Supplement to

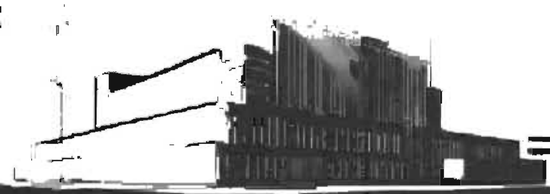
DESIGN OF PLYWOOD WEBS IN BOX BEAMS

THE EFFECT OF REPEATED BUCKLING ON THE ULTIMATE STRENGTH OF BOX BEAMS WITH SHEAR WEBS IN THE INELASTIC BUCKLE RANGE

Information Reviewed and Reaffirmed

January 1959

No. 1318-E



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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE

In Cooperation with the University of Wisconsin

Supplement to

DESIGN OF PLYWOOD WEBS IN BOX BEAMS

THE EFFECT OF REPEATED BUCKLING ON THE ULTIMATE STRENGTHS OF BOX BEAMS WITH SHEAR WEBS IN THE INELASTIC BUCKLE RANGE[1]

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Summary

This report presents the results of a limited number of tests to determine the effect of repeated buckling on the ultimate strengths of box beams with shear webs in the inelastic buckle range. The study was made on box beams with 45° grain shear webs and with a/a_0 values less than 1.6, loaded repeatedly to about two-thirds of the design ultimates for the webs, as established by the curves[3] of figure 4 of Forest Products Laboratory Mimeograph No. 1318, and subsequently tested to failure. While the tests reported herein were of an exploratory nature and were too few in number to establish quantitative data, the results show that plywood webs that are buckled inelastically[4] under repeated stresses of approximately two-thirds of the design ultimate are measurably damaged.

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[1] This report is one of a series of progress reports prepared by the Forest Products Laboratory to further the nation's war effort. Results here reported are preliminary and may be revised as additional data become available. Original report published December 1944.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3] The curves were subsequently published as a part of figure 2-41 of the Army-Naval-Civil Committee on Aircraft Design Criteria Bulletin 18, "Design of Wood Aircraft Structures."

[4] Inelastic buckling is discussed and defined in Forest Products Laboratory Mimeograph No. 1318-B, "Buckling in Shear Webs of Box and I-Beams and the Effect Upon Design Criteria."

After approximately 40 repetitions of about two-thirds of the design ultimate load, the strengths of the beams varied from 80 to 97 percent of the design ultimate when loaded to failure in the normal position and from 83 to 99 percent of the design ultimate when loaded to failure in the inverted position. All the beams failed at stresses less than design ultimate. In previous tests where the beams were loaded to failure in one loading, the ultimate shear stresses in the webs were usually a little higher than indicated by the design curves of figure 4 and only occasionally were lower.

Damage to the webs by buckling was progressive and indications are that the greatest damage occurred in the webs the first time they were buckled. Damage per cycle decreased as the number of cycles increased. This was observed from measurements of the deflections and deformations of the different parts of the beams for each application and release of load.

Most of the plywood webs were visibly damaged by the repeated stresses. This damage ranged from slight residual buckles which remained in the webs after the load was released, to buckles that were so deep that compression failures were visible in the valleys of the buckles.

The results suggest that care should be exercised to avoid the use of webs that may be damaged by buckling before the limit or expected load is reached.

Introduction

This report is the sixth of a series pertaining to the design of plywood webs in shear for box and I-beams in aircraft. Details of testing and means of analyzing data not included in this report may be obtained from the previous reports (Forest Products Laboratory Mimeographs Nos. 1318, 1318-A, 1318-B, 1318-C, and 1318-D).

The beams discussed in this report were constructed and tested to determine whether or not repetitions of the buckling stress adversely affect the strengths of beams with webs which might buckle inelastically. Two-thirds of the design ultimate for the webs was chosen for the maximum repeated load to correspond with the assumed factor of safety of 1.5. Thus, field conditions were simulated in these tests by loading the beams repeatedly to about two-thirds of the design ultimate before loading to failure.

Some of the beams were loaded to failure in the normal position to determine the reduction in strength for normal loading and some were loaded to failure in the inverted position to determine the corresponding reduction in strength for upside-down loading.

These beams were all designed to fail by shear in the webs. The stresses in the compression and tension flanges and in shear in the glue lines joining the flanges and the webs were not critical at any time during the loading of the beams.

Notation[5]

The following symbols, ANC whenever possible, are used in this report. All quantities are in inch and pound units.

a = the length of the short side of the panel (the distance between flanges or between stiffeners, whichever is smaller).

a_o = the width of a hypothetical panel of length b which will buckle theoretically at a shearing stress of $F_{s\theta}$.

b = the length of the long side of the panel.

C_c = the distance from the neutral axis to extreme fiber of the compression flange when the beam was loaded in the normal position.

C_t = the distance from the neutral axis to extreme fiber of the tension flange when the beam was loaded in the normal position.

E_L = modulus of elasticity of wood in the direction parallel to the grain (calculated).

E_1 = effective bending modulus of elasticity of the plywood when the grain of the face plies is parallel to the span.

E_2 = effective bending modulus of elasticity of the plywood when the grain of the face plies is perpendicular to the span.

E_a = effective modulus of elasticity of the plywood in compression or tension, when the applied stress is parallel to the grain in the face plies. (E_w in ANC 18)

E_b = effective modulus of elasticity of the plywood in compression or tension, when the applied stress is perpendicular to the grain in the face plies. (E_x in ANC 18)

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[5] For methods of computing results of test, see sample calculations in Mimeograph No. 1318 on pages 4 to 7, inclusive.

