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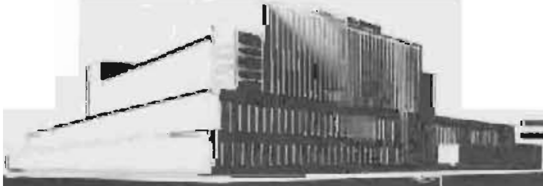

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

BUCKLING OF STIFFENED, FLAT PLYWOOD PLATES IN COMPRESSION--
A SINGLE STIFFENER PERPENDICULAR TO STRESS[1]

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Summary and Conclusions

A mathematical analysis of the critical stress of a plywood plate in edge compression stiffened by means of a stiffener glued to the plate is presented in this report. The analysis yields an approximate formula for the minimum stiffness of the stiffener required to cause the plate to buckle into 2 half-waves rather than into 1. The data from 371 tests of 60 plates suggest a modification of the formula by an empirical factor, probably made necessary by the original lack of flatness of the plates.

Introduction

The critical buckling stress of a flat plywood plate with simply supported edges in edgewise compression can be increased appreciably by the addition of a small stiffener at the center of the plate and parallel to its loaded edge. A sufficiently large stiffener will restrain the plate so that it will buckle in two half-waves with a node at the stiffener. If the depth of the stiffener is slightly reduced and the plate again loaded, the node between the 2 half-waves will move away from the stiffener, and the buckle pattern will show 2 unequal half-waves. Such buckle patterns are consistent with the mathematical analysis given herein. Further reduction of the depth of the stiffener will allow the plate to buckle in a single half-wave somewhat flattened in the vicinity of the stiffener. This flat spot will decrease in length as the depth of the stiffener is decreased until, when the stiffener is entirely removed, the buckle trace will be nearly a perfect sine curve. This evolution of the buckle pattern as viewed along the center line perpendicular to the stiffener is shown by traces of the various patterns in figure 1.

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[1] This is one of a series of progress reports prepared by the Forest Products Laboratory relating to the use of wood in aircraft, issued in cooperation with the Army-Navy-Civil Committee on Aircraft Design Criteria. Original report published in 1946.

If the stiffener is sufficiently stiff, the plate may be considered as two plates each having a length-to-width ratio of half that of the entire plate. The critical stress is therefore greater than that of the unstiffened plate. As the stiffener is reduced in depth, the critical stress remains constant at this higher value until the plate buckles into a single half-wave. From this point the critical stress steadily decreases with the reduction of the stiffener down to the critical stress of the unstiffened plate. Many of the plates having stiffeners of nearly the critical size act peculiarly in their buckling behavior. There is a tendency for the critical stress to increase slightly as the decreasing stiffener size passes the critical point.

This report presents a mathematical analysis of the critical stress of such plates in which an approximate formula is derived for the minimum stiffness of the stiffener necessary to cause the plate to act as two plates. The data from 371 tests of 60 plates suggest an empirical modification of the formula for use in design.

Mathematical Analysis

Consider a plywood panel (fig. 2) with a central horizontal stiffener, and let the dimensions of the panel be such that without the stiffener it would buckle into a single half-wave when subjected to a sufficiently large compressive load. All edges are assumed to be simply supported. It is also assumed that the torsional rigidity of the stiffener can be neglected and that the effect of the stiffener is concentrated along the center line of the panel. An approximate method will be developed to determine the least stiffness of the stiffener that will cause the panel to buckle into 2 half-waves instead of 1 when sufficient compressive load is applied. A method of derivation will be adopted that will furnish a means of interpreting the buckling patterns that are experimentally observed. It will be assumed that the panel is initially not perfectly flat. The initial small departure from perfect flatness can be represented by the following double Fourier's series:

$$w_o = \Sigma\,\Sigma\, a_{ij} \sin i\,\alpha x \sin j\,\beta y \qquad (1)$$

where $\alpha = \frac{\pi}{a}$, $\beta = \frac{\pi}{b}$, and $\underline{i}$ and $\underline{j}$ are integers that may take values from 1 to ∞. Later it will be assumed for purposes of approximation that only 2 of the coefficients $\underline{a_{ij}}$ are different from 0. The early stages of the calculations will be carried out for the general form.

Since the panel is not initially perfectly flat, it will deflect laterally under the action of even a small compressive load $\underline{P}$ per inch of edge. The deflected surface at any load will be represented in the following form:

$$w = \sum \sum b_{ij} \sin i \alpha x \sin j \beta y \qquad (2)$$

In accordance with (1), since the stiffener is attached to the panel the initial departure of the stiffener from perfect straightness is given by

$$w_{os} = \sum \sum a_{ij} \sin i \alpha x \sin j\frac{\pi}{2} = \sum A_i \sin i \alpha x \qquad (3)$$

where

$$A_i = \sum_{j \text{ odd}} (-1)^{\frac{j-1}{2}} a_{ij} \qquad (4)$$

In accordance with (2), the deflection of the stiffener under compressive load, as measured from a straight line, is given by

$$w_s = \sum B_i \sin i \alpha x \qquad (5)$$

$$B_i = \sum_{j \text{ odd}} (-1)^{\frac{j-1}{2}} b_{ij} \qquad (6)$$

The energy method will be used to determine the values of the coefficients $\underline{b_{ij}}$ in terms of the coefficients $\underline{a_{ij}}$ for a given value $\underline{P}$ of the load per inch of loaded edge. These coefficients determine the shape of the panel in equilibrium under a given load. For this purpose it is necessary to calculate the flexural energies of the plate and stiffener and the loss in potential energy of the load due to the vertical shortening of the distance between the loaded edges associated with the bending of the plate.

The flexural energy of the plate is given by the expression

$$W_1 = \frac{h^3}{24\lambda} \int_0^a \int_0^b \left\{ E_1 \left[\frac{\delta^2 (w - w_o)}{\delta x^2} \right]^2 + E_2 \left[\frac{\delta^2 (w - w_o)}{\delta y^2} \right]^2 + \right.$$

$$\left. 2E_L \sigma_{TL} \frac{\delta^2 (w - w_o)}{\delta x^2} \frac{\delta^2 (w - w_o)}{\delta y^2} + 4\lambda\mu_{LT} \left[\frac{\delta^2 (w - w_o)}{\delta x \delta y} \right]^2 \right\} dy\, dx \qquad (7)$$

where coefficients have the meanings given them in Forest Products Laboratory Reports Nos. 1312 and 1316 and in the table of notation.

After substituting (1) and (2) in (7) and performing the integrations, it is found that

$$W_1 = \frac{h^3ab}{96\lambda}\Big\{E_1\alpha^4\Sigma\,\Sigma\, i^4(b_{ij} - a_{ij})^2 + E_2\beta^4\Sigma\,\Sigma\, j^4(b_{ij} - a_{ij})^2 + 2A\alpha^2\beta^2\Sigma\,\Sigma\, i^2j^2(b_{ij} - a_{ij})^2\Big\} \qquad (8)$$

where

$$A = E_L\sigma_{TL} + 2\lambda\mu_{LT} \qquad (9)$$

The flexural energy of the stiffener is given by the expression

$$W_2 = \frac{(EI)_s}{2}\int_0^a\left[\frac{\delta^2(w_s - w_{os})}{\delta x^2}\right]^2 dx \qquad (10)$$

where $(EI)_s$ denotes the stiffness of the stiffener as calculated by the method described in Forest Products Laboratory Report No. 1557.

After using equations (3) and (5) and performing the integrations, it is found that

$$W_2 = \frac{(EI)_s\alpha^4a}{4}\,\Sigma\, i^4(B_i - A_i)^2 \qquad (11)$$

The loss in potential energy of the load is equal to the work done by the load during the shortening of the panel due to bending. Hence,

$$W_3 = \frac{P}{2}\int_0^a\int_0^b\left[\left(\frac{\delta w}{\delta y}\right)^2 - \left(\frac{\delta w_o}{\delta y}\right)^2\right]dy\,dx \qquad (12)$$

where P is the applied load per inch of edge of the panel.

After using equations (1) and (2) and performing the integrations, it is found that

$$W_3 = \frac{P\beta^2ab}{8}\,\Sigma\,\Sigma\, j^2(b_{ij}{}^2 - a_{ij}{}^2) \qquad (13)$$

For equilibrium the expression

$$W = W_1 + W_2 - W_3 \qquad (14)$$

is a minimum.

In accordance with (8), (11), and (13),

$$W = D_1 \frac{ab}{8}\left\{\Sigma\,\Sigma\,\lambda_{ij}(b_{ij} - a_{ij})^2 + \frac{2\gamma a}{b}\,\alpha^4\,\Sigma\,i^4(B_i - A_i)^2 \right. \tag{15}$$

$$\left. - \frac{P\beta^2}{D_1}\,\Sigma\,\Sigma\,j^2(b_{ij}{}^2 - a_{ij}{}^2)\right\}$$

where

$$\lambda_{ij} = \alpha^4 i^4 + \delta\beta^4 j^4 + 2\epsilon\alpha^2\beta^2 i^2 j^2 \tag{16}$$

$$\delta = \frac{D_2}{D_1} \tag{17a}$$

$$\epsilon = \frac{K}{D_1} \tag{17b}$$

$$\gamma = \frac{(EI)_s}{D_1 a} \tag{17c}$$

$$D_1 = \frac{E_1 h^3}{12\lambda} \tag{18a}$$

$$D_2 = \frac{E_2 h^3}{12\lambda} \tag{18b}$$

$$K = \frac{Ah^3}{12\lambda} \tag{18c}$$

The conditions for equilibrium are then

$$\frac{\delta W}{\delta b_{ij}} = 0, \qquad i = 1, 2, 3,\ldots \quad j = 1, 2, 3,\ldots \tag{19}$$

It is possible to complete the analysis based on this infinite system of equations. Approximate results, however, can be obtained by supposing that all coefficients $\underline{b_{ij}}$ and $\underline{a_{ij}}$ are 0 with the exception of $\underline{b_{11}}$, $\underline{b_{12}}$, $\underline{a_{11}}$, and $\underline{a_{12}}$. This means that only 2 "modes" of deflection are considered, the mode (1,1) in which the deflection is proportional to $\underline{\sin \alpha x \sin \beta y}$ and the mode (1,2) in which the deflection is proportional to $\underline{\sin \alpha x \sin 2\beta y}$. The mode (1,1) has no nodes except at the edges of the panel, while the mode (1,2) has a node at the stiffener also. The consideration of these two modes is sufficient to provide an explanation of the observed buckling patterns. Further, the consideration of 2 modes only leads in a simple way to an approximate expression for the stiffness of the stiffener necessary to make the plate buckle into 2 half-waves.

Equation (19), after omitting all coefficients except those mentioned previously, yields two equations, which are:

$$\frac{\delta W}{\delta b_{11}} = \frac{D_1 ab}{8}\left\{2\lambda_{11}(b_{11} - a_{11}) + \frac{4\gamma\alpha^4 a}{b}(b_{11} - a_{11}) - \frac{P\beta^2 2b_{11}}{D_1}\right\} = 0$$

$$\frac{\delta W}{\delta b_{12}} = \frac{D_1 ab}{8}\left\{2\lambda_{12}(b_{12} - a_{12}) - \frac{P\beta^2}{D_1}\, 8b_{12}\right\} = 0 \qquad (20)$$

From these equations the following values for b_{11} and b_{12} are readily found:

$$b_{11} = \frac{a_{11}}{1 - \frac{P}{P_{11}}} \qquad (21)$$

$$b_{12} = \frac{a_{12}}{1 - \frac{P}{P_{12}}} \qquad (22)$$

$$P_{11} = \frac{D_1(\lambda_{11} + \frac{2\gamma a\alpha}{b})^4}{\beta^2} \qquad (23)$$

$$P_{12} = \frac{D_1\lambda_{12}}{4\beta^2} \qquad (24)$$

After introducing the expressions for λ_{11} and λ_{12} and making the substitutions indicated by equations (17) and (18), the following values are obtained for P_{11} and P_{12}:

$$P_{11} = \frac{\pi^2}{12\lambda}\left[E_1 \frac{b^2}{a^2} + 2A + E_2 \frac{a^2}{b^2}\right]\frac{h^3}{a^2} + 2\pi^2 \frac{b}{a^4}(EI)_s \qquad (25)$$

$$P_{12} = \frac{\pi^2}{12\lambda}\left[E_1 \frac{b^2}{4a^2} + 2A + E_2 \frac{4a^2}{b^2}\right]\frac{h^3}{a^2} \qquad (26)$$

It may be seen from equations (21) and (22) that P_{11} is the critical load at which the stiffened panel buckles in a single half-wave and that P_{12} is the critical load at which the stiffened panel will buckle in two half-waves. If the panel buckled in two waves, there would be a node at the stiffener of an initially flat panel. If, however, the panel is not perfectly flat initially, the mode (1,1) may be expected to be present in the Fourier representation of its surface. The amplitude of this mode will be increased to a greater or lesser extent, depending upon the stiffness of the stiffener, as the load approaches the critical load P_{12}. The resulting combination of the modes (1,1) and (1,2) will lead to a buckling pattern consisting of two unequal half-waves, and the stiffener will be bent. If the stiffener is very stiff, the development of mode (1,1) to any great extent is prevented, and the panel buckles into two nearly equal half-waves. An illustration will be given later of the relative amplification of the two modes for different stiffnesses of stiffener. Equation (26) agrees with equation (1) of Forest Products Laboratory Report No. 1316 for the case of a buckle form of two half-waves, and equation (25) agrees with the same equation for the case of a buckle form of a single half-wave, except for the added term due to the presence of the stiffener. It should be noted that equations (25) and (26) are written for critical load per inch of edge, while equation (1) of Report No. 1316 is written for critical stress.

