PROGRESS' REPORT
OF
TESTS OF STABILITY OF STIFFENED PLATES
by Andrew Brodsky*

Foreword
This is a report of the progress made in the first year of a two-year investigation of the behavior of stiffened plate elements loaded in compression, sponsored by the American Institute of Steel Construction. The investigation is under a regular research fellowship of the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania.

Introduction
The program for the A.I.S.C. research fellowship was outlined as follows:
"Tests of plate elements in compression, with both longitudinal and lateral stiffeners. This program would consider some of the fundamental analytical problems in Chapter IV of the paper on Elastic Stability by Messrs. Moisseiff and Lienhard\(^1\)*, and would include experimental corroboration of the stability problems involved. Variations in plate thickness ratios and in the relative size and spacing of the stiffener elements would be considered."

* These numerals indicate references.

The tests were to deal primarily with the fundamental plate elements for cellular tower construction. Previous tests on the behavior of plates reinforced by stiffeners, made especially in Europe, have been limited in their scope. Theoretical investigations of the problem have been made by several authors, but have been rather general in scope and have furnished very involved results for approximate solutions.

Program

In outlining the program for the tests to be conducted, the project was necessarily limited by the capacity of the 800,000-lb. testing machine at Fritz Engineering Laboratory. It was decided to use various plate thicknesses and various numbers of stiffeners. In accordance with suggestions made by Mr. Moisseiff the plates were designed by use of the equation

\[ \frac{d}{t} = 50(N+1) \]  

where \( d \) = total width of plate  
\( t \) = thickness of plate  
\( N \) = number of longitudinal stiffeners

It was decided to make a series of pilot tests to work out a satisfactory method of setting up and detailing the larger tests to be made later.
Plates 25 by 1/4-in. by 4 ft. 4 in. with one vertical stiffener were selected for the pilot tests; larger plates with varying thicknesses and varying numbers of longitudinal and lateral stiffeners were to be used for later tests.

It was decided to apply the load in such a way that the longitudinal stiffener sustains its proportionate share of the load. The plates were to be fixed at the horizontal edges while at the vertical edges conditions in a cellular tower were to be simulated.

**General Progress**

During the first one-year period preliminary theoretical studies in the theory of stability of plates were made. A device for the uniform application of the load was designed and the material ordered and fabricated. Various test setups were tried and the test method was improved in each case. A total of ten pilot tests was made. From the experience gained from each of these tests a smoothly functioning test setup has evolved. The methods which have proven most satisfactory will be used for testing the large plates. The large plates and their stiffeners were designed and the material ordered and received. The specimens are being fabricated at Fritz Engineering Laboratory at present.
**Test Procedure and Results**

Great pains were taken to obtain a distribution of load as nearly uniform as possible.

Two bearing blocks five inches by eight inches by two inches thick were tack-welded to a large bearing block four feet two inches by four inches by nine inches deep. The load was applied through these bearing blocks. To obtain a fixed-end condition along two edges, two 5/8-in. angles were bolted to the large bearing block. These angles were in turn connected by means of bolts, three inches center-to-center, which passed through the test plate. A bearing plate four feet two inches by eight inches by three inches deep with the identical type of angles was used as lower bearing block.

The arrangement can be seen in Fig. 1 and 2 which are, respectively, a drawing and a photograph of a typical test setup.

At the beginning of each test vertical strain measurements were taken at various load intervals within the elastic range by means of a 10-in. Whittemore strain gage near the vertical edges of the specimen. If there was a discrepancy in the amount of strain, the loading head was adjusted by means of shims until the strain was nearly equal at both edges.
The various pilot tests made during the past year are briefly described in the following. Unless otherwise noted, a plate of size 25 by 1/4-in. by 4 ft. 4 in. (with a clear length of 4 ft. 1/2 in.) was used with the two edges (25-in.) perpendicular to the direction of the load clamped.

The stiffened plates should fail due to yielding of the material.

**Test No. 1** - An unstiffened plate with the two vertical edges unsupported was loaded elastically up to 14,000 lb. and lateral deflections were measured. The plate was bending in a simple half-wave. The critical Euler buckling load is 20,850 lb.