$(F_{cu})_a$ = ultimate compressive strength of the plywood with the grain of the face plies parallel to the stress. (F_{cuw} in ANC 18)

$(F_{cu})_b$ = ultimate compressive strength of the plywood, with the grain of the face plies perpendicular to the stress. (F_{cux} in ANC 18)

$(F_{tu})_a$ = ultimate tensile strength of the plywood, with the grain of the face plies parallel to the stress. (F_{tuw} in ANC 18)

$(F_{tu})_b$ = ultimate tensile strength of the plywood, with the grain of the face plies perpendicular to the stress. (F_{tux} in ANC 18)

F_{su} = the design ultimate shear stress for the webs as calculated from the ultimate shear curves of figure 4 of Mimeograph No. 1318.

$F_{s\theta}$ = allowable (ultimate) stress for plywood in shear, where θ is the angle of the grain of the face plies from the axis of the beam.

f_{scr} = calculated unit shear stress at buckling load during first cycle of loading,

$$= \frac{VQ}{It} = \frac{P_{cr}Q}{2It}$$

f_{sr} = calculated unit shear stress at maximum load for repeated loading,

$$= \frac{P_rQ}{2It}$$

f_{su} = calculated unit shear stress at ultimate load,

$$= \frac{P_uQ}{2It}$$

G = effective shearing modulus of plywood with the grain oriented in the same direction as in the beam.

I = moment of inertia[6] of the cross section of the beam about its neutral axis.

P_{cr} = load on beam at buckling during first cycle of loading.

P_r = maximum load on beam for repeated loading.

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[6] The area of the webs was transformed by using the modular ratio 1/4 (see ANC 18, section 3.1151), both in locating the neutral axis and in calculating I and Q.

P_u = ultimate load on beam.

Q = statical moment[6] of the cross section of the beam about its neutral axis.

t = total thickness of the webs.

t_w = thickness of thinner web.

V = total shear.

$+$ = positive grain, diagonal tension in webs parallel to the grain in face plies.

$-$ = negative grain, diagonal tension in webs perpendicular to the grain in face plies.

Description of Beams

The beams were from 4-1/6 to 5-1/2 inches wide, from 9 to 18 inches high, and 10-1/2 feet long. Aircraft grade yellow-poplar plywood with the grain of the face plies sloping 45° downward towards the reactions (negative grain) was used for the webs of the beams. The flanges were of Sitka spruce. Details of construction and pertinent information for the beams[7] are shown in figures 43 and 44.

Plywood for the webs had a 1:2:1 veneer thickness ratio and was manufactured at the Forest Products Laboratory from veneers that were rotary-cut and prepared at the Laboratory. Nominal plywood thicknesses were 1/4, 1/8, and 1/12 inch. Sitka spruce for the flanges and incidental parts of the beams was from planks sawn and kiln-dried at the Laboratory. All flanges were laminated. The stiffeners, load blocks, and reaction blocks were of a built-up design similar to those used in previous beams and described in the earlier reports of this series. The plywood was bonded with a phenolic-resin film glue set in hot presses. A cold-setting urea-formaldehyde-resin glue was used for laminating flanges and for all assembly gluing.

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[7] The figures and tables in this report are numbered consecutively with those of the previous mimeograph in this series.

Selection and Matching

Sitka spruce flange material was flat-sawn and was selected by examination and on the basis of results from minor tests made prior to constructing the beams. Minor specimens for toughness, static-bending, and compression-parallel-to-the-grain tests were prepared from the sides or ends of the planks.

Minor specimens, representative of the material in the webs of beams, were prepared from the same panels of plywood as were used to make the webs of the beams.

Methods of Test

The beams were tested in a 200,000-pound screw-type testing machine by loading at the third points of a 10-foot span. Deformation was applied to the beams at standard rates as established by the American Society for Testing Materials. Enough initial load, 200 or 300 pounds, was applied to each beam to bring the movable head of the testing machine in contact with the beams. Load was then applied to the beams in predetemined increments until the maximum load for the repeated stress was attained. Loading was stopped while readings were taken at the end of each increment and at maximum repeated load (P_r). The loads were then removed from the beams in three increments, with readings taken at the end of each increment and when initial load was again reached. This procedure was repeated until at least 10 full cycles of data were obtained. Data was obtained for initial and maximum loads only for the remaining repetitions of load.

After the repeated stress phases of the tests were completed, dials and gages were removed, and the beams were loaded to failure in either the normal or inverted positions. The webs were examined during test and any indications of damage were noted.

Figure 45 shows a beam in the testing machine ready for test with the strain- and deflection-measuring instruments in place. Visible in this photograph are the dials used to measure deflections of the webs, dials used to measure deformations between flanges in the vertical and inclined directions, Huggenberger tensometers, dials and scale used to measure deflections of the beam with respect to reaction and load points, and metalectric strain gages and automatic recorder.

Tests of minor specimens for the webs included static bending with the grain of the face plies parallel to the span, static bending with the grain of the face plies perpendicular to the span, compression and tension with the applied stress parallel to the grain in the face plies, compression and tension with the applied stress perpendicular to the grain in the face plies, and plate shear.

Static-bending tests were made on the plywood to determine the effective moduli of elasticity in bending when the grain of the face plies was parallel to the span (E_1), and when perpendicular to the span (E_2). Specimens were tested under center loading of a simply-supported span. Specimens were 2 inches wide for the 1/4- and 1/8-inch plywood and 1 inch wide for the 1/12-inch plywood. Spans were 48 times the nominal thickness when the grain of the face plies was parallel to the span, and 24 times the nominal thickness when perpendicular.