Let $\underline{(EI)_s}$ be increased through a series of values. A study of equations (25) and (26) together with (21) and (22) shows that the panel will buckle in mode (1,1) with some amplification of the mode (1,2) until $\underline{(EI)_s}$ is so large that

$$P_{11} = P_{12}$$

that is, until

$$\frac{\pi^2}{12\lambda}\left[E_1\frac{b^2}{a^2} + 2A + E_2\frac{a^2}{b^2}\right]\frac{h^3}{a^2} + 2\pi^2\frac{b}{a^4}(EI)_s = \frac{\pi^2}{12\lambda}\left[E_1\frac{b^2}{4a^2} + 2A + E_2\frac{4a^2}{b^2}\right]\frac{h^3}{a^2}$$

From this equation it follows that the critical value of $\underline{(EI)_s}$ at which the plate will buckle into two half-waves with a node at the stiffener is

$$(EI)_{scr} = \frac{h^3b}{8\lambda}\left[E_2\frac{a^4}{b^4} - \frac{1}{4}E_1\right] \qquad (27)$$

A square panel of isotropic material with a central horizontal stiffener will be considered for the purpose of illustrating the relative rates of increase of the amplitudes $\underline{b_{11}}$ and $\underline{b_{12}}$ of the modes (1,1) and (1,2) from their initial values $\underline{a_{11}}$ and $\underline{a_{12}}$ for different stiffnesses of the stiffener as the load approaches a critical value. Since the panel is isotropic

$$E_1 = E_2 = A = E$$

By using these relations and the fact that the panel is square, equations (25) and (26) are reduced to the forms

$$P_{11} = \frac{Eh^3}{12\lambda}\frac{\pi^2}{a^2}\left[4 + 2\,\frac{12\lambda}{h^3a}(EI)_s\right] = D\alpha^2(4 + 2\gamma) \qquad (28)$$

$$P_{12} = \frac{25}{4}\,\frac{Eh^3}{12\lambda}\,\frac{\pi^2}{a^2} = \frac{25}{4}\,D\alpha^2 \tag{29}$$

It will be convenient to write equations (21) and (22) in the forms

$$\frac{b_{11}}{a_{11}} = \frac{1}{1 - \frac{P}{P_{11}}} \tag{30}$$

$$\frac{b_{12}}{a_{12}} = \frac{1}{1 - \frac{P}{P_{12}}} = \frac{1}{1 - \frac{P_{11}}{P_{12}}\,\frac{P}{P_{11}}} \tag{31}$$

For given values of γ it is then possible to calculate $\frac{b_{11}}{a_{11}}$ and $\frac{b_{12}}{a_{12}}$ for various values of P. For example, if $\gamma = 0.5$, $P_{11} = 5D\alpha^2$ and $P_{12} = 6.25D\alpha^2$. The following results are then readily obtained:

if $P = 0.5P_{11}$	$b_{11} = 2a_{11}$	$b_{12} = 1.67a_{12}$
$P = 0.7P_{11}$	$b_{11} = 4a_{11}$	$b_{12} = 2.5a_{12}$
$P = 0.9\,P_{11}$	$b_{11} = 10a_{11}$	$b_{12} = 3.57a_{12}$

These results and those for other values of γ are plotted in figure 3.

The least value of γ for which the panel will buckle into 2 half-waves is found to be 1.125 by equating P_{11} and P_{12} as given by equations (28) and (29). The curves show that for values of γ in the neighborhood of this critical value there is nearly equal amplification of the amplitudes of the modes (1,1) and (1,2). The vertical asymptotes at the right in figure 3 correspond to the critical load P_{11} when $\gamma < 1.125$ and to P_{12} when $\gamma > 1.125$.

From this example it is clear that the initial lack of flatness of the panel will complicate the observed form of the deflected surface of the panel as the load is gradually increased to the buckling load. The initial departure from perfect flatness must be small if the preceding discussion is to apply. If it is not, membrane stress will be developed, and the situation will be more complicated. This may account for some of the scatter of the experimental points.

For the purpose of obtaining approximate results in relatively simple form, only two modes (1,1) and (1,2) of the deflection pattern were considered. More exact results can be obtained by carrying the analysis through for the general form of equation (15). A general analysis has been carried out by Lundquist[2] from a somewhat different standpoint for the case of several horizontal stiffeners. Timoshenko[3] has treated the case of an isotropic panel with horizontal stiffeners. Values of γ for isotropic plates, obtained by substituting in equation (17c) the values of $(EI)_s$ given by equation (27) based on only the 2 modes considered, are found to average about 6 percent less than those given by Timoshenko.[3]

Description of Stiffened Plates

The plates were cut from yellow birch plywood of aircraft grade. Three different thicknesses and constructions of plywood were selected: (1) 3 plies of 1/16-inch veneer, the direction of the grain of the core perpendicular to that of the faces; (2) 4 plies of 1/20-inch veneer, the direction of the grain of the 2 inner plies parallel to each other and perpendicular to that of the outer plies; and (3) 5 plies of 1/20-inch veneer, the direction of the grain of each ply perpendicular to that of adjacent plies. The plates varied in width from 8 to 12 inches and in length from 6 to 20 inches. In the tests the load was applied to edges of the plates having the 8- to 12-inch dimensions. The direction of the grain of the face plies of each plate was parallel or perpendicular to the direction of the load.

The stiffeners were made of sitka spruce and varied in width from 1/8 to 3/8 inch and in depth from 0 to 1 inch. Each stiffener was cut 1-1/4 inches shorter than the width of the plate to which it was glued, as shown in figure 2.

Before assembling, both the plates and the stiffeners were conditioned in an atmosphere of 65 percent relative humidity and a temperature of 70° F. After assembly, they were stored under the same conditions until the time of test.

Method of Test

The following conditions are assumed in the theory and were approximated in the tests: The plywood is initially nearly flat; all four edges of the panel remain in a plane and are simply supported; and the loaded edges are displaced with respect to each other uniformly across the width of the specimen.

[2]Lundquist, E., Journal of Aeronautical Sciences 6: 269, 1939.

[3]Timoshenko, S., Theory of Elastic Stability, p. 378 and table 41, p. 379, New York, 1936.

The restraining frame used (fig. 4) is described in Forest Products Laboratory Reports Nos. 1316-D, E, and G except that the conditions at the loaded edges of the test specimen were slightly modified. The loaded edges of the specimen were fitted into segmented cylindrical steel rods instead of the continuous rods previously used, which were in turn held in position by the loading head shown in figure 5. The top and bottom loads were applied to the heads through two sets of knife edges, each set free to rotate about a single axis perpendicular to the plane of the specimen. The unloaded edges of the test specimen were positioned as shown in figure 6.

The segmented rod was used to increase accuracy in the determination of critical loads of low values. In the present investigation it was necessary to choose the dimensions of the plates such that the critical loads obtained with a heavy stiffener were well below the proportional limit of the material and also to determine the critical loads after the stiffeners were removed. The critical loads when the sitffeners were removed were so low that they were unduly influenced by the restraint imposed by the solid rod previously used.

The testing procedure was as follows:

The dimensions of the specimen were measured, the thickness to 0.001 inch and the length and width to 0.01 inch. The width and depth of the stiffener were measured to 0.001 inch.

The edges of the specimen to be tested were snugly fitted into rectangular slots in the segmented cylindrical steel loading rods. The segments were spaced upon the specimen so as to allow approximately 1/16 inch between them. Tension springs whose free length was approximately 9/10 of the length of the unloaded edge of the specimen were attached to screws fastened to the loading rods 3/16 inch from the unloaded edges of the specimen. Clamps were applied to the stiffener near its ends to prevent its separation from the plywood plate. A specimen prepared for test is shown in figure 7.

The restraining frame was placed on the bed of the testing machine and centered beneath the upper set of knife edges. The 2 guide rails for 1 face of the specimen were adjusted by means of the adjusting screws to be vertical and in a plane. The lower loading head was placed on the lower set of knife edges and centered in the restraining frame. The specimen was set in the frame; the upper loading head was placed on the specimen and the movable posts of the restraining frame adjusted to be vertical and just to clear the unloaded edges of the specimen. Then the adjustable rails were moved toward the specimen until a 0.002-inch clearance was obtained between the tension springs and rails. The edge conditions at time of test are shown in figures 5 and 6. A stiffened plate ready for test is shown in figure 8.

Data for load-strain curves were observed, and the load increments were so chosen as to define clearly the slope of the curve. The strain was measured by means of metalectric strain gages mounted on each face of the specimen at the center of the width and just below the stiffener. The strain was read to the nearest 0.00001 inch. These gages were mounted directly opposite each other and were connected in series so that they recorded the average compressive strain. Loading of the specimen was continued until the strain began to decrease.

Each plate was tested first with a stiffener of 1-inch depth (perpendicular to plate). Then the depth was reduced and the specimen tested again. This was continued until the stiffener was reduced to nothing and the plate alone had been tested.

Coupons were cut from the specimen after test, from which the elastic properties were obtained. They include 1 for a static bending test, the face grain parallel to the span; 1 for a static bending test, the face grain perpendicular to the span; 2 for compression tests, the face grain parallel to the direction of applied stress; 2 for compression tests, the face grain perpendicular to the direction of applied stress; and 1 for a plate shear test.

The static bending tests were made to determine the effective modulus of elasticity in bending parallel and perpendicular to the face grain. The specimens were tested as simply supported beams centrally loaded. The coupons were 2 inches wide, and the spans used were 48 or 24 times the thickness of the coupon when the face grain was parallel or perpendicular to the span, respectively.

The coupons that were tested in compression were 4 inches long by 1 inch wide by the thickness of the plywood and were tested in a device that provided lateral support to keep the specimen in the plane of the load. The effective moduli of elasticity in compression were thus obtained in the two different grain directions.

Plate shear tests were made to determine the shear modulus of the plywood. The coupons were cut into squares in which the dimensions of the sides were 30 to 40 times the thickness. The test is described in Forest Products Laboratory Report No. 1301.

The stiffeners, prior to attachment to the plywood, were tested as simply supported beams centrally loaded on a span of 14 inches to determine the modulus of elasticity.

Determination of the Critical Load

The critical stress of flat rectangular plywood plates subjected to a uniformly distributed compressive stress applied either parallel or perpendicular to the direction of the face grain of the plywood and buckling in ($\underline{n}$) half-waves has been defined by formula (1) in Forest Products Laboratory Report No. 1316 as follows:

$$p_{cr} = \frac{\pi^2}{12\lambda}\left[E_1 \frac{b^2}{n^2a^2} + 2A + E_2 \frac{n^2a^2}{b^2}\right]\frac{h^2}{a^2} \qquad (32)$$

This formula was substantiated experimentally in Forest Products Laboratory Report No. 1316-D. In this substantiation the original lack of flatness of the panel was compensated for by slightly bending the edges of the plate. It was then possible to determine accurately the critical load from the load deflection curve obtained in the test. In the present investigation it was not practical to use this method because of the presence of the stiffener, and a different method was adopted and checked against equation (32).

The critical stress can be defined as the stress at which the compressive strain in the center of the plate is relieved. The relieving action, however, does not take place instantly due to lack of original perfect flatness of the plate and variations in its elastic properties. The stress at which the average compressive strain at the center of the plate stops increasing and starts decreasing with an increasing load is taken as the critical stress (fig. 9). In other words, the critical stress is the stress at which the slope of the load-strain curve becomes parallel to the load axis.

Computed critical stresses for each plate without a stiffener ($n = 1$) and for each plate having a stiffener of sufficient stiffness to hold the buckle in two half-waves ($n = 2$) are compared with observed values in figure 10. The computed and observed values of stress are each divided by the proportional limit stress of the material and are plotted as abscissas and ordinates respectively. The inclined straight line in the figure passes through points that indicate perfect agreement between the theory and test results. Although the individual points scatter considerably, the average of the experimental critical stresses was within 2 percent of the average of the computed critical stresses. The method used in the present investigation for the determination of the critical stress is therefore, on the average, an adequate one, but the observed critical stress of an individual panel may be in error.

Explanation of Tables

The pertinent data obtained from the tests are presented in tables 1 and 2. The first seven columns in table 1 contain a description and dimensions of the stiffened plates. In column 8 are listed the critical stresses of the plates with the stiffeners removed as obtained from equation (32) with n = 1. Column 9 contains the critical stresses obtained when the stiffener is very stiff, which were computed by use of the same formula with n = 2. Columns 10 and 11 contain the corresponding values obtained from test. These values were obtained by dividing the observed critical loads by the area of the cross section of the plate. Ratios of critical stresses to the proportional limit stress of the plywood are presented in the next four columns. The values in columns 12, 13, 14, and 15 are those in columns 8, 9, 10, and 11, respectively, each divided by the values in column 22. The next seven columns contain data from minor tests of the plywood and the stiffeners. The effective moduli of elasticity of the plywood in bending measured parallel and perpendicular to the side of length _a_ are presented in columns 16 and 17. These values were obtained from the static bending tests using the formula

$$E_1 \text{ or } E_2 = \frac{P'L^3}{4bd^3y}$$

where _P'_ is load in pounds, _L_ is span in inches, _b_ is breadth in inches, _d_ is depth (thickness of plywood) in inches, and _y_ is deflection at center of span in inches.

