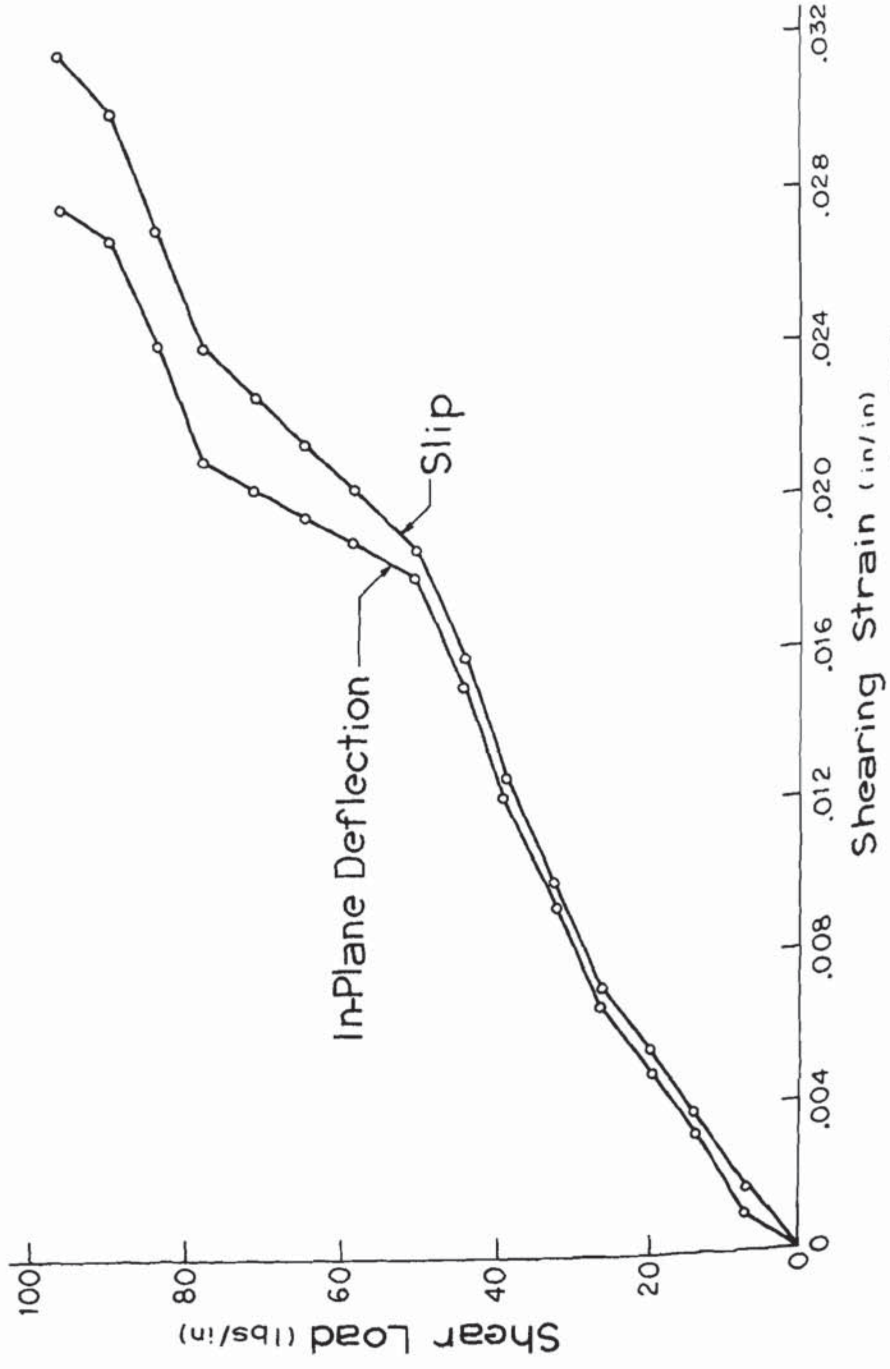

Fig. 14 Shear Load Vs. Shear Strain Curves for Test SF-4

4. DISCUSSION OF TEST RESULTS

4.1 Ultimate Shear Strength of Diaphragms

Buckling strength of 24 gage (0.0239 inch) and 22 gage (0.0299 inch) shear diaphragms are 51.8 lbs/in (2160 psi) and 97.2 lbs/in (3260 psi), respectively.

Among the six tests on four diaphragm specimens the failure due to buckling was in tests SF-2 and SF-4. The rest of the tests had to be terminated due to the limitation of testing arrangement. No attempt in this report is made to present the theoretical approach for the prediction of the strength of the diaphragms in shear.*

4.2 Shear Load Versus Shearing Strain

Shear load versus shearing strain obtained experimentally and theoretically for test SF-2 are shown in Fig. 15. Curve (b) in the figure shows the shearing strains calculated by assuming that sheet-purlin slip equal to one-half of the slip at the intermediate lap joint fasteners. Curve (d) represents the theoretical shearing strain which no slip at sheet-purlin connection is considered.

All curves, experimental and theoretical curves as well, behave identically for test SF-2 up to about the buckling

*The theoretical approach on this subject is reported in Reference 7.