Tension specimens[8] were 16 inches long with a minimum section of 1/2 inch by the thickness of the plywood. These tests gave the effective moduli of elasticity in tension, E_a and E_b, and the ultimate tensile strengths, $(F_{tu})_a$ and $(F_{tu})_b$.

The dimensions of the compression specimens were 1 by 4 inches 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, E_a and E_b, and the ultimate compressive strengths, $(F_{cu})_a$ and $(F_{cu})_b$ were thus obtained.

The plate shear tests determined the moduli of rigidity of the plywood (G). This test is described in detail in Forest Products Laboratory Mimeograph No. 1301.

The dimensions and methods of test of the minor specimens conformed to the recommendations of the report of Committee D-7 on Timber of the American Society for Testing Materials, entitled "Proposed Methods of Testing Veneer, Plywood, Wood and Wood-Base Laminated Material," preprint of 1944. To minimize moisture content differences between the beams and the minors, the minor test coupons were kept with the beams until test, and were tested as nearly concurrently with the test of the beam as was possible.

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[8] The tension specimen is detailed in figure 24 of Forest Products Laboratory Mimeograph No. 1318-C.

Presentation of Data

The data from individual tests of the box beams are presented in table 10. The values of $\frac{I}{C_c}$ and $\frac{I}{C_t}$, are given in columns 12 and 13, are for the beams when loaded in the normal position--for inverted loading, these values should be interchanged. The values of E_L, $F_{s\theta}$ for normal loading (- grain), and $F_{s\theta}$ for inverted loading (+ grain), in columns 18, 19, and 20, respectively, were calculated from the averaged minor tests for each thickness of plywood in table 12. The design values for normal and inverted loading in columns 21, 22, 23, 24, 25, and 26 were obtained from the curves of figure 4 of Forest Products Laboratory Mimeograph No. 1318. The ratios of the calculated shear stresses in the webs at failure of the beams to the design ultimate shear stresses for the webs $(\frac{f_{su}}{F_{su}})$, in column 37, show the apparent degree to which the shear strengths of the webs were reduced by the repeated loadings.

The results of the static-bending, compression, tension, and plate shear plywood minor tests are presented in table 11. Table 12 presents a summary of the average values of moduli of elasticity and compression and tension ultimate strengths for the plywood web minors. These results are listed in this table by nominal web thicknesses. The averaged results were used to calculate the values of E_L and $F_{s\theta}$ which appear in columns 18, 19, and 20 of table 10.

The moisture content differentials between the webs of the beams and the minor test specimens and among the webs of the different beams were small. The effects of corrections for moisture content differences were studied and, after due consideration, were omitted in determining the average values of E_L and $F_{s\theta}$ and in calculating a/a_o, F_{su}, f_{sr}/F_{su}, $f_{scr}/F_{s\theta}$, and f_{su}/F_{su}.

Figures 46 and 47 are load-deflection-of-web curves for panels of two of the beams for the first 10 cycles of loading. Figure 46 shows the curves for one panel of the web of beam 3-RP which was considerably damaged by repeated buckling. Figure 47 shows the curves for beam 3-RV which was damaged only a small amount. Similar sets of curves were obtained for nearly all of the other beams.

The deflection of the plywood webs at the buckle dial for initial load (300 pounds) and at maximum repeated load (25,000 pounds) for each cycle of repeated loading for beam 2-RVB is shown in figure 48. Curves similar to this one were obtained for nearly all beams. Similar conditions occurred at the inclined diagonal compression dials and at the dial which measured the movement of the lower flange with respect to the upper flange at the end of the beam.

Figures 49 and 50 show the extent to which two of the beams were damaged by repeated buckling. Figure 49 shows a compression failure in the valley of the buckle in one web of beam 2-RVA at 24,200 pounds total load during the first cycle. Figure 50 shows the compression failure in the valley of a buckle in the web of beam 3-RP after 13 repetitions of stress. This failure was definitely visible in the web at the end of the ninth cycle. Figure 51 shows beam 3-RP after final failure. It shows the end opposite that shown in figure 50 and shows the diagonal tension failure, in the web, which followed the compression failures in the valleys of the buckles.

Observations made of the beams during test or from the plotting of data are appended to this report.

Analysis of Results

Data obtained from these tests indicate that 45°-grain shear webs, in the inelastic buckling range, are damaged by repeated buckling. These tests were exploratory and were too few in number to establish definitely the magnitude of the damage to the webs when they buckle inelastically. The reduction in strength at failure for the few beams tested, however, is significant.

Beams 2-RPB, 3-RP, 4-RP, and 5-RP were loaded repeatedly approximately 40 times to two-thirds of the design ultimate for the webs before they were loaded to failure in the normal position. The ratios of shearing stress at ultimate load to the design ultimate shear stresses $(\frac{f_{su}}{F_{su}})$ for these beams were 0.97, 0.89, 0.80, and 0.90, respectively.

Beams 1-RV, 2-RVB, and 3-RV were loaded to failure in the inverted position after loading 40 times to about two-thirds of the design ultimate for the webs in the normal position. Ratios of $\frac{f_{su}}{F_{su}}$ for these beams were 0.83, 0.87, and 0.99, respectively. These values are significant and indicate damage to the webs by the repeated loading. In previous tests of box and I-beams where loading was carried to failure in one operation, the ultimate shear stresses in the webs were usually a little higher than indicated by the design curves of figure 4 of Forest Products Laboratory Mimeograph No. 1318 and only occasionally were lower.