**Test No. 2** - The plate of Test No. 1 was used again. In this test, however, the plate was supported in the vertical direction by 1/4-in. \( \phi \) by 3-in. long bars spaced 3 in. center-to-center. These bars were lined up at a distance of about 3/8-in. from the vertical edges of the plate. The purpose of these bars was to prevent lateral displacement, but to permit rotation around the vertical edges of the plate.

The theoretical critical compressive stress for this condition is given by the formula

\[
cr = k \frac{\pi^2 E}{12(1 - \nu^2)} \left( \frac{t}{d} \right)^2
\]

(2)
where $k$ is a constant depending on the ratio of the sides of the plate. For the given plate $k = 4.85^2$. The theoretical buckling load is about 103,000 lb. During the test the plate could be seen to buckle in a full wave at the load of 103,000 lb. A maximum load of 122,500 lb. was reached, when a number of bars buckled and the plate buckled in a half-wave.

Test No. 3 - In this test the same procedure as in Test No. 2 was used, with the difference that the horizontal bars were lined up by means of timber strips, into which holes for the rods had been drilled. The load in the test reached a maximum of 110,800 lb., when the beams into which the bars had been screwed, slid, freeing the plate from the bar, and the plate again buckled in a half-wave.

Test No. 4 - In order to prevent the sliding of the beams, spacers were inserted between beams and plate. At a load of 125,100 lb. a number of bars buckled and the plate showed a large permanent deflection. There were signs of yield at many points of the plate.

During Tests No. 2, 3, and 4 lateral deflection readings were taken at the center and at quarter-points of the plate. This data was used as a means of determining the critical load by the method given by Professor Southwell$^3$.

2. S. Timoshenko, THEORY OF ELASTIC STABILITY, p.364.
It consists of drawing a straight line through a point ob-
tained by plotting deflection divided by load against de-
flection; the inverse slope of that line giving the critical compressive load. In Test No. 4 this method gave a critical buckling load of 135,000 to 140,000 lb. against the theoretical value of about 103,000 lb.

From these test results the conclusion was drawn that it would be inadvisable to proceed using the bars as a means of supporting the edges of the plate. These bars were apparently responsible for the fact that the maximum load was much greater than the theoretical load. The fact that they buckled showed that they were taking a considerable part of the load and after the buckling of the bars the test could not be continued.

A number of other possibilities for obtaining edge support was considered, such as V-notches and rollers, but none of them was found to be practical. It was therefore finally decided to weld flanges to the vertical edges of the plates and apply the load to this built-up column. The flanges had to be designed in such way as to make the built-up column stronger than the web plate, which was being tested.

Test No. 5 - A plate 4 by 1/4-in. by 4 ft. 1/2-in. was welded with a continuous 3/16-in. weld to both sides of the vertical edges of the test specimen. During the welding pro-
cess, which, like all welding work in this series of tests
was carried out by a qualified welded at Fritz Engineering Laboratory, an effort was made to keep the plate as straight as possible. After setting up the plate in the testing machine, the flange plates were made to bear against the clamping angles, so that they would take their proportionate share of the load. Deflection readings were again taken at three points. The structure was behaving as a column deflecting in a full wave up to a load of 135,000 lb., which corresponds to the computed critical load, at which point the plate buckled as such in a single half-wave. The maximum load was reached at 143,000 lb., causing a center deflection of about 1-7/8 in.

Test No. 6 - A plate 2-1/2 by 1/4-in. by 4 ft. 1/2-in. was used as vertical stiffener along the center line of the plate and plates of the same size were used as flanges. Both stiffener and flanges were welded to the plate with continuous 3/16-in. weld.

In order to prevent the flanges from bending extensively, steel strips were welded to the flanges at the center points and at points about three inches from top and bottom. According to theory there should be a point of inflection in the lateral deflection curve. The strips at the center would therefore be just at that inflection point.

Steel strips 1 by 1/4-in. with a clear length of 7 in. were used. In order to reduce the vertical load that they would absorb, the thickness of the pieces was reduced to about 1/8-in. at two points close to each end.
While one end of the strip was welded to the flanges of the built-up column section, the other end was welded to the inside of the flanges of beams. The arrangement can clearly be seen in the photograph of Fig. 2, which shows the setup after the supporting beam on one side had been removed.

A preliminary test was made to see the amount of load that the strips would possibly absorb and the load was found to be only about 1000 lb. It was obvious that in the worst case these strips would not taken more than one percent of the total load, but actually even less.