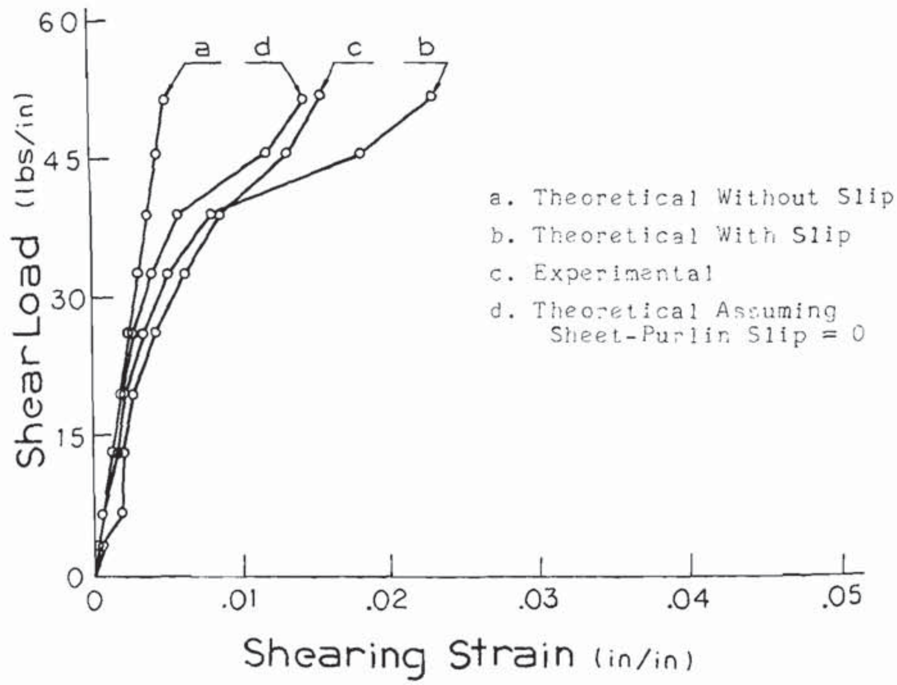

FIG. 15 COMPARISONS FOR TEST SF-2

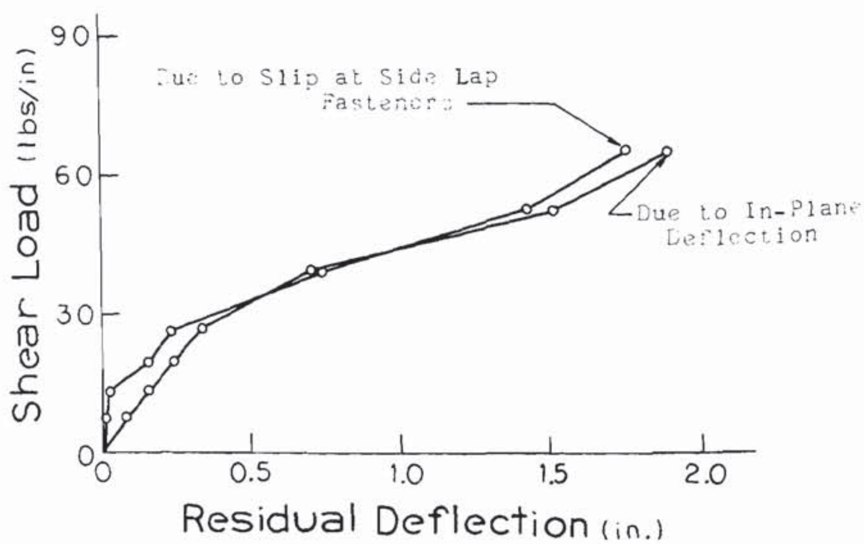

FIG. 16 LOAD VS. RESIDUAL DEFLECTION CURVES FOR TEST SF-4

load of 52.0 lbs/in, shown in Fig. 15. Curve (d) shows better agreement with the experimental results of curve (c). The conclusion seems to be justified as that no caulking compound was placed between the sheet-purlin connections. The sheets were connected to the specimen frame through 3/4 inch steel plates and it would produce more frictional resistance.

4.3 Residual Deflections

During each cyclic loading, a certain amount of permanent in-plane deflection of the diaphragm was observed. It increased almost linearly until the failure took place. Figure 16 displays the residual deflections obtained from the load-deflection and load-slip relationships for test SF-4. It indicates that the residual deflection of the diaphragm is mainly due to the effect of the residual slip at the lap joints.

4.4 Slip Between Panels

The test results indicate that slip has significant effect on the shearing strain of the diaphragm. Curve (a) in Fig. 15 shows the shearing strain obtained theoretically without slip. It, however, deviates considerably from the experimental curve (c) and the theoretical curves (b) and

(d) as well. The main reason may be drawn here is that the caulking compound placed between the lap joints of the neighboring panels increases the slip.

4.5 Strength of Fasteners

During the tests, no failure due to shearing of lap joint fasteners or crippling of diaphragm material at fastener locations was observed. It may be concluded that the size of bolts and washers, and pitch used for fastening the panels together and to the specimen frame, would provide sufficient strength for the type of diaphragms used in this experiment.

5. CONCLUSIONS

This report summarizes the experimental results of six shear tests on four light gage corrugated diaphragms. The conclusions drawn from this investigation are as follows:

(a) The main factors affecting the shear strength of the diaphragms of the type used in this experiment are: seam slip, panel thickness and number of lap joint fasteners.

(b) Caulking compound causes considerable amount of seam slip. The stiffness of the diaphragms to resist shear forces decreases as the seam slip increases.

(c) The diaphragm shear strength at a particular deflection varies with the panel thickness, being greater for the thicker diaphragms.

(d) Thicker diaphragms have less residual deflections.

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SUMMARY

This report summarizes the experimental results of in-plane shear tests on four deep section (seven inches) light gage cold-formed corrugated panels. Failure occurred by in-plane buckling at shear loads of 51.8 and 97.2 pounds per inch for the 24 and 22 gage panels.

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