Damage to the webs by repeated buckling was progressive and indications are that most of the damage usually occurred during the first application of load as is shown by figures 46, 47, and 48. In figure 46, the load-deflection-of-web curves for one panel of beam 3-RP are plotted for the first 10 applications of load. This web was damaged considerably by the repeated applications of stress. A compression failure was visible in the valley of the buckle in this panel at the end of the ninth cycle. Damage to the web for each cycle is shown by the difference in readings at initial load for the beginning and end of each cycle. This difference is considerable for the first cycle and in general becomes less with each successive loading. The accumulative damage to the web is shown by the general increase in deflections at initial and maximum repeated load.

The area enclosed by each curve is mainly due to the effects of hysteresis and damage to the web. The hysteresis effects should be nearly constant for each cycle; therefore, the differences in area are probably due to differences in damage to the webs for the different cycles of loading. The area enclosed by the curve for the first cycle is large and in general the area is smaller for each succeeding cycle. This indicates also that most of the damage occurred during the first application of load, and that damage to the webs was generally less per cycle as the number of cycles increased. Another indication of damage to the web is the change in initial slope of the curves for the first and second cycles. That the initial slopes were flatter for all curves after the first cycle, shows that the webs were damaged during the first buckling and some residual buckling remained.

Figure 47 is a similar series of curves for one panel of beam 3-RV and shows many of the same characteristics as figure 46 but to a lesser degree. The webs of this beam were damaged less than the webs of beam 3-RP. Similar curve series were obtained in nearly all instances for the other beams. In some, the damage to the beams was great enough to be reflected in a similar manner in the data obtained from the diagonal compression dials and the dials used to measure the movement of one flange with respect to the other one.

The deflection of the plywood web at the buckle dial for one web of beam 2-RVB for initial and maximum repeated load for each cycle is shown in figure 48. This plot is typical of many others obtained and shows that the damage to the web is progressive, but that most of the damage occurs during the first cycle. These curves also show that the damage per cycle appears to decrease with increasing repetitions of load.

Most of the beams were visibly damaged by repeated loading to approximately two-thirds of design ultimate. This visible damage varied from slight residual buckles which remained in the webs at initial load to compression failures in the valleys of buckles. One web of beam 2-RVA was so severely buckled at maximum repeated load on the first loading that a compression failure extended from corner to corner of the panel. This beam failed in the webs at the end of the third application of load. Beam 3-RP was damaged to the extent that a compression failure was visible in the valley of a buckle in one panel after nine repetitions of load and in two more panels after 40 repetitions. Evidence of visible damage to each beam is presented in more detail in the appendix to this report.

The results of these tests have shown that webs of beams with low a/a_o values, in the inelastic buckle range, are damaged by repeated applications of load of approximately two-thirds of the design ultimate for the webs, and that care should be exercised to avoid the use of webs that may be damaged by repeated buckling before the limit or expected loads are reached.

Conclusions

A limited number of tests of box beams with webs with a/a_o values of less than 1.6 indicates that the webs are damaged by repeated buckling. The beams in this series of tests were loaded repeatedly to about two-thirds of the design ultimate for the webs before being loaded to failure in either the normal or inverted position.

While the tests herein reported were exploratory, and were too few in number to establish quantitative values, the results show that plywood webs which are repeatedly buckled inelastically under repeated stresses of approximately two-thirds of the design ultimate are measurably damaged.

The strengths of the beams varied from 80 to 97 percent of the design ultimates when tested to failure in the normal position after approximately 40 repetitions of approximately two-thirds of the design ultimate stress as determined for the webs from figure 4 of Forest Products Laboratory Mimeograph No. 1318. The strength of the beams which were loaded to failure in the inverted position after being loaded repeatedly 40 times in the normal position varied from 83 to 99 percent of the design ultimate. All the beams failed at stresses less than design. In previous tests where the beams were tested to failure in one loading, the ultimate shear stresses in the webs were usually a little higher than indicated by the design curves of figure 4, and only occasionally were lower.

Damage to the webs by buckling was progressive and it appears that the greatest damage occurred during the first cycle of loading. Damage per cycle decreased as the number of cycles increased.

Most of the beams were visibly damaged by the repeated loading. This damage ranged from slight residual buckles, which remained in the webs when loads were removed, to visible compression failures in the valleys of buckles.

The results suggest that care should be exercised to avoid the use of webs that may be damaged by buckling before the limit or expected load is reached.

Appendix

Beam 1-RP.--This beam, being the first test in the series, was subjected to a different load repeating program from the other beams. The beam was loaded and unloaded 10 times to a calculated shear stress of 2,690 pounds per square inch, which was 0.76 of design ultimate. There was no perceptible buckling in the web at any time during these repetitions. The beam was then loaded and unloaded four times to a maximum calculated shear stress of 2,940 pounds per square inch, which was 0.83 of design ultimate. The next three cycles of load were of a magnitude to give a calculated shear stress of 3,180 pounds per square inch at maximum, which was 0.90 of design ultimate. The beam was then loaded twice to a calculated shear stress of 3,430 pounds per square inch, which was 0.97 of design ultimate. The webs were definitely buckled at maximum load for these repetitions. The webs of the beam failed at a calculated shear stress of 3,410 pounds per square inch during the next loading. Failure in the webs appeared to be primarily in diagonal tension.

Beam 2-RP.--This beam was loaded 10 times to 12,000 pounds before being loaded to failure. The calculated shear stress in the webs was 2,390 pounds per square inch, which was 0.71 of the design ultimate. The webs buckled at 10,000 pounds total load during first loading. Buckles were about 1/16 inch deep in each panel at the maximum load of 12,000 pounds for the repeated loads. Deformation readings indicated that the damage to the webs after 10 cycles was only slight. Compression wrinkles were visible in the valleys of the buckles at 16,000 pounds total load just before the web of the beam failed in diagonal tension at 16,880 pounds total load.