Connection angles were bolted to the supporting beams and a reference plate of the same size as the test plate was bolted to the angles. This plate was at a distance of about 16 in. from the test plate and it was necessary to design a special deflectometer for reading lateral deflections. An extension was made for a 1/1000-in. dial gage. Gage holes were drilled into the reference plate and punch marks were made in the test plate; deflection readings were taken along a number of points at different loads.

At 240,000 lb. there was general yielding of the plate; a maximum load of 260,000 lb. was reached, which corresponds to an average direct stress of 30,500 p.s.i.

Test No. 7 - An angle 2-1/2 by 2 by 3/16-in. by 4 ft. 1/2-in. was used as center stiffener with the items in the setup the same as in Test No. 6.
The angle was riveted to the plate with the gage line coinciding with the vertical centerline of the plate. One-half inch diameter rivets were used. At a load of 240,000 lb. there was general yielding; the maximum load was 275,000 lb. There were some strain lines on the outstanding leg of the stiffener. The maximum load corresponds to an average direct unit stress of 31,550 p.s.i. Fig. 1 gives a side view of this specimen after the maximum load had been reached, while Fig. 3a and 3b show the specimen after it had been removed from the testing machine.

Test No. 8—A plate 22 by 1/4-in. by 4 ft. 4 in. was used as test specimen. Plates 2-1/2 by 1/4-in. by 4 ft. 1/2-in. were used as flanges, and a plate 2-1/2 by 1/4 in. by 4 ft. 6 in. was used as center stiffener. The center stiffener was somewhat longer than in the other tests and cut so as to fit the clamping angles and was partly bearing against the loading blocks. The plate was thereby prevented from bending in the direction of the stiffener and as load was applied it bent in the other direction.

At 140,000 lb. there were strain lines throughout the plate and on the center stiffener. The ultimate load was reached at 241,000 lb., when the stiffener buckled in the lower half. The plate buckled in a half-wave with a maximum deflection in the lower part. The width of the plate was below the allowable maximum as given by Eq. 1 and the specimen yielded at an average direct unit stress of 31,950 p.s.i. Fig. 4 shows the specimen.
Test No. 9 - A plate that was above the allowable width (Eq.1) was used. The test specimen was a 28 by 1/4 in. by 4 ft. 4 in. plate with flanges 2-1/2 by 1/4-in. by 4 ft. 1/2-in. and a 2-1/2 by 1/4-in. by 4 ft. 2-3/4 in. center stiffener. This stiffener was cut to bear closely against the clamping angles both on top and bottom. In addition, a steel strip 2-1/2 by 1/4 by 4 in. was welded to the test specimen both on top and bottom in back of the center stiffener. These pieces were also made to fit the angles. Their purpose was to give added rigidity to the plate which would prevent it to a certain extent from bending in either direction. The test specimen can be seen in Fig. 5a and 5b.

At a load of 250,000 lb. the center stiffener began to yield rapidly and it buckled at 261,000 lb., i.e., a direct average unit stress of 28,400 p.s.i. In Tests No. 8 and 9 the center stiffener buckled, although its width-to-thickness ratio was only 10. The steel used had a lower proportional limit than the material of the main plate.

It was decided to make use of wider flanges for the final pilot test. The flange plates should furnish a radius of gyration of approximately the same magnitude as the center stiffener. The larger flanges would add to the rigidity of the built-up column and would probably allow to make full use of the strength of the plate.
Test No. 10 - In this final test use was made of all the experience gained in the previous tests. To summarize: the test specimen was a plate 25 by 1/4-in. by 4 ft. 4 in., with two edges clamped; to the free edges, plates 4 by 1/4-in. by 4 ft. 1/2-in. were welded with 3/16 in. continuous weld on both sides; along the center of the plate a vertical stiffener plate 2-1/2 by 1/4-in. by 4 ft. 2-3/4 in. was welded. Both flanges and stiffener were made to take their proportionate share of the compressive load. Strips 2-1/2 by 1/4 by 4 in. were welded to the plate in back of the center stiffener on top and bottom to increase rigidity and to prevent the plate from bending excessively. Other steel strips 1 by 1/4 by 6-1/2 in. were welded horizontally at one end to the flange plates and at the other end to the inside of the flanges of WF-beams. These strips were attached as lateral supports to prevent excessive bending of the flanges and were welded at points about three inches from each end of the flanges and at the center where a point of inflection of the deflection curve of the plate had to be expected.