The effective moduli of elasticity of the plywood in compression measured parallel and perpendicular to the side of length _a_ are presented in columns 18 and 19 and were obtained from the laterally supported column compression tests by the formula

$$E_a \text{ or } E_b = \frac{P'L}{Ay}$$

where _P'_ is load in pounds, _L_ is gage length in inches (2 inches), _A_ is cross sectional area in square inches, and _y_ is deformation in gage length in inches.

Column 20 contains the moduli of elasticity of the sitka spruce stiffeners as determined from the static bending test using the formula

$$E_s = \frac{P'L^3}{4bd^3y}$$

where _P'_ is load in pounds, _L_ is span in inches, _b_ is breadth in inches, _d_ is depth in inches, and _y_ is deflection at center of span in inches.

Column 21 contains the shear moduli in the _LT_ plane obtained by using the data from the plate shear test and the formula

$$\mu_{LT} = \frac{3}{2}\,\frac{Pu^2}{h^3w}$$

where _P_ is load in pounds, _u_ is gage length in inches, _h_ is thickness in inches, and _w_ is deflection in inches.

The proportional limit stress of the plywood material was observed during the laterally supported column compression tests and computed by the formula

$$p_{PL} = \frac{P'}{A}$$

where P' is load at proportional limit in pounds and A is cross sectional area in square inches.

Column 23 contains some pertinent remarks concerning the behavior of the stiffened plate during test.

Table 2 contains the observed critical stress and the two ratios plotted in figure 11 for each depth of stiffener. The observed critical stress was obtained by dividing the observed critical load by the cross sectional area of the stiffened plate. The ratios presented are ratios of the increase in critical stress due to a stiffener of less than the critical stiffness to the increase due to a very heavy stiffener. The denominator in each case is obtained by subtracting the observed critical stress of the plate without a stiffener from that of the plate with a very heavy stiffener. The numerator of the observed ratio is obtained by subtracting the observed critical stress of the plate without a stiffener from that of the plate with a stiffener of that particular depth. The numerator of the computed ratio is obtained by using equation (34).

Analysis of Experimental Results

The mathematical analysis suggests that the ratio obtained from experiment of the increase in the critical stress due to a stiffener of less than the critical stiffness to the increase due to a heavy stiffener be plotted against the similar ratio obtained by theory. The critical load per inch of width of a plate with a stiffener of less than the critical stiffness is given by equation (25), and the critical stress is

$$p_{cr} = \frac{\pi^2}{2\lambda}\left[E_1 \frac{b^2}{a^2} + 2A + E_2 \frac{a^2}{b^2}\right]\frac{h^2}{a^2} + 2\pi^2 \frac{b}{ha^4}(EI)_s \qquad (33)$$

A comparison of this equation with equation (32) when $n = 1$ shows that the first part of the right hand member is equal to the critical stress p_{crp} of the plate with the stiffener removed, provided the plate has such dimensions that it will buckle into a single half-wave. Equation (33) can therefore be written

$$p_{cr} - p_{crp} = 2\pi^2 \frac{b}{ha^4}(EI)_s \qquad (34)$$

The right hand member is the increase in the critical stress due to the presence of the stiffener.

The maximum critical stress that the stiffened plate can attain is obtained when the plate buckles into two half-waves. The critical load per inch of width of the plate is given by equation (26), and the critical stress p_{crm} is given by equation (32) when n = 2. Using equation (32), when n = 2 and when n = 1 the following equation can be obtained:

$$p_{crm} - p_{crp} = \frac{\pi^2 h^2 b^2}{4\lambda a^4}\left[E_2 \frac{a^4}{b^4} - \frac{1}{4} E_1\right] \qquad (35)$$

This equation can be combined with (34) and (27) with the following result:

$$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}} = \frac{(EI)_s}{(EI)_{scr}} \qquad (36)$$

If values of the left hand member of this equation are plotted as ordinates and values of the right hand member as abscissas, a straight line connecting the origin with the point 1,1 is obtained. At this point

$$p_{cr} = p_{crm}$$

and, therefore, greater values of the ordinate cannot be obtained. The stiffness of the stiffener, however, is not limited, and therefore the values of the abscissa are not limited. This fact is represented by a line starting at the point 1,1 and drawn parallel to the X-axis. These two lines are drawn in figure 11.

The experimental data are also plotted in figure 11 as points. The ordinates of these points were determined by substituting experimental values in the left hand member of equation (36). The critical stress of each panel with the heaviest stiffener with which it was tested was substituted for p_{crm}. These values were taken from column 11 of table 1. The values for p_{crp} are those obtained from tests of plates from which the stiffeners were removed and were taken from column 10 of the same table. The experimental values of p_{cr} were taken from table 2.

The abscissas of the experimental points were calculated by use of the expression

$$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}} \qquad (37)$$

which is mathematically equivalent to the right hand member of equation (36). In this expression, experimental values were substituted in the denominator and theoretical values in the numerator. The stiffness of the stiffener $(EI)_s$ is computed about a neutral axis, the position of which is found by the following formula obtained from Forest Products Laboratory Report No. 1557, equation (68):

$$z_n = \frac{1}{2} \frac{d + h}{\dfrac{2ahEa}{\pi\alpha\left(\frac{E_a}{E_b}\right)^{\frac{1}{4}} tdE_s} + 1 + \dfrac{E_a h}{E_s d}}$$

where

$$\alpha = \sqrt{k + \sqrt{k^2 - 1}}$$

$$k = \frac{\sqrt{E_a E_b}}{2\mu_{LT}} - \frac{\sigma_{TL} E_L}{\sqrt{E_a E_b}}$$

The plotted points in figure 11 scatter considerably but nevertheless group themselves around the two straight lines OAC. They more approximately follow the curved broken line from O to B and then along BC. The scatter can be attributed to several causes: There are small errors due to the approximate method used in the theory; there are also some approximations made in the derivation of the formula for $(EI)_s$; and, probably most important, the plates tested were not perfectly flat. As is pointed out in the mathematical analysis, even a very small departure from perfect flatness complicates the situation considerably. Also, this irregularity affects the accuracy of the observations of the critical load, as is illustrated by the scatter of the points in figure 10. Although the plywood was carefully selected for initial flatness, the cutting of the specimen and the gluing of the stiffeners tend to warp the plate.

All the plates reach unit ordinate between abscissas of 0.7 and 1.7. Therefore, for design purposes, stiffeners having a computed ratio of $\frac{(EI)_s}{(EI)_{scr}}$ (abscissa of fig. 11) of 1.8 or more are sufficiently stiff to produce the maximum critical load of the plate. If the computed ratio is equated to 1.8 and the equation solved for $(EI)_s$, a formula for the critical size stiffener is obtained, thus:

$$(EI)_{scr} = \frac{h^3 b}{4.6\lambda}\left[E_2 \frac{a^4}{b^4} - \frac{1}{4} E_1\right] \tag{37}$$

The critical stresses of plates for which values of the ratio $\frac{(EI)_s}{(EI)_{scr}}$ lay between the limits of 1.2 to 1.7 were sometimes higher than that indicated by the theory; that is, higher than p_{crm}. Also, in this range the stiffeners seemed likely to fail in bending when the plate buckled. It is suggested that this range be avoided in the design of stiffened plates.

Notation

The following symbols are the major ones used in this report. All quantities are in inch and pound units.

a = the length of the loaded sides of a plywood plate for compressive loads.

b = the length of the unloaded sides of a plywood plate for compressive loads.

E_a = effective modulus of elasticity of plywood in compression measured parallel to the side of length $\underline{a}$ of plywood plates.

E_b = effective modulus of elasticity of plywood in compression measured perpendicular to the side of length $\underline{a}$ of plywood plates.

E_1 = effective modulus of elasticity of plywood in bending measured parallel to the side of length $\underline{a}$ of plywood plates.

E_2 = effective modulus of elasticity of plywood in bending measured perpendicular to the side of length $\underline{a}$ of plywood plates.

E_L = modulus of elasticity of wood in the direction parallel to the grain (assumed to be $\frac{20}{21}(E_1 + E_2)$).

E_s = modulus of elasticity of sitka spruce stiffener in the direction parallel to the grain, as determined from a static bending test.

d = depth of stiffener (perpendicular to the plane of the plywood plate).

t = width of stiffener (parallel to the plane of the plywood plate).

p_{cr} = critical compressive stress for the buckling of a stiffened plywood plate. Computed values are obtained by use of equation (25).

p_{crp} = critical compressive stress for the buckling of a plywood plate having no stiffener.

p_{crm} = critical compressive stress for the buckling of a stiffened plate having a stiffener large enough to cause a two half-wave buckle.

p_{PL} = proportional limit stress of the plywood material as obtained by compression minor tests.

$(EI)_s$ = a measure of the stiffness of the stiffener. Product of modulus of elasticity and moment of inertia.

$(EI)_{scr}$ = the minimum stiffness of the stiffener required to cause a plywood plate to buckle into two half-waves.

σ_{TL} = Poisson's ratio of extension in the longitudinal direction to compression in the tangential direction due to a compressive stress in the tangential direction (assumed to be 0.02 for yellow birch).

μ_{LT} = shear modulus in the LT plane as determined by the plate shear test.

z_n = distance from the center of the plywood to the neutral axis which has been shifted by attaching a stiffener to the plywood.

Table 1.—Computed and observed critical stresses for stiffened and unstiffened plywood panels in compression, with data from minor tests

Description			Dimensions				Critical stresses				Ratios				Information from minor tests							Remarks
							Computed		Observed		Computed		Observed									
Plate No.	Construction	Face grain to load	Thickness of plywood (h)	Length of loaded edge (a)	Length of unloaded edge (b)	Width of stiffener (w)	P_{crp}	P_{crm}	P_{crp}	P_{crm}	$\frac{P_{crp}}{P_{PL}}$	$\frac{P_{crm}}{P_{PL}}$	$\frac{P_{crp}}{P_{PL}}$	$\frac{P_{crm}}{P_{PL}}$	E_1	E_2	E_a	E_b	Stiffener E_s	μ_{LT}	P_{PL}	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
			Inch	Inches	Inches	Inch	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.					1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	Lb. per sq. in.	
1	1:1:1	Parallel	0.180	10.00	15.00	0.375	548	995	611	1,037	0.107	0.195	0.120	0.203	160	2,280	509	1,609	1,530	147	5,100	
2		Parallel	.179	10.02	15.02	.250	531	969	524	973	.112	.204	.110	.205	153	2,250	490	1,570	1,615	149	4,750	
3		Parallel	.178	10.00	18.01	.193	570	1,027	674	998	.108	.195	.128	.189	185	2,450	715	1,786	1,540	141	5,270	
4		Parallel	.179	10.01	18.03	.125	580	1,058	614	983	.150	.273	.158	.254	170	2,470	756	1,378	1,700	158	3,872	
5	1:2:1	Parallel	.132	10.00	14.00	.375	738	1,299	833	1,385	.209	.368	.236	.393	365	1,608	1,215	946	1,645	158	3,525	
6		Parallel	.193	10.02	14.02	.272	792	1,465	879	1,461	.236	.437	.262	.435	369	1,840	1,061	1,088	1,540	164	3,355	
7		Parallel	.192	10.00	14.00	.188	792	1,427	846	1,311	.227	.408	.242	.375	380	1,782	1,174	1,018	1,607	169	3,495	
8		Parallel	.193	10.01	14.02	.125	787	1,376	738	1,273	.301	.526	.282	.487	365	1,660	1,196	1,016	1,660	184	2,615	
9	1:1:1	Parallel	.180	8.00	15.01	.128	963	1,646	955	1,457	.235	.402	.233	.356	166	2,535	812	1,517	1,433	172	4,095	
10		Parallel	.182	8.00	15.02	.130	905	1,509	1,030	1,334	.188	.323	.213	.276	163	2,268	702	1,508	1,455	152	4,825	
11		Parallel	.175	8.01	14.02	.126	944	1,635	827	1,598	.202	.350	.177	.342	214	2,393	696	1,745	1,683	150	4,665	0.312 inch stiffener failed at 1,950 lb. per sq. in.
12		Parallel	.176	8.01	13.01	.126	907	1,761	869	1,648	.200	.393	.192	.364	180	2,300	750	1,567	1,818	154	4,528	0.310 inch stiffener failed at 1,930 lb. per sq. in.
13		Parallel	.179	8.00	12.92	.125	989	1,984	869	1,682	.247	.495	.217	.420	270	2,430	854	1,564	1,710	184	4,008	0.307 inch stiffener failed at 1,750 lb. per sq. in.
14		Parallel	.178	8.01	12.01	.127	936	2,092	856	1,859	.212	.474	.194	.422	171	2,380	602	1,515	1,320	150	4,410	
15		Parallel	.180	8.00	13.00	.248	922	1,886	868	1,628	.201	.410	.189	.354	170	2,379	685	1,638	1,588	148	4,595	
16		Parallel	.177	8.02	12.01	.248	951	2,091	951	1,890	.220	.485	.220	.438	184	2,388	480	1,612	1,760	156	4,312	
17	1:2:1	Parallel	.188	8.01	12.02	.123	1,499	2,420	1,394	2,146	.401	.648	.373	.574	465	2,225	1,261	1,233	1,708	209	3,735	0.488 inch stiffener failed at 2,260 lb. per sq. in.
18		Parallel	.188	8.01	12.03	.183	1,482	2,547	1,411	2,413	.388	.666	.369	.631	429	2,416	1,244	1,408	1,455	202	3,822	
19		Perpendicular	.188	8.01	6.00	.130	1,491	2,153	1,062	1,688	.369	.533	.263	.418	2,118	473	1,320	1,226	1,567	200	4,038	0.382 inch stiffener failed at 1,830 lb. per sq. in.
20		Perpendicular	.193	8.01	6.01	.128	1,581	2,206	1,106	1,946	.402	.562	.282	.495	2,190	453	1,340	1,296	1,635	200	3,928	1.000 inch stiffener failed at 2,040 lb. per sq. in.
21		Parallel	.189	8.00	12.02	.183	1,424	2,345	......	......	.387	.637	......	......	406	2,120	1,087	1,361	1,570	210	3,681	Plate apparently damaged on first run.
22		Parallel	.188	8.01	12.01	.187	1,368	2,184	1,345	2,130	.415	.663	.408	.646	414	1,971	1,255	1,279	1,703	204	3,295	0.192 inch stiffener failed at 2,080 lb. per sq. in.
23	1:1:1	Perpendicular	.180	10.00	6.00	.130	589	786	422	701	.323	.431	.231	.384	2,229	171	1,500	511	1,652	160	1,825	
24		Perpendicular	.180	10.00	6.01	.115	566	722	539	792	.316	.404	.301	.443	2,160	151	1,400	593	1,332	160	1,788	
25	1:2:1	Perpendicular	.185	10.01	7.01	.250	911	1,342	829	1,382	.272	.400	.247	.413	2,393	417	1,247	1,115	1,580	205	3,350	
26		Perpendicular	.185	10.02	7.00	.250	865	1,400	917	1,510	.288	.466	.305	.502	2,062	451	1,400	1,257	1,670	200	3,005	
27		Perpendicular	.189	10.02	8.00	.188	1,037	1,265	924	1,115	.287	.350	.256	.309	2,470	455	1,458	1,222	1,568	198	3,612	
28		Perpendicular	.188	10.01	8.01	.187	994	1,091	886	1,156	.364	.398	.323	.421	2,466	365	1,338	1,214	1,538	203	2,744	
29	1:1:1:1:1:1	Parallel	.231	10.00	14.03	.257	1,591	2,682	1,658	2,454	.312	.526	.325	.481	646	2,348	1,042	1,801	1,680	186	5,100	
30		Parallel	.234	10.02	15.02	.252	1,672	2,516	1,749	2,580	.296	.446	.310	.457	662	2,370	1,048	1,756	1,551	184	5,640	0.244 inch stiffener failed at 2,340 lb. per sq. in.