Beam 2-RPA.--This beam was loaded to failure without being subjected to repeated loads in order that a direct comparison between two similar beams might be had when one was subjected to repeated loads and one was not. The failure of this beam, however, was premature, due to a defective load block which separated at the glue joints between the vertical and upper horizontal components. The test value should not be used because the primary failure was not in the web. The webs buckled at 10,000 pounds.

Beam 2-RPB. -- This beam was loaded 40 times to 12,000 pounds before it was loaded to failure. The calculated shear stress in the webs at this load was 2,320 pounds per square inch, which was 0.68 of design ultimate for the webs. Buckles were visible in the webs during the first application of load, at 10,000 pounds total load. At 12,000 pounds, the maximum repeated load, 75 percent of the panels were definitely buckled. The readings of buckle, shear, and diagonal dials all indicated that the webs were damaged by the first application of stress. After 40 cycles, slight residual buckles with maximum depths of from 1/16 to 1/8 inch remained in the plywood. The beam failed suddenly in the webs, apparently due to excessive buckling and diagonal tension at 17,000 pounds total load. Compression wrinkles were visible in the valleys of buckles for the last 3,000 pounds of load.

Beam 3-RP. --This beam was loaded 40 times to 10,500 pounds before being loaded to failure. The calculated shear stress in the web at this load was 2,150 pounds per square inch and was 0.72 of the design ultimate for the webs. Buckles were visible in a few panels at 9,000 pounds load on the beam during the first cycle. At the end of the first cycle, at least three of the panels were visibly damaged. Some residual buckles remained in these panels when the load was removed. The residual buckles in the webs became deeper as the number of cycles of loading increased, indicating that the damage to the webs was progressive. At the end of the tenth cycle, residual buckles were in 8 of the 12 panels in shear portions of the beams.

Compression wrinkles were definitely visible in the valley of the buckle in one panel at the end of the ninth cycle, but their presence was suspected before that time. At the end of the 40 cycles, compression wrinkles were visible in the valleys of buckles in three panels. The shear and buckle dials and the dials measuring deformation along the compression diagonal indicated that the webs were damaged during the first application of load. These dials showed also that the damage was progressive as the number of loadings increased, but that the amount of damage per cycle was a decreasing function.

The beam failed suddenly in the webs at 13,000 pounds total load, apparently due to excessive buckling. The web that failed was not the one with the first compression failure.

Beam 4-RP. -- This beam was loaded 43 times to a maximum of 25,000 pounds before it was loaded to failure. The calculated shear stress in the webs at this load was 1,680 pounds per square inch and was 0.67 of the design ultimate for the webs. Buckling probably occurred at 20,000 pounds during the first cycle; the buckles were definitely visibly at 22,500 pounds total load.

Residual buckles remained in the webs after several repetitions of stress, and after 38 cycles they varied in depth from 1/32 to 1/16 of an inch. There were no visible compression failures in the webs after 43 repetitions, but the webs were damaged as is evidenced by the residual buckles. Considerable evidence of damage was shown by some of the buckle dials.

During loading to failure and just before ultimate load was reached, the buckles, suddenly changed angle and became much deeper. At this time the beam suddenly failed with a loud report at a total load of 30,000 pounds. Failure appeared to be due to excessive buckling. The principal failures were along the ridges and valleys of the buckles. Shear failures at 45° to the grain of the plywood were probably secondary.

Beam 5-RP. -- This beam was loaded 40 times to a maximum of 4,400 pounds before it was loaded to failure. The calculated shear stress in the webs at this load was 1,750 pounds per square inch and was 0.70 of the design ultimate for the webs. The probable buckle load for the webs during the first loading was 2,400 pounds.

That the webs were damaged by repeated buckling was evidenced by the buckle dials and the visible buckles which remained in the panels. After 40 cycles of repeated loading, the residual buckles were measured. The maximum depths in each panel varied from 3/64 to 1/8 inch. There were no visible compression failures in the valleys of the buckles at any time during the test.

The beam failed suddenly at 5,600 pounds total load. Failure was in diagonal tension with compression failures in the valleys of the buckles occurring simultaneously with the other web failures.

Beam 1-RV. -- This beam was loaded 40 times to a maximum of 12,000 pounds before it was inverted in the testing machine and loaded to failure. The calculated shear stress in the webs at this load was 2,410 pounds per square inch and was 0.71 of the design ultimate for the webs. Most panels were slightly buckled and two panels were considerably buckled at maximum load during the first cycle. The critical buckle load was not clearly defined for this beam, but was probably 10,000 pounds.

Damage to the webs was indicated by two of the buckle dials and the diagonal compression dials. Visible damage to the webs of this beam due to repeated buckling was not so apparent as in most of the beams.

After 40 repetitions of stress, the beam was inverted and loaded to failure. At 8,740 pounds total load, there was a failure of one web in diagonal tension in the panel adjacent to the load block. This failure was about 4-1/2 inches long. The remainder of the webs appeared to be undamaged so loading was continued until complete failure of the webs occurred at 9,700 pounds total load. Failure at ultimate load was primarily in diagonal tension. Owing to the unusual character of the failure of this beam, the test values may not be representative of similar beams.

Beam 2-RV.--This beam was loaded 40 times to a maximum of 25,000 pounds before it was inverted in the testing machine and loaded to failure. The calculated shear stress in the webs at this load was 1,680 pounds per square inch and was 0.67 of the design ultimate for the webs. The webs were visibly buckled at 22,500 pounds load during the first loading. Residual buckles remained in the panels after several cycles of loading, indicating some damage to the webs. Damage to the webs due to repeated buckling was indicated by the diagonal compression and the buckle dials.