This specimen gave the highest average direct unit stress. The maximum load was 309,000 lb., which is 33,600 p.s.i. The plate buckled in a half-wave with at least two intermediate smaller full waves in each panel. Photographs of the specimen are shown in Fig. 6a and 6b.
From the deflection readings taken at 81 points along the plate a drawing of the deflection surface has been prepared and is appended in Fig. 7. A load-deflection curve for the center point of the plate has been prepared and is shown in Fig. 8. The test specimens reached maximum direct average unit stresses ranging from 28,400 to 33,600 p.s.i., varying with the test arrangement. The low value was obtained in Test No. 9, which had a plate of a width above the allowable given by Eq. 1 and small-size flanges. The high value was obtained in Test No. 10 which was designed in accordance with Eq. 1 and had flanges with about the same radius of gyration as the center stiffener.

Coupon tests of the plates tested show that the steel had a yield strength of about 42,500 p.s.i., a maximum strength of about 64,000 p.s.i., and a modulus of elasticity of about 29,800,000 p.s.i. The proportional limit of the material is roughly 29,000 p.s.i. which is probably one of the reasons for the failure of the specimens at stresses of approximately that magnitude.

The material that was used for the flanges in Tests No. 8 and 9 and for the stiffener in Tests No. 8, 9, and 10 had a proportional limit of about 26,000 p.s.i., an upper yield strength of 41,450 p.s.i., a lower yield strength of 39,250 p.s.i., and a maximum strength of 58,500 p.s.i. The modulus of elasticity of the material was 29,600,000 p.s.i.
The steel used for the flanges of Tests No. 5 and 10 had a proportional limit of about 39,000 p.s.i., an upper yield point of 43,000 p.s.i., a lower yield point of 40,600 p.s.i., a maximum strength of 62,600 p.s.i. and a modulus of elasticity of 29,800,000 p.s.i.

Tests in 1942-1943

The stiffeners for the reinforced plates were designed in accordance with formula (21), Fig. 1, and Table 6 given in the paper by Messrs. Moisseiff and Lienhard. The designs were checked by Messrs. Moisseiff and Lienhard and adopted after a few minor changes.

The following list gives the details for the six tests to be made, beginning in September 1942.

<table>
<thead>
<tr>
<th>Plate Size</th>
<th>Longitudinal Stiffeners</th>
<th>Transverse Stiffeners</th>
<th>Flanges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Size, in.</td>
<td>No.</td>
</tr>
<tr>
<td>33&quot; X 3/8&quot;</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>X 19'0&quot;</td>
<td>1</td>
<td>2-1/2</td>
<td>4</td>
</tr>
<tr>
<td>45&quot; X 5/16&quot;</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>X 17'0&quot;</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>50&quot; X 1/4&quot;</td>
<td>3</td>
<td>3-1/2</td>
<td>1</td>
</tr>
<tr>
<td>X 12'8&quot;</td>
<td>3</td>
<td>2-1/2</td>
<td>2</td>
</tr>
</tbody>
</table>

All stiffeners and flanges will be welded to the plates with continuous 3/16-in. welds.

The flanges were designed large enough to give sufficient strength to the entire built-up section and also to make each individual panel strong enough.
The specimens are at present being fabricated at Fritz Engineering Laboratory.

It is planned to use steel strips welded to the flanges at intermediate points so as to divide the individual panels into squares, since according to theory, long plates buckle into squares. The ends of the strips will be welded to columns.

In these tests lateral and longitudinal deflection measurements will be made.

The effectiveness of the plates with varying numbers of stiffeners will be studied and analyzed. A thorough theoretical investigation of the problem will be made after completion of the tests.
Fig. 2 - Typical Test Set-Up
Fig. 4 - Pilot Test Specimen No. 8
Fig. 5a

Fig. 5b - Pilot Test Specimen No. 9
Fig. 7. DEFLECTION SURFACE PILOT TEST NO. 10
DEFLECTIONS IN INCHES AFTER FAILURE
Fig. 8. Pilot Test No. 10
Load-Deflection Curve for Center Point of Plate