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Table 1.--Computed and observed critical stresses for stiffened and unstiffened plywood panels in compression, with data from minor tests (continued)

Plate No.	Construction	Face grain to load	Thickness of plywood (h)	Length of loaded edge (a)	Length of unloaded edge (b)	Width of stiffener (w)	Critical stresses, Computed, p_{crp}	Critical stresses, Computed, p_{crm}	Critical stresses, Observed, p_{crp}	Critical stresses, Observed, p_{crm}	Ratios, Computed, $\frac{p_{crp}}{p_{PL}}$	Ratios, Computed, $\frac{p_{crm}}{p_{PL}}$	Ratios, Observed, $\frac{p_{crp}}{p_{PL}}$	Ratios, Observed, $\frac{p_{crm}}{p_{PL}}$	E_1	E_2	E_a	E_b	Stiffener E_s	μ_{LT}	p_{PL}	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
			Inch	Inches	Inches	Inch	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.					1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	Lb. per sq. in.	
31		Parallel	0.235	10.00	14.02	0.251	1,590	2,580	1,726	2,702	0.226	0.368	0.245	0.384	647	2,159	1,032	1,[illegible]	1,454	181	7,045	0.362 inch stiffener failed at 2,980 lb. per sq. in.
32		Parallel	.231	10.02	13.98	.390	1,618	2,716	1,685	2,684	.330	.554	.344	.547	681	2,362	1,054	1,562	1,775	184	4,905	
33		Parallel	.232	10.02	14.02	.126	1,521	2,426	1,577	2,667	.336	.536	.348	.589	646	2,051	996	1,632	1,604	185	4,530	0.503 inch stiffener failed at 2,370 lb. per sq. in.
34		Parallel	.231	10.02	14.02	.252	1,547	2,656	1,685	2,715	.348	.598	.380	.612	635	2,349	1,038	1,782	1,692	172	4,438	0.358 inch stiffener failed at 2,680 lb. per sq. in.
35		Parallel	.231	10.03	16.01	.252	1,681	2,120	1,755	2,331	.338	.426	.352	.468	685	2,140	1,024	1,660	1,570	195	4,980	0.309 inch stiffener failed at 2,370 lb. per sq. in.
36	1:2:1	Parallel	.192	10.00	18.01	.185	859	957	964	1,097	.299	.333	.336	.382	417	1,625	1,100	1,090	1,700	151	2,870	
37		Parallel	.193	10.00	16.01	.185	791	1,121	759	1,266	.252	.357	.242	.403	393	1,666	955	1,222	1,678	156	3,140	
38		Parallel	.186	10.00	13.02	.120	947	1,997	1,171	1,980	.253	.532	.312	.528	459	2,393	1,208	1,450	1,578	203	3,750	0.505 inch stiffener failed at 2,070 lb. per sq. in.
39		Perpendicular	.185	10.01	6.00	.187	796	1,339	827	1,624	.208	.349	.216	.424	2,268	315	1,334	1,168	1,836	204	3,832	0.509 inch stiffener failed at 1,810 lb. per sq. in.
40	1:1:1	Perpendicular	.176	10.00	5.00	.123	733	1,647	668	1,061	.261	.586	.238	.378	2,288	337	1,707	955	1,820	171	2,809	
41	1:2:1	Perpendicular	.185	10.02	6.00	.187	798	1,434	922	1,507	.212	.381	.245	.401	2,122	348	1,307	1,168	2,146	202	3,760	
42	1:1:1:1:1	Parallel	.234	10.00	17.02	.379	1,753	2,082	1,660	2,083	.367	.435	.347	.436	633	2,244	1,109	1,870	1,766	194	4,782	
43		Parallel	.232	10.00	15.50	.380	1,726	2,210	1,580	2,076	.363	.465	.333	.437	726	2,088	1,130	1,696	1,754	198	4,750	
44		Perpendicular	.224	10.00	8.00	.252	1,415	2,316	1,339	1,903	.609	.996	.576	.818	1,850	682	1,650	1,052	1,455	200	2,325	0.252 inch stiffener failed at 2,100 lb. per sq. in.
45	1:1:1	Perpendicular	.175	10.00	6.50	.190	693	828	543	575	.281	.335	.220	.233	2,651	213	1,872	930	1,715	188	2,468	
46	1:1:1:1:1	Perpendicular	.233	12.02	9.02	.383	1,180	2,157	989	1,689	.337	.616	.282	.482	2,176	783	1,742	1,193	1,749	210	3,500	
47		Perpendicular	.235	12.00	9.82	.376	1,261	2,071	947	1,645	.417	.685	.313	.544	2,257	855	1,579	1,271	1,799	199	3,025	
48		Perpendicular	.233	12.01	11.00	.380	1,236	1,543	965	1,436	.388	.483	.302	.449	2,252	723	1,315	1,223	1,704	197	3,195	
49		Parallel	.231	12.01	17.04	.501	1,195	1,867	1,031	1,862	.237	.371	.205	.370	763	2,330	1,052	1,754	1,794	206	5,035	
50		Parallel	.233	12.00	19.02	.380	1,283	1,630	1,263	1,538	.255	.324	.251	.306	790	2,342	1,128	1,820	1,768	186	5,022	
51		Parallel	.232	12.00	18.03	.381	1,184	1,656	1,103	1,657	.246	.344	.229	.345	742	2,219	1,248	1,723	1,729	193	4,808	
52		Parallel	.233	12.01	16.00	.502	1,145	1,966	1,036	1,790	.226	.389	.205	.354	720	2,200	1,226	1,648	1,348	203	5,058	
53		Parallel	.235	12.00	15.00	.502	1,157	2,226	1,188	2,012	.243	.468	.250	.423	729	2,251	1,062	1,665	1,372	184	4,755	
54	1:2:1	Parallel	.189	12.00	20.00	.380	638	974	758	1,019	.181	.276	.215	.289	420	2,429	1,134	1,327	1,372	187	3,528	
55		Parallel	.189	11.98	15.00	.377	621	1,074	685	1,038	.164	.284	.181	.274	417	2,254	1,162	1,328	2,002	197	3,785	
56		Parallel	.190	12.02	16.00	.379	618	1,201	718	1,340	.177	.345	.206	.384	416	2,032	1,105	1,976	1,330	214	3,485	0.301 inch stiffener failed at 1,270 lb. per sq. in.
57	1:1:1	Parallel	.182	12.00	18.00	.375	356	744	460	874	.117	.244	.151	.287	160	1,755	775	1,263	1,605	142	3,049	
58		Parallel	.181	11.98	16.00	.375	390	947	461	903	.112	.271	.132	.258	161	1,896	632	1,241	1,568	140	3,495	
59		Parallel	.175	11.98	14.00	.377	404	1,125	534	1,321	.112	.312	.148	.367	136	1,926	724	1,480	1,566	137	3,599	
60		Perpendicular	.178	12.00	6.00	.377	331	596	314	666	.150	.270	.142	.301	1,859	154	1,387	609	1,537	140	2,209	

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(Sheet 2 of 2)

Table 2.—Observed critical stresses and the coordinates of figure 10

Depth of stif-fener	Observed critical stress	$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}}$	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}}$
Inch	P.s.i.		
	Plate No. 1		
1.000	1,056	1.04	43.46
.750	1,044	1.02	22.03
.500	1,056	1.04	8.99
.375	1,014	.95	4.95
.....	.....	.....	.....
.250	1,014	.95	2.26
.....	.....	.....	.....
.125	875	.62	.68
.....	.....	.....	.....
0	641	0	0
	Plate No. 2		
1.000	976	1.01	32.73
.750	976	1.01	16.81
.500	962	.98	6.88
.375	1,004	1.07	3.77
.....	.....	.....	.....
.250	948	.94	1.68
.....	.....	.....	.....
.125	836	.70	.49
.062	613	.20	.17
0	524	0	0
	Plate No. 3		
1.000	1,000	1.01	42.04
.746	989	.97	21.33
.489	989	.97	8.26
.371	989	.97	4.54
.304	1,011	1.04	2.99
.238	1,011	1.04	1.81
.186	921	.76	1.12
.117	764	.28	.49
.061	680	.02	.17
0	674	0	0
	Plate No. 4		
1.005	1,005	1.06	31.66
.749	977	.98	15.83
.495	977	.98	6.09
.367	991	1.02	3.12
.306	977	.98	2.10
.247	977	.98	1.34
.190	851	.64	.79
.109	739	.34	.28
.063	614	.00	.12
0	614	0	0
	Plate No. 5		
1.000	1,419	1.06	34.53
.....	.....	.....	.....
.500	1,380	.99	7.27
.375	1,380	.99	3.96
.....	.....	.....	.....
.250	1,359	.95	1.76
.....	.....	.....	.....
.125	1,107	.50	.50
.062	1,016	.33	.17
0	833	0	0

Depth of stif-fener	Observed critical stress	$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}}$	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}}$
Inch	P.s.i.		
	Plate No. 6		
1.000	1,487	1.04	24.85
.747	1,474	1.02	12.69
.502	1,435	.96	5.22
.360	1,435	.96	2.56
.309	1,474	1.02	1.86
.248	1,293	.71	1.19
.195	1,215	.58	.75
.123	995	.20	.33
.055	957	.13	.10
0	879	0	0
	Plate No. 7		
1.000	1,315	1.01	26.36
.743	1,302	.98	13.14
.496	1,289	.95	5.21
.374	1,302	.98	2.79
.303	1,328	1.04	1.77
.237	1,328	1.04	1.07
.177	1,094	.53	.60
.115	1,042	.42	.28
.057	911	.14	.09
0	846	0	0
	Plate No. 8		
1.000	1,242	.94	18.20
.744	1,294	1.04	8.93
.495	1,242	.94	3.42
.367	1,380	1.09	1.73
.310	1,268	.99	1.19
.250	1,113	.70	.76
.181	958	.42	.39
.126	929	.34	.20
.062	854	.22	.06
0	738	0	0
	Plate No. 9		
1.000	1,483	1.05	41.62
.744	1,424	.93	20.76
.495	1,448	.98	8.12
.364	1,483	1.05	4.09
.317	1,437	.96	3.03
.245	1,465	1.02	1.76
.184	1,431	.95	.99
.115	1,205	.50	.42
.065	1,031	.15	.16
0	955	0	0
	Plate No. 10		
1.000	1,339	1.02	66.83
.748	1,356	1.07	33.94
.499	1,308	.92	13.49
.369	1,380	1.15	6.93
.303	1,332	1.00	4.55
.233	1,339	1.02	2.64
.183	1,329	.98	1.64
.112	1,178	.49	.67
.046	1,071	.14	.18
0	1,030	0	0