After 40 repetitions of stress, the beam was inverted in the testing machine and loaded to failure. The beam failed suddenly with a loud report at 17,320 pounds total load, after indicating visibly and audibly that failure was imminent. Failure of the beam appeared to be due to a failure at the glue line between a web and flange in tension at the glue line caused by an outward buckle. The ultimate strength is therefore probably somewhat lower than could be expected of similar panels. Beam 2-RVB, which was similar to this beam, developed a stress at failure approximately 14 percent greater than this beam after being loaded in the same manner.

Beam 2-RVA.--This beam failed at the end of the third loading to 25,000 pounds. The webs started buckling at a load of 15,000 pounds during the initial cycle. Buckles were shallow up to 22,500 pounds of load, but between 22,500 and 25,000 pounds the buckle in one web suddenly became so deep that a compression failure was visible in the valley and extended from corner to corner of the panel. The buckling consisted of one outward buckle ending at the corner of the panel and one inward buckle ending at the diagonally opposite corner until 22,500 pounds of load. During the next increment of load, the shape and orientation of the buckle in one panel changed rapidly until the main buckle was inward and was oriented approximately along the diagonal of the panel.

The web opposite to the one that developed failure in the valley of the buckle had a tension failure along the ridge of the buckle which extended from corner to corner of the panel at the end of the second loading. There was a compression failure on the inner side of this web opposite the tension failure. This web probably carried a larger proportion of the load during the second cycle than during the first because of damage to the opposite web near the end of the first cycle.

The beam failed in the webs at the end of the third cycle under a maximum load of 25,000 pounds. It gave many audible signs of damage at loads from 22,500 to 25,000 pounds during all three cycles of loading. The calculated shear stress in the web at 25,000 pounds total load was 1,670 pounds per square inch, which was 0.66 of the design ultimate for the beams.

Beam 2-RVB.--This beam was loaded 40 times to a maximum of 25,000 pounds before it was inverted in the testing machine and loaded to failure. The calculated shear stress in the webs at this load was 1,710 pounds per square inch, which was 0.69 of the design ultimate for the webs. Buckles were first apparent in the webs in three of the four panels at a load of 17,500 pounds during the first loading. The only visible damage to the webs at any time during the repeated loading phase of the test were slight residual buckles remaining in some of the webs after the beams were loaded 40 times. The buckling was not severe in the webs at maximum repeated load. Damage to the webs, however, was indicated by the diagonal tension and compression dials and by some of the buckle dials.

After 40 repetitions of stress the beam was inverted in the testing machine and loaded to failure. It failed in the webs with a loud report at a total load of 19,870 pounds. Buckles were pronounced just before the web failed; depths of buckles, from ridge to valley, exceeded 1 inch at failure of the beam. Primary failure was probably due to combined buckling and diagonal tension.

Beam 3-RV.--This beam was loaded 40 times to a maximum of 4,400 pounds before it was inverted in the testing machine and loaded to failure. The calculated shear stress in the webs at maximum for the repeated loads was 1,780 pounds per square inch, which was 0.70 of the design ultimate for the webs. The webs buckled at a load of 2,400 pounds on the beam during the first loading. Damage to the webs due to repeated buckling appeared to be slight.

There was no visible damage to the webs except that slight residual buckles remained in the webs after the 40 repetitions of stress. Some of the buckle dials and the diagonal compression dials indicated that the webs were damaged by the repeated buckling.

After 40 repetitions of stress the beam was inverted in the testing machine and loaded until it failed in the webs at a total load of 3,600 pounds, Failure was sudden with little advance warning and seemed to be primarily in diagonal tension and shear with the diagonal tension concentrated in the corners of the panels. The repeated stress did not seem to affect the character of the failure of the beam when loaded in the inverted position.

Table 10.--Results of individual tests of box beams with plywood webs with the grain at 45° to the horizontal, which were subjected to repetitions of load before being loaded to failure in the normal or inverted position[1]

Construction details					Moisture content at test			Cross-section properties						Panel information			Averages from minor tests[2]		
Beam No.	Nominal depth of beam	Nominal width of beam	Nominal plywood thickness	Stiffeners and spacing	Webs	Upper flange	Lower flange	t Both webs	t_w Thinner webs	I	$\frac{I}{C_c}$	$\frac{I}{C_t}$	Q	a V = vertical H = horizontal	b	$\frac{a}{b}$	E_L	F_{SP} For negative grain direction[4]	F_{SP} For positive grain direction[4]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
	In.	In.	In.	In.	Per-cent	Per-cent	Per-cent	In.	In.	In.^{4}	In.^{3}	In.^{3}	In.^{3}	In.	In.		1,000 lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.
1- HP	13-1/2	4-1/2	1/4	5 at 6-3/4	2.8	8.0	9.4	0.474	0.237	668.6	116.66	86.33	62.02	5.13 H	7.45	0.69	1,720	3,530	....
2- HP	12	4-1/4	1/8	5 at 6	2.9	7.5	7.7	.240	.120	309.0	61.30	44.75	29.50	4.88 H	9.06	.54	1,386	3,430	....
2-HPA	12	4-1/4	1/8	5 at 6	4.0	9.2	8.4	.244	.122	310.6	61.11	44.86	30.25	4.88 H	9.11	.54	1,386	3,430	....
2-HPB	12	4-1/4	1/8	5 at 6	4.3	8.9	8.4	.246	.123	316.7	62.67	45.58	30.10	4.88 H	9.10	.54	1,386	3,430	....
3- HP	12	4-1/4	1/8	4 at 9-1/4	3.5	8.2	7.6	.240	.120	331.9	75.16	44.29	32.60	8.28 V	8.38	.99	1,386	3,430	....
4- HP	18	5-1/2	1/4	1 at 33-5/16	3.2	8.6	8.4	.480	.240	1,480.2	183.78	148.94	95.30	13.21 V	30.00	.44	1,720	3,530	....
5- HP	9	4-1/6	1/12	4 at 8-1/8	......	....	....	.156	.078	110.7	30.84	20.52	13.74	7.20 V	7.25	.99	1,425	3,410	....
1- HV	12	4-1/4	1/8	5 at 6	3.0	7.8	7.7	.238	.119	305.9	60.91	44.35	29.24	4.88 H	9.06	.54	1,386	3,430	3,460
2- HV	18	5-1/2	1/4	1 at 33-5/16	3.1	9.3	8.8	.478	.239	1,465.5	182.57	147.09	94.32	13.23 V	30.00	.44	1,720	3,530	3,710
2-HVA	18	5-1/2	1/4	1 at 33-5/16	5.2	9.8	9.8	.482	.241	1,500.8	185.08	151.28	96.49	13.21 V	30.00	.44	1,720	3,530	....
2-HVB	18	5-1/2	1/4	1 at 33-5/16	6.4	10.4	10.7	.470	.235	1,488.8	184.77	149.31	95.55	13.27 V	30.00	.44	1,720	3,530	3,710
3- HV	9	4-1/6	1/12	4 at 8-1/8	3.8	6.6	6.1	.160	.080	102.1	29.80	18.51	13.24	7.20 V	7.25	.99	1,425	3,410	2,950

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[1] Beams were tested under third-point loading over a 10-foot span; flanges were Sitka spruce; webs were 3-ply yellow-poplar with a 1:2:1 veneer thickness ratio with negative grain when in normal position.

[2] These values were calculated from the arithmetic means obtained from plywood minor tests for each thickness of plywood. See tables 11 and 12 for further information.

[3] The design values were obtained from figure 4 of Forest Products Laboratory Mimeo. No. 1318, "Design of Plywood Webs in Box Beams."

[4] (-) grain indicates that the diagonal tensile stress was perpendicular to the grain in the face plies. (+) grain indicates that the diagonal tensile stress was parallel to the grain in the face plies.

[5] See "Remarks" (column 38) of this table and appendix for repeated loading for this beam.

[6] Beam 1-HP did not buckle during first loading.

[7] No repeated loading.

Table 10.--Results of individual tests of box beams with plywood webs with the grain at 35° to the horizontal, which were subjected to repetitions of load before being loaded to failure in the normal or inverted position. [illegible]

Beam No.	Design values for beam in normal position[1]			Design values for beam in inverted position[1]			Data for repeated loading				Data for buckling during first cycle			Data for loading beam to failure				Remarks
	$\frac{a}{a_0}$	$\frac{F_{su}}{F_{s\theta}}$	Maximum shearing stress F_{su}	$\frac{a}{a_0}$	$\frac{F_{su}}{F_{s\theta}}$	Maximum shearing stress F_{su}	Repeated load P_r	Number of cycles	f_{sr}	$\frac{f_{sr}}{F_{su}}$	Load at first buckle P_{cr}	Maximum shearing stress at buckling f_{scr}	$\frac{f_{scr}}{F_{s\theta}}$	Position of beam during loading to failure	Ultimate load P_u	Maximum flexure stress at failure f_{su}	$\frac{f_{su}}{F_{su}}$	
(1)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)
			Lb. per sq. in.			Lb. per sq. in.	Lb.		Lb. per sq. in.		Lb.	Lb. per sq. in.			Lb.	Lb. per sq. in.		
1- RP	0.42	1.00	3,530	....	....	....	(5)	(5)	(5)	(5)	(6)	(6)	(6)	Normal	35,000	3,430	0.972	Beam was subjected to following repeated loadings: 10 cycles f_{sr}/F_{su} = 0.76; 4 cycles f_{sr}/F_{su} = 0.83; and 3 cycles f_{sr}/F_{su} = 0.90 before failing in the web near the end of third cycle of f_{sr}/F_{su} = 0.97.
2- RP	.97	.985	3,380	....	....	....	12,000	10	2,390	0.707	10,000	1,990	0.580	.....do.....	16,880	3,360	.995	Beam failed in web in outer third of beam in diagonal tension
2-RPA	.96	.990	3,390	....	....	....	(7)	(7)	(7)	(7)	10,000	2,000	.583	.....do.....	14,690	2,930	.865	Failure probably due to defective load block, ultimate value not significant.
2-RPB	.95	.990	3,390	....	....	....	12,000	40	2,320	.685	10,000	1,930	.563	.....do.....	17,000	3,280	.968	Beam failed in the webs in outer third of beam due to excessive buckling and in diagonal tension.
3- RP	1.14	.875	3,000	....	....	....	10,500	40	2,150	.717	9,000	1,840	.536	.....do.....	13,000	2,660	.887	Beam failed in the webs in outer third of beam due to excessive buckling and in diagonal tension.
4- RP	1.26	.710	2,510	....	....	....	25,000	43	1,680	.670	20,000	1,340	.380	.....do.....	30,000	2,010	.801	Beam failed in the webs in outer third of beam due to excessive buckling.
5- RP	1.49	.730	2,490	....	....	....	4,400	40	1,750	.703	2,400	960	.281	.....do.....	5,600	2,230	.896	Beam failed in the webs in outer third of beam in diagonal tension.
1- RV	.98	.985	3,380	1.96	0.680	2,350	12,000	40	2,410	.713	10,000	2,010	.586	Inverted	9,700	1,950	.830	Beam failed in the webs in outer third of beam in diagonal tension. Ultimate value may not be representative.
2- RV	1.26	.710	2,510	2.52	.420	1,560	25,000	40	1,680	.670	22,500	1,510	.428	.....do.....	17,320	1,170	.750	Beam failed in the webs in outer third of beam probably at glue lines between flanges and web due to outward buckle, hence test value is probably low. Ultimate value not significant.
2-RVA	1.25	.715	2,520	....	....	....	25,000	3	1,670	.663	15,000	1,000	.283	Normal	25,000	1,670	.663	Beam failed in web in outer third of beam at end of third cycle of loading, due to excessive buckling.
2-RVB	1.29	.700	2,470	2.56	.420	1,560	25,000	40	1,710	.692	17,500	1,190	.337	Inverted	19,870	1,360	.872	Beam failed in the webs in outer third of beam due to excessive buckling and in diagonal tension.
3- RV	1.46	.745	2,540	3.30	.500	1,480	4,400	40	1,780	.701	2,400	970	.284	.....do.....	3,600	1,460	.987	Beam failed in the webs in outer third of beam due to diagonal tension.