Depth of stif-fener	Observed critical stress	$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}}$	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}}$
Inch	P.s.i.		
	Plate No. 14		
1.000	1,859	1.00	14.58
.747	1,859	1.00	7.37
.492	1,964	1.10	2.84
.369	1,455	.60	1.50
.311	1,399	.54	1.04
.251	1,315	.46	.66
.177	1,136	.28	.33
.....	.....	.....	.....
.056	912	.06	.05
0	856	0	0
	Plate No. 15		
1.000	1,660	1.04	34.96
.729	1,649	1.03	16.81
.495	1,597	.96	7.17
.365	1,639	1.01	3.79
.296	1,597	.96	2.49
.234	1,736	1.14	1.58
.181	1,656	1.04	.98
.....	.....	.....	.....
.057	931	.08	.16
0	868	0	0
	Plate No. 16		
1.006	1,902	1.01	25.66
.741	1,877	.99	12.46
.490	1,867	.98	5.00
.348	1,913	1.02	2.48
.297	1,891	1.00	1.82
.234	1,655	.75	1.16
.119	1,303	.38	.36
.....	.....	.....	.....
.....	.....	.....	.....
0	951	0	0
	Plate No. 18		
.985	2,401	.99	23.09
.740	2,397	.98	11.79
.497	2,440	1.03	4.72
.373	2,540	1.13	2.49
.....	.....	.....	.....
.237	2,075	.66	.96
.....	.....	.....	.....
.106	1,444	.03	.21
.....	.....	.....	.....
0	1,411	0	0
	Plate No. 22		
.987	2,148	1.02	32.90
.737	2,102	.96	16.67
.489	2,115	.98	6.57
.369	2,125	.99	3.54
.304	2,132	1.00	2.35
.249	2,158	1.04	1.56
.192	1,932	.82	.93
.....	.....	.....	.....
.....	.....	.....	.....
0	1,345	0	0

Depth of stif-fener	Observed critical stress	$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}}$	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}}$
Inch	P.s.i.		
	Plate No. 23		
1.002	700	1.00	16.19
.739	703	1.01	7.76
.505	694	.98	3.14
.387	708	1.03	2.04
.329	633	.76	1.18
.....	.....	.....	.....
.185	547	.45	.35
.....	.....	.....	.....
.067	467	.16	.06
0	422	0	0
	Plate No. 24		
1.001	833	1.16	14.00
.754	786	.98	6.96
.505	767	.90	2.64
.394	781	.96	1.47
.333	739	.79	1.00
.....	.....	.....	.....
.194	608	.27	.31
.....	.....	.....	.....
.063	592	.21	.04
0	539	0	0
	Plate No. 25		
1.000	1,404	1.04	13.98
.741	1,385	1.00	6.94
.508	1,358	.96	2.94
.371	1,331	.91	1.47
.....	.....	.....	.....
.243	1,134	.55	.60
.....	.....	.....	.....
.115	899	.13	.15
.....	.....	.....	.....
0	829	0	0
	Plate No. 26		
1.000	1,510	1.00	13.69
.748	1,510	1.00	6.95
.530	1,540	1.05	3.16
.370	1,349	.73	1.43
.....	.....	.....	.....
.259	1,136	.37	.67
.....	.....	.....	.....
.135	1,025	.18	.19
.....	.....	.....	.....
0	917	0	0
	Plate No. 27		
1.001	1,156	1.22	39.50
.767	1,109	.97	20.96
.508	1,077	.80	8.01
.376	1,127	1.07	4.06
.309	1,104	.94	2.65
.256	1,170	1.29	1.78
.192	1,096	.90	.99
.....	.....	.....	.....
.067	945	.11	.16
0	924	0	0

Depth of stif-fener	Observed critical stress	$\frac{p_{cr} - p_{crp}}{p_{crm} - p_{crp}}$	$\frac{2\pi^2 \frac{b}{ha^4}(EI)_s}{p_{crm} - p_{crp}}$
Inch	P.s.i.		
	Plate No. 28		
1.000	1,178	1.08	26.96
.755	1,178	1.08	13.82
.491	1,152	.98	5.07
.373	1,117	.85	2.73
.309	944	.22	1.81
.....	.....	.....	.....
.193	1,029	.53	.69
.....	.....	.....	.....
.059	886	.00	.09
0	886	0	0
	Plate No. 29		
0.997	2,468	1.02	17.72
.756	2,431	.97	8.46
.513	2,463	1.01	4.03
.370	2,361	.91	2.03
.....	.....	.....	.....
.244	1,970	.39	.89
.....	.....	.....	.....
.115	1,877	.27	.24
.....	.....	.....	.....
0	1,658	0	0
	Plate No. 30		
.998	2,538	.95	17.00
.759	2,574	.99	9.11
.498	2,629	1.06	3.59
.376	2,687	1.13	1.98
.315	2,644	1.08	1.38
.244	2,218	.56	.84
.....	.....	.....	.....
.....	.....	.....	.....
.....	.....	.....	.....
0	1,749	0	0
	Plate No. 32		
.998	2,679	.99	18.60
.739	2,679	.99	9.49
.493	2,694	1.01	4.00
.372	2,707	1.02	2.26
.309	2,664	.98	1.57
.242	2,577	.89	.99
.....	.....	.....	.....
.120	1,685	.00	.30
.....	.....	.....	.....
0	1,685	0	0
	Plate No. 36		
1.006	1,120	1.17	117.99
.762	1,094	.98	61.81
.508	1,146	1.37	24.61
.379	1,081	.88	12.93
.318	1,102	1.04	8.96
.245	1,068	.78	5.20
.189	1,102	1.04	3.13
.132	1,062	.74	1.62
.066	1,010	.35	.53
0	964	0	0

Columns (each plate): Depth of stiffener (Inch); Observed critical stress (P.s.i.); $\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$; $\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$

Plate No. 37

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.005	1,295	1.06	26.51
.751	1,269	1.01	13.49
.499	1,249	.97	5.36
.375	1,251	.97	2.87
.319	1,275	1.02	2.04
.254	1,256	.98	1.28
.185	1,174	.82	.69
.059	873	.22	.10
0	759	0	0

Plate No. 40

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.005	1,065	1.01	10.35
.754	1,057	.99	5.15
.506	1,017	.89	1.99
.375	830	.41	.99
.261	730	.16	.44
.128	648	.05	.11
0	668	0	0

Plate No. 41

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.000	1,537	1.05	11.28
.705	1,500	.99	5.00
.500	1,484	.96	2.30
.375	1,397	.81	1.22
.251	1,206	.48	.52
.135	1,065	.24	.16
0	922	0	0

Plate No. 42

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.001	2,130	1.11	54.37
.752	2,088	1.01	28.63
.509	2,045	.91	12.38
.376	2,073	.98	6.67
.311	2,079	.99	4.59
.254	2,186	1.24	3.13
.186	2,301	1.52	1.79
.068	1,731	.17	.38
0	1,660	0	0

Plate No. 43

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.005	2,123	1.09	42.99
.765	2,058	.96	23.27
.504	2,047	.94	9.47
.384	2,084	1.02	5.42
.316	2,069	.99	3.69
.250	2,026	.90	2.36
.175	2,101	1.05	1.25
.066	1,696	.23	.28
0	1,580	0	0

Plate No. 46

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.010	1,710	1.03	10.28
.749	1,660	.96	5.18
.502	1,696	1.01	2.13
.371	1,525	.77	1.12
.246	1,153	.23	.49
.129	1,343	.08	.15
0	989	0	0

Plate No. 47

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.000	1,656	1.02	10.65
.747	1,631	.98	5.49
.501	1,649	1.01	2.28
.366	1,426	.59	1.18
.246	1,216	.39	.54
.117	1,028	.12	.15
0	947	0	0

Plate No. 48

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.001	1,433	0.99	16.47
.750	1,483	1.10	8.56
.500	1,397	.92	3.52
.345	1,429	.99	1.63
.244	1,383	.89	.82
.178	1,294	.70	.46
.123	1,127	.35	.25
.065	1,049	.18	.10
0	965	0	0

Plate No. 49

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.000	1,853	0.99	16.66
.759	1,864	1.00	8.97
.504	1,871	1.01	3.73
.379	1,874	1.01	2.09
.314	1,694	.80	1.45
.250	1,532	.60	.94
.163	1,283	.30	.45
.083	1,164	.16	.16
0	1,031	0	0

Plate No. 50

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.000	1,531	0.97	47.00
.743	1,491	.83	24.09
.496	1,574	1.13	10.06
.372	1,556	1.06	5.55
.304	1,549	1.04	3.72
.259	1,574	1.13	2.73
.187	1,609	1.26	1.51
.127	1,516	.92	.78
.066	1,373	.40	.30
0	1,263	0	0

Plate No. 51

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.001	1,692	1.06	22.80
.750	1,674	1.03	11.87
.491	1,652	.99	4.72
.360	1,649	.99	2.47
.307	1,618	.93	1.80
.250	1,661	1.01	1.21
.189	1,604	.90	.72
.134	1,440	.61	.40
.063	1,293	.34	.13
0	1,103	0	0

Plate No. 52

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.997	1,819	1.04	15.39
.755	1,794	1.01	8.19
.502	1,805	1.02	3.35
.372	1,742	.94	1.79
.312	1,581	.72	1.25
.255	1,644	.81	.85
.124	1,211	.23	.24
0	1,036	0	0

Plate No. 53

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.002	2,021	1.01	12.70
.750	2,004	.99	6.61
.508	2,103	1.11	2.84
.367	2,064	1.06	1.45
.251	1,647	.56	.69
.124	1,309	.15	.20
0	1,188	0	0

Plate No. 54

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
1.000	1,014	0.98	49.48
.758	1,023	1.02	26.01
.509	908	.58	10.58
.375	882	.47	5.43
.315	873	.44	3.76
.253	904	.56	2.40
.187	913	.59	1.33
.116	869	.42	.56
.063	710	.19	.22
0	758	0	0

Plate No. 55

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.995	1,047	1.02	39.90
.754	1,033	.99	21.08
.508	1,033	.99	8.80
.376	1,153	1.32	4.66
.251	1,058	1.06	2.07
.125	780	.27	.58
0	685	0	0

Plate No. 57

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.987	897	1.06	24.93
.748	868	.98	13.13
.498	863	.97	5.35
.371	865	.98	2.88
.304	863	.97	1.93
.252	859	.96	1.33
.189	902	1.07	.78
.134	604	.35	.42
.096	545	.20	.25
.046	495	.08	.09
0	460	0	0

Plate No. 58

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.993	867	0.92	19.75
.758	839	.86	10.54
.511	959	1.13	4.41
.363	945	1.10	2.16
.310	973	1.16	1.57
.242	918	1.03	.97
.171	636	.40	.52
.088	487	.06	.17
0	461	0	0

Plate No. 59

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.992	1,343	1.03	10.15
.747	1,309	.98	5.24
.494	1,312	.99	2.10
.366	1,245	.90	1.12
.315	1,107	.73	.82
.217	777	.31	.40
.104	546	.02	.11
0	534	0	0

Plate No. 60

Depth of stiffener (Inch)	Observed critical stress (P.s.i.)	$\frac{P_{cr} - P_{crp}}{P_{crm} - P_{crp}}$	$\frac{2\pi^2 b}{ha^4}(EI)_s / (P_{crm} - P_{crp})$
0.993	709	1.12	11.61
.754	646	.94	6.12
.504	641	.93	2.47
.376	666	1.00	1.30
.250	515	.57	.56
.127	391	.22	.16
0	314	0	0

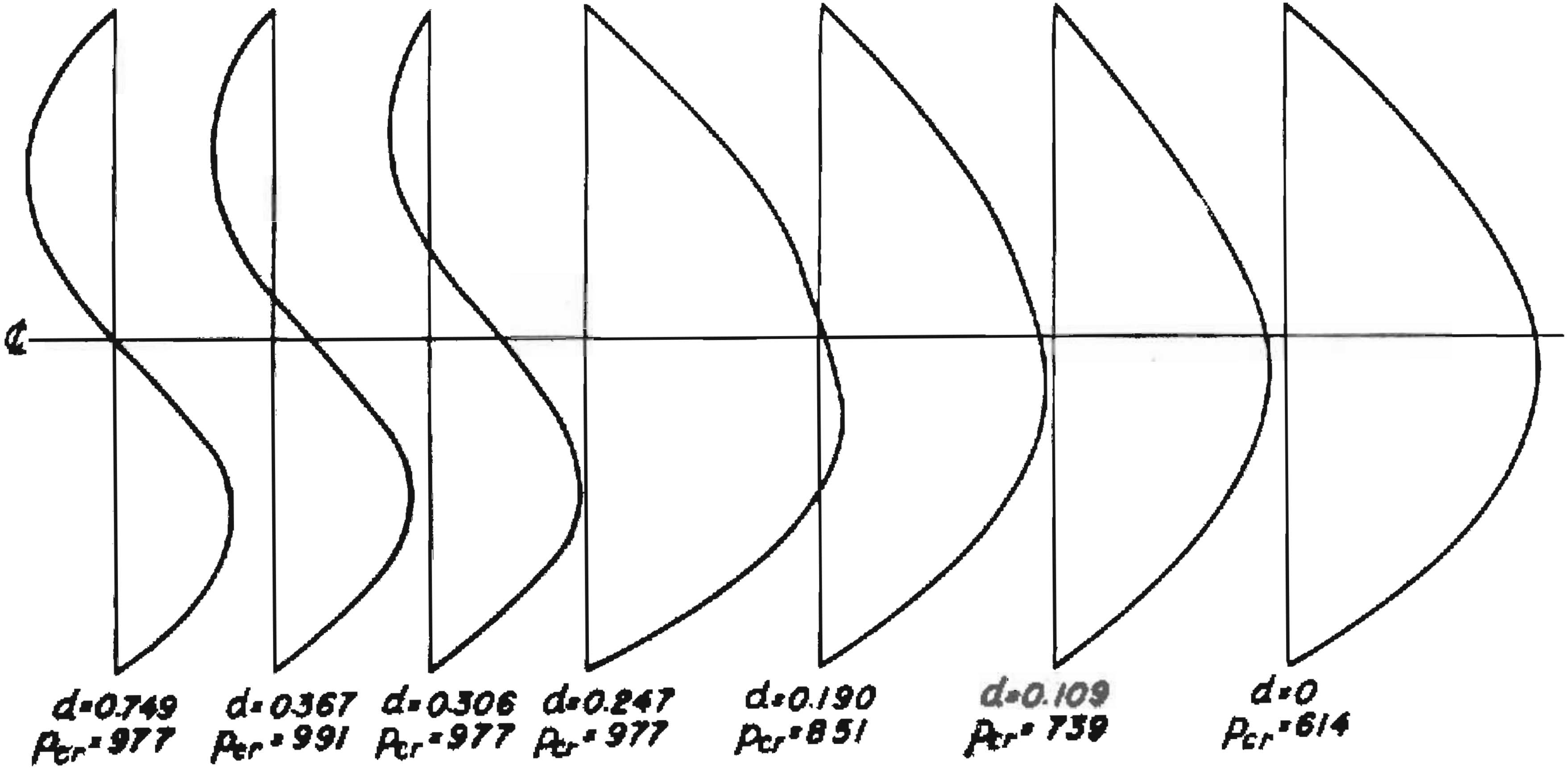

Figure 1.--Typical buckle patterns as viewed along the centerline perpendicular to the stiffener of a stiffened plate obtained by making a trace on the vertical centerline of the plate while it is buckled in the testing machine. (Plate No. 4)

Z M 57776 F

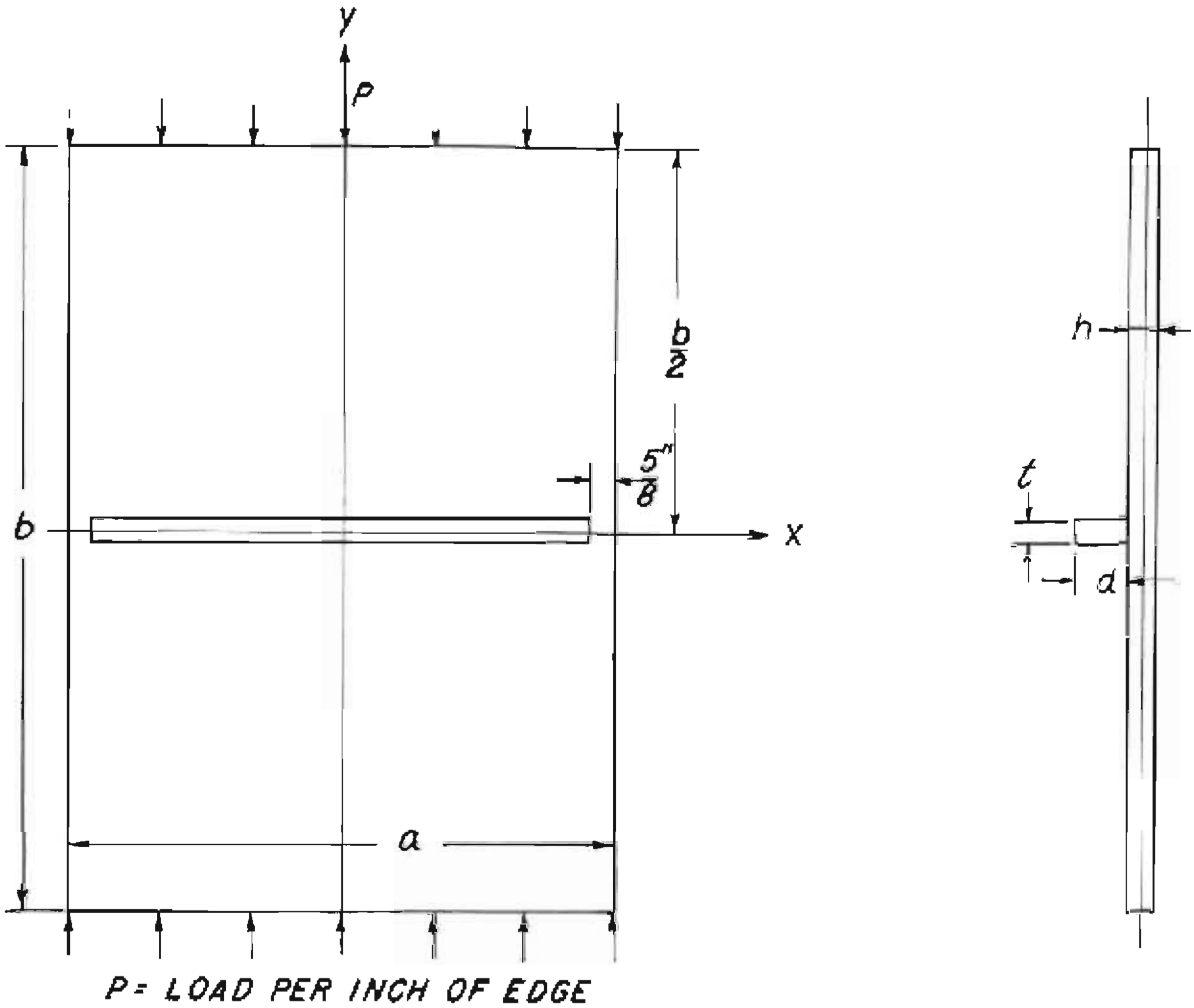

Figure 2.--A stiffened plate, showing dimensions, position of stiffener, and direction of stress.

Z M 87773 F

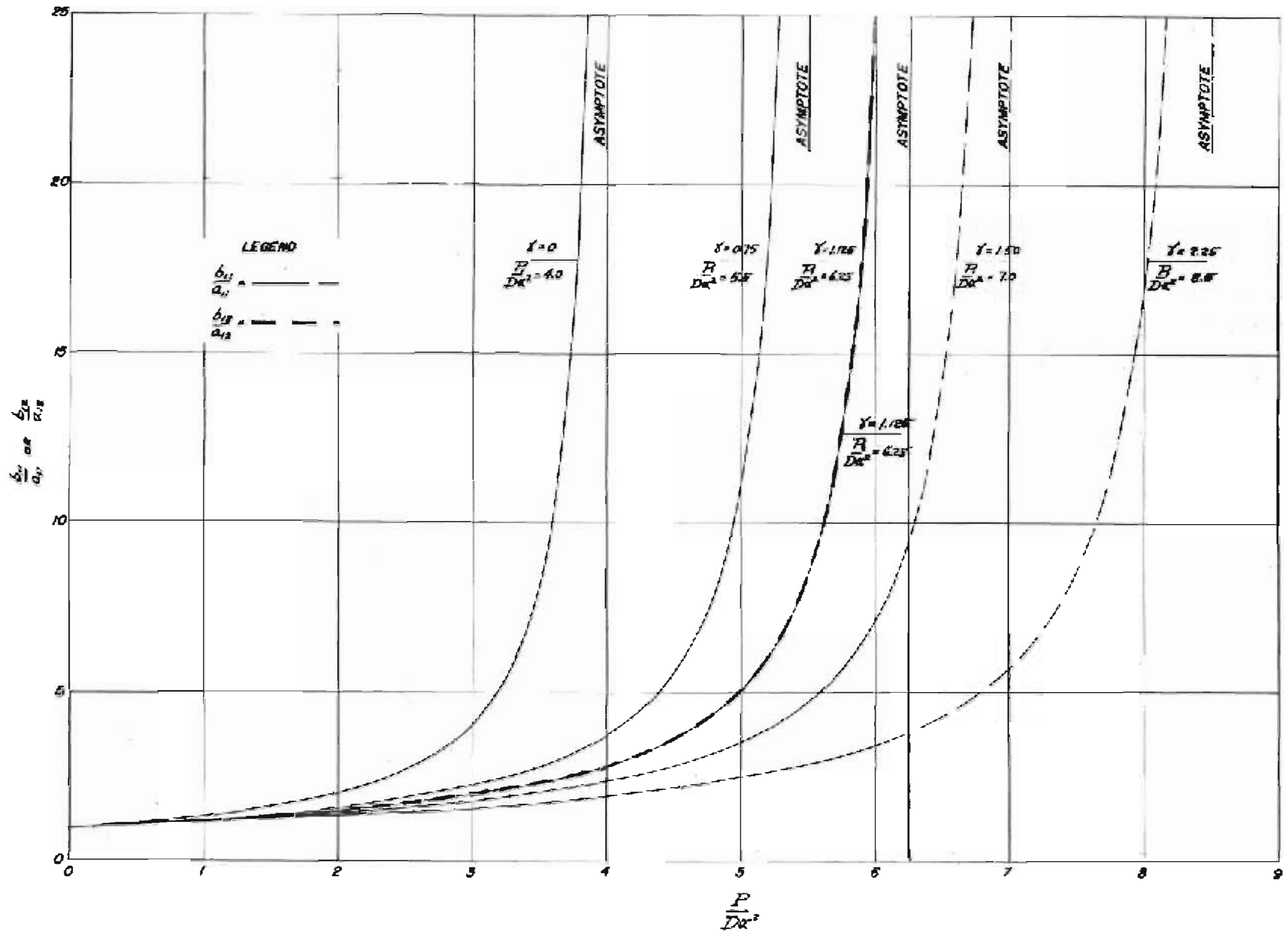

Figure 3.--The amplification of the first and second modes for an isotropic plate with one horizontal stiffener for stiffeners with different stiffness ratios $y = \frac{(EI)_s}{D \text{ plate} \times a}$

Z M 67778 F

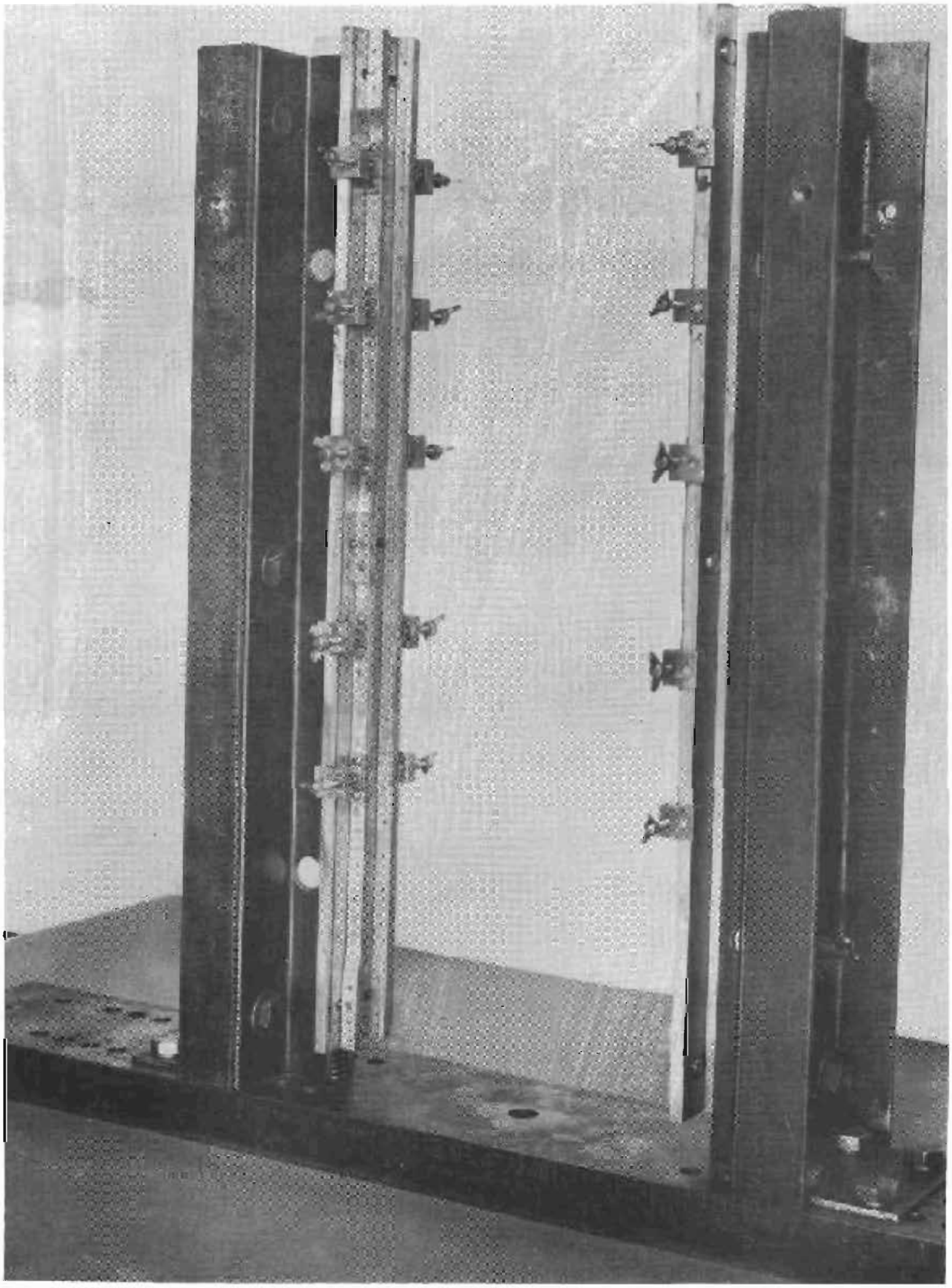

Figure 4.--Side view of panel buckling apparatus showing movable post in place.

Z M 68856 F

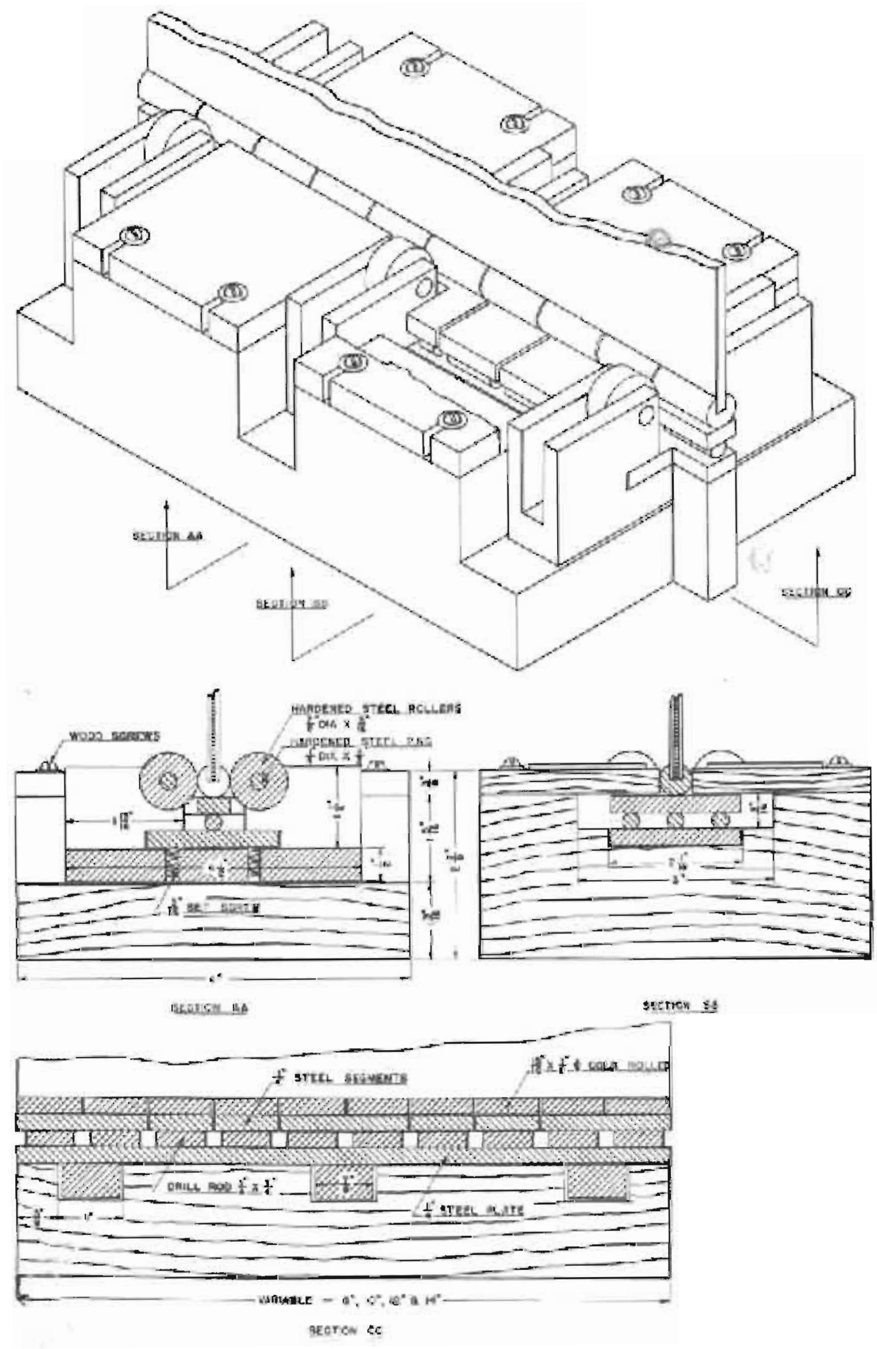

Figure 5.--Design details of loading head used in tests of stiffened flat plywood plates.

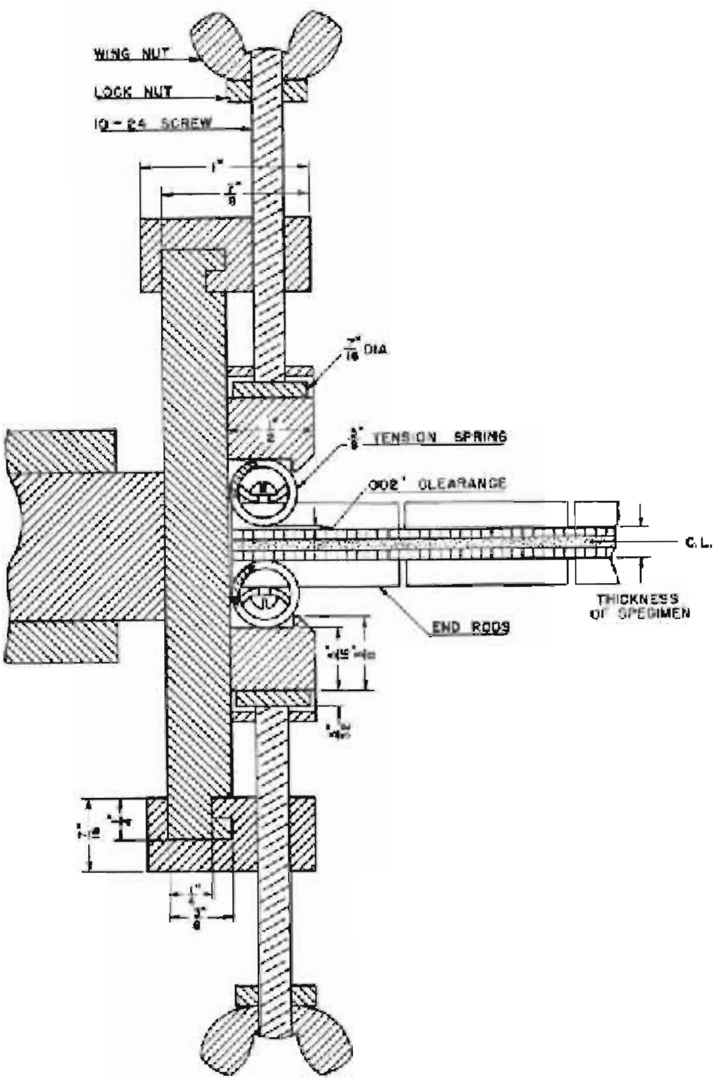

Figure 6.--Detail of edge support for panel buckling test of stiffened flat plywood plates.

Z M 57773 F

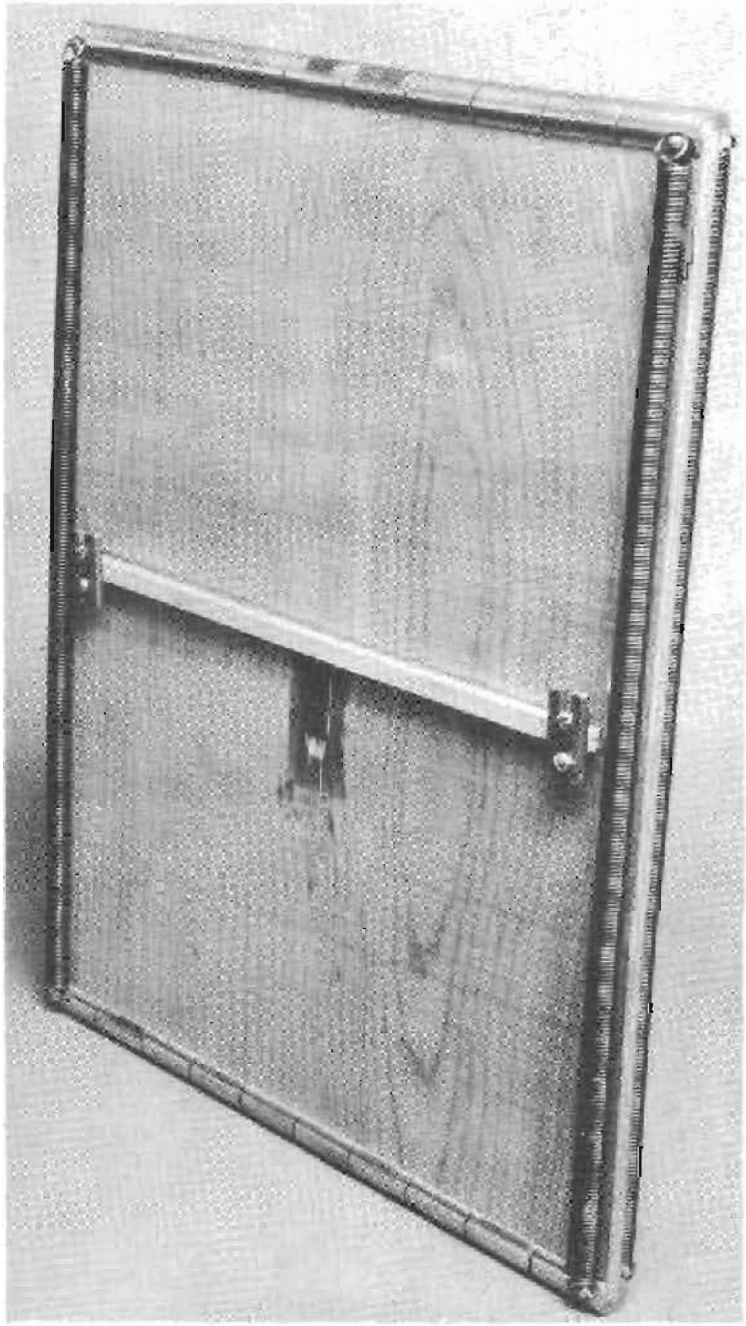

Figure 7.--Stiffened flat plywood plate mounted in segmented cylindrical steel loading rods prior to test. The method of restraining the ends of the stiffener to prevent separation at the ends, the metalectric strain gage for measuring deformations, and the attachment of coil springs at the edges to reduce frictional restraint during test are shown.

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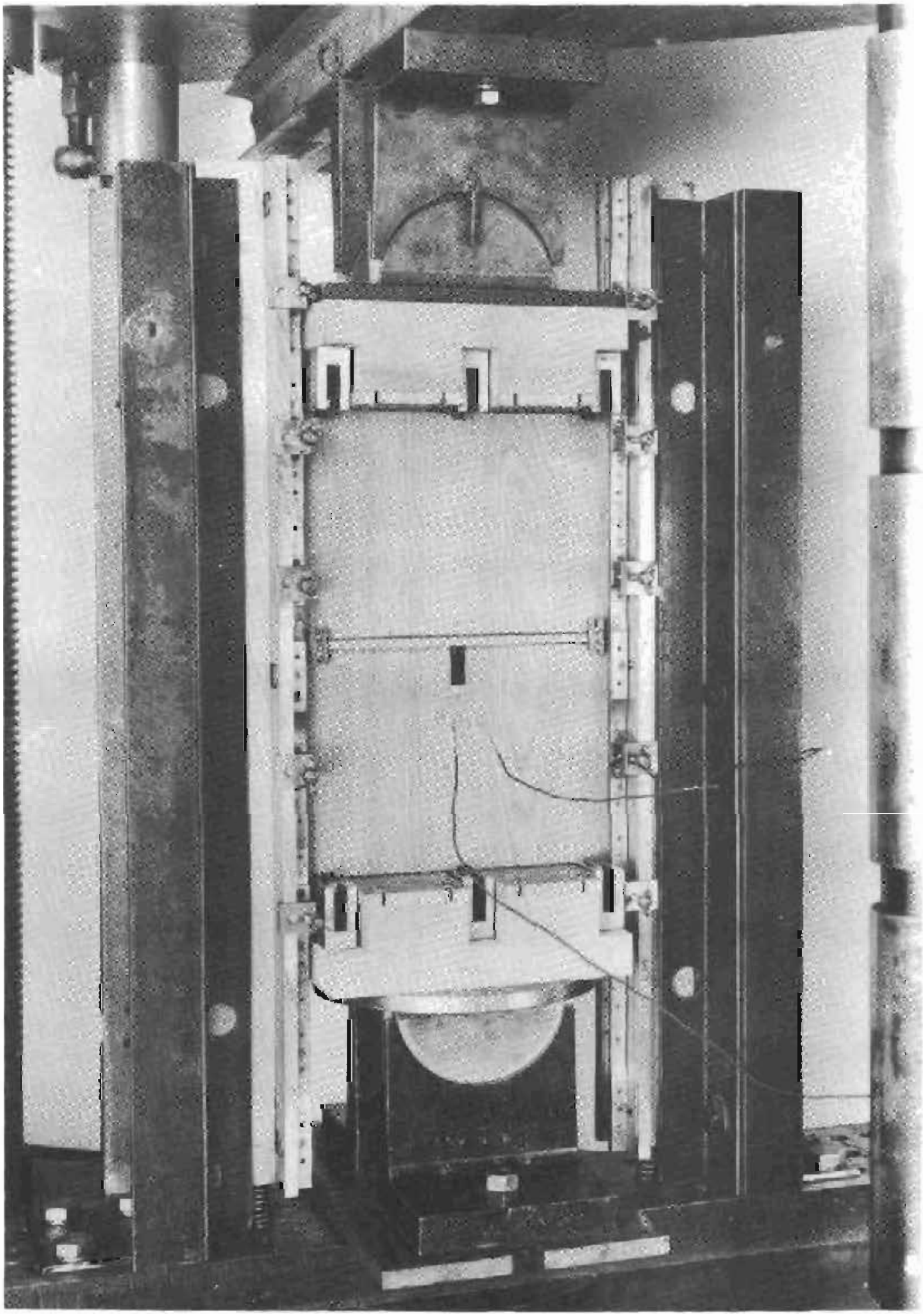

Figure 8.--Stiffened flat plywood plate ready for test. Metalectric strain gage mounted below horizontal stiffener is used in measuring deformations in the specimen.

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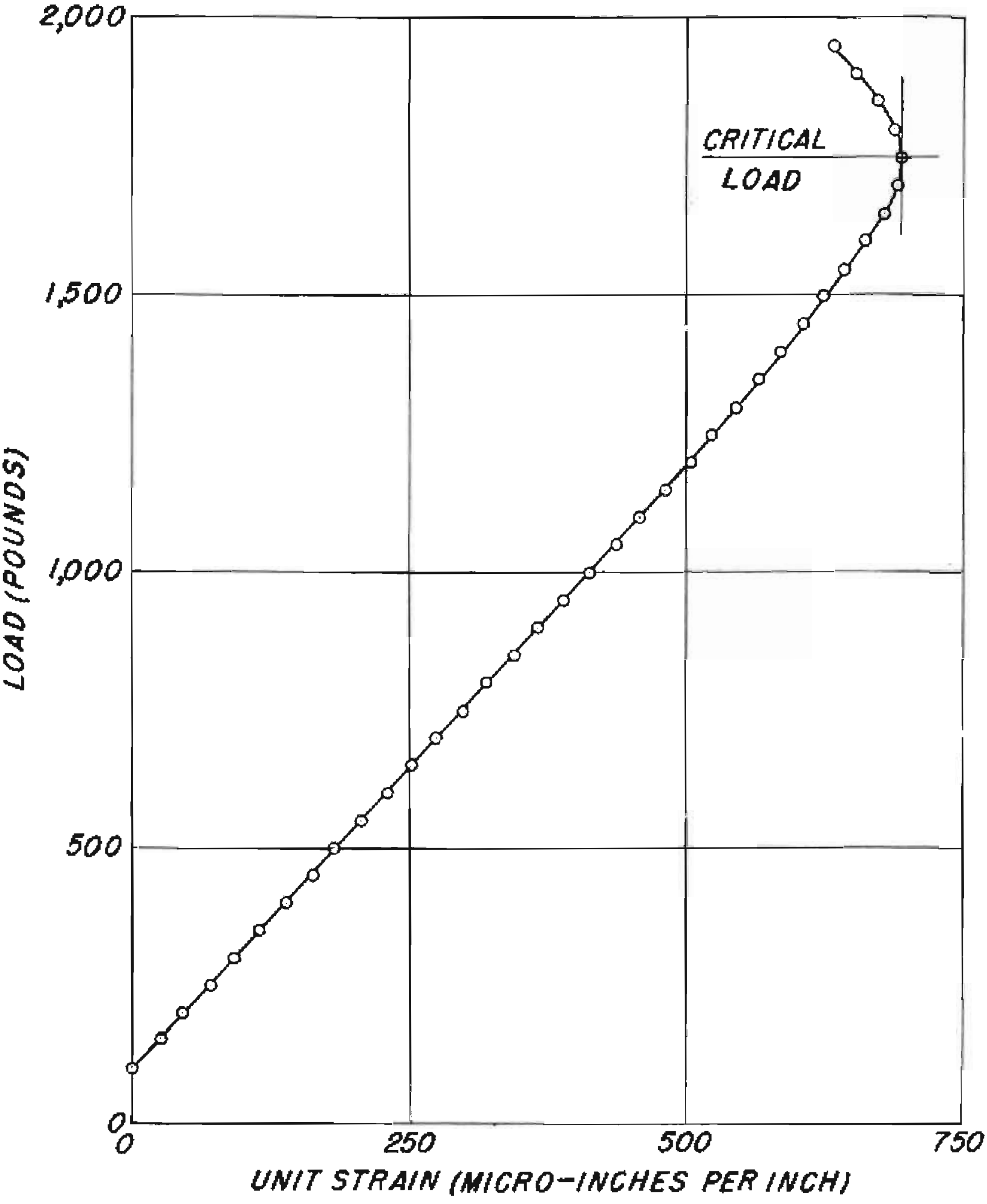

Figure 9.--Typical load-strain curve, plotted to determine critical load of a stiffened plywood plate in compression.

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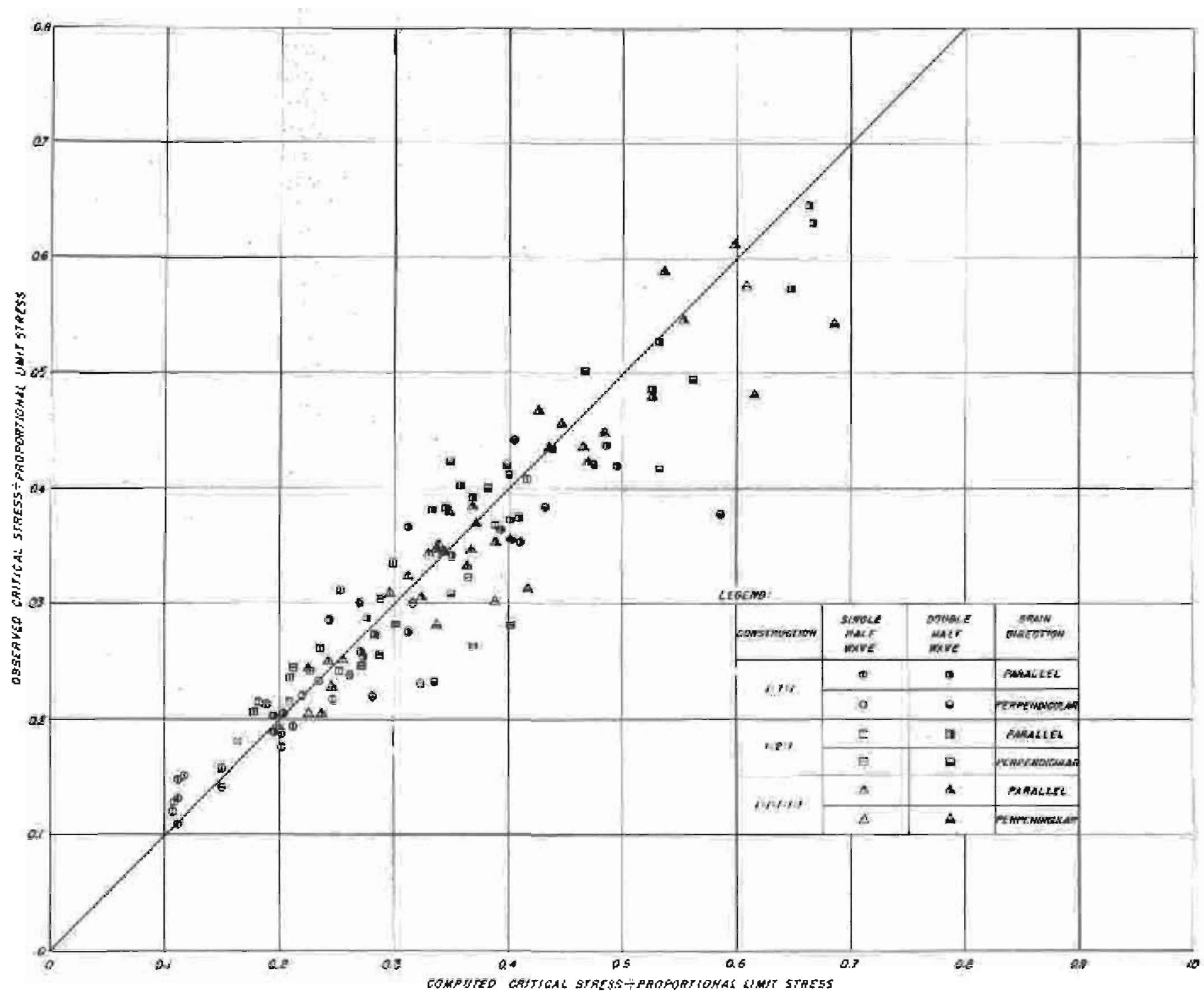

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Figure 10.--Comparison of observed critical load with computed critical load -- both expressed as ratios to computed proportional limit load. Direction of face grain parallel or perpendicular to direction of compression.

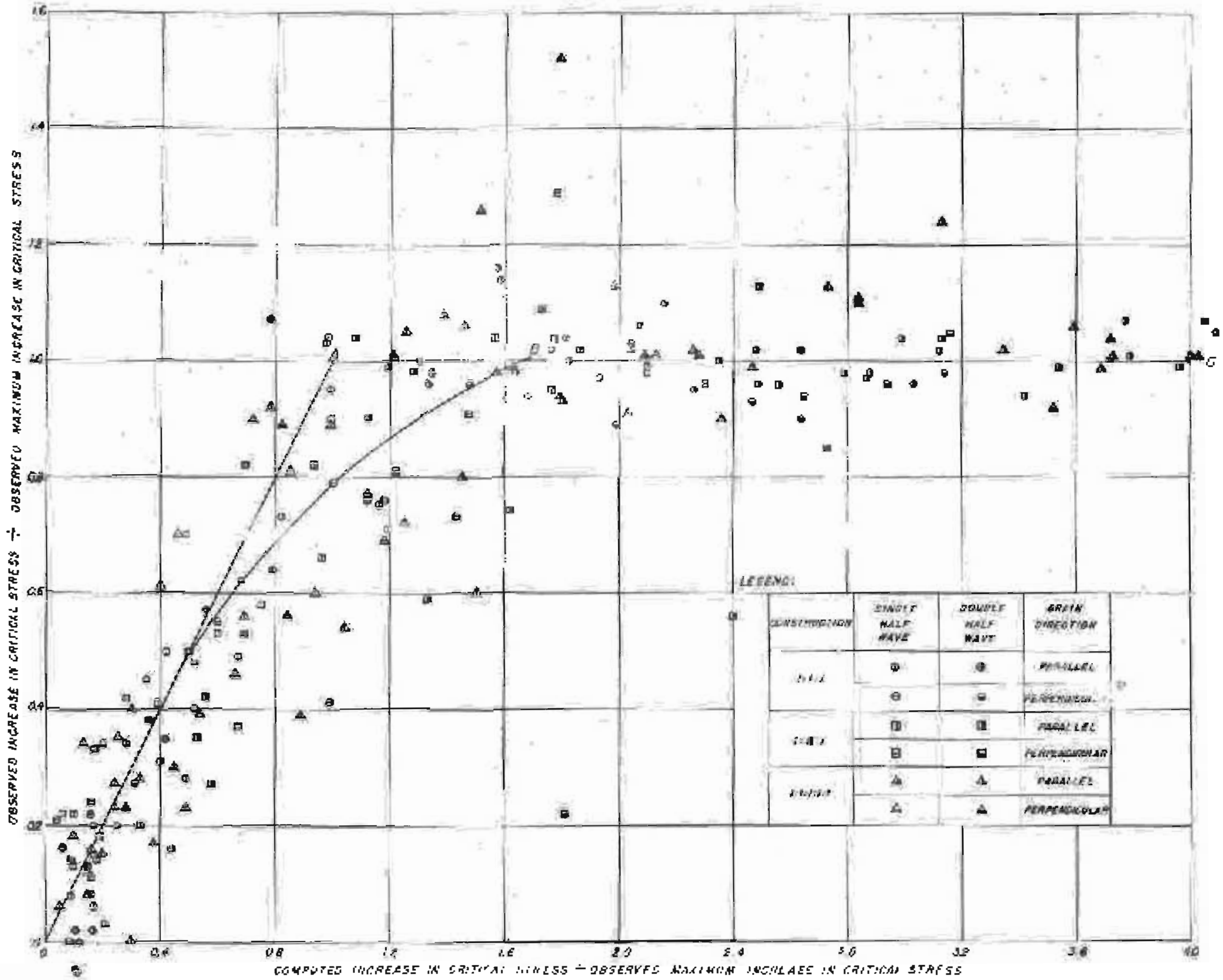

Figure 11.--Comparison of observed increase in critical stress with theoretical increase in critical stress -- both expressed as ratios to observed maximum increase in critical stress.

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