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Table 11.--Results of minor tests of plywood for webs of box beams which were subjected to repeated loading before being loaded to failure in normal or inverted position[1]

Beam No.	Nominal plywood thickness	Static bending, face grain direction parallel to span			Static bending, face grain direction perpendicular to span			Compression, face grain direction parallel to applied stress				Compression, face grain direction perpendicular to applied stress				Tension, face grain direction parallel to applied stress			Tension, face grain direction perpendicular to applied stress			Effective shearing modulus in the plane of the plywood G
		Moisture content	Specific gravity[2]	E_1	Moisture content	Specific gravity[2]	E_2	Moisture content	Specific gravity[2]	$(F_{cu})_a$	E_a	Moisture content	Specific gravity[2]	$(F_{cu})_b$	E_b	Moisture content	$(F_{tu})_a$	E_a	Moisture content	$(F_{tu})_b$	E_b	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
	In.	Percent		1,000 lb. per sq. in.	Percent		1,000 lb. per sq. in.	Percent		Lb. per sq. in.	1,000 lb. per sq. in.	Percent		Lb. per sq. in.	1,000 lb. per sq. in.	Percent	Lb. per sq. in.	1,000 lb. per sq. in.	Percent	Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.
1- EP	1/4	3.1	0.506	1,686	3.0	0.513	325	3.0	0.502	5,020	1,003	3.0	0.494	5,180	1,067	3.8	7,460	1,067	3.2	9,000	1,171	250
2- EP	1/8	3.2	.463	1,131	3.2	.465	317	3.2	.472	3,510	758	3.1	.475	4,520	1,046	4.0	5,280	810	3.0	6,890	1,094	370
2-EPA	1/6	3.7	.453	1,128	4.6	.450	239	3.2	.460	3,890	711	3.6	.457	3,850	707	3.5	5,670	818	3.5	7,720	834	402
2-EPB	1/8	4.7	.491	1,492	4.9	.467	312	4.2	.474	4,080	742	4.3	.489	4,930	1,045	5.4	7,060	848	4.8	9,980	1,126	405
3- EP	1/8	3.8	.440	673	3.8	.478	324	3.2	.464	3,400	640	3.2	.480	4,310	1,036	4.2	4,720	696	3.7	8,500	1,079	354
4- EP	1/4	3.1	.466	1,427	3.3	.464	303	3.2	.458	4,080	657	3.1	.447	4,670	937	3.8	7,190	1,031	3.7	7,470	1,006	415
5- EP	1/12	3.4	.490	1,238	3.8	.458	216	4.8	.464	3,820	853	3.9	.441	3,200	693	3.5	5,160	876	4.0	7,020	747	377
1- EV	1/8	3.2	.470	1,045	3.7	.470	328	3.3	.479	3,400	708	3.2	.486	4,140	1,036	3.9	5,290	758	3.2	8,900	1,103	365
2- EV	1/4	3.6	.448	1,106	3.7	.439	282	3.2	.450	3,940	850	3.2	.473	4,860	1,136	3.5	6,120	750	3.6	7,620	936	415
2-EVA	1/4	5.1	.411	1,121	5.3	.418	291	5.2	.414	2,980	648	5.1	.426	4,220	944	5.3	5,230	633	5.9	7,980	1,011	349
2-EVB	1/4	5.6	.472	2,035	5.1	.492	339	5.7	.476	4,310	1,191	5.8	.479	3,660	869	6.2	9,240	1,354	5.9	9,520	1,005	466
3- EV	1/12	5.7	.459	1,271	6.3	.450	232	3.0	.479	4,180	849	3.3	.462	3,600	871	3.6	6,840	824	3.0	6,100	799	366

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[1] Plywood was yellow-poplar with a light veneer thickness ratio and was bonded with a phenolic-resin film glue. Test coupons were prepared from the same panels as were used in the webs of the beams.

[2] Specific gravity based on volume at test and weight when oven dry with no correction for glue lines.

Table 12.--Summary of average values of bending moduli of elasticity and compression and tension ultimate strengths from minor tests and values of E_θ and $F_{s\theta}$ calculated therefrom[1]

Beam No.	Nominal plywood thickness	Static bending, face grain direction parallel to span			Static bending, face grain direction perpendicular to span			Modulus of elasticity of wood E_L[2]	Compression, face grain direction parallel to stress			Compression, face grain direction perpendicular to stress			Tension, face grain direction parallel to stress			Tension, face grain direction perpendicular to stress			Calculated[3] $F_{s\theta}$ = 45°	
		Number of specimens	Moisture content	E_1	Number of specimens	Moisture content	E_2		Number of specimens	Moisture content	$(F_{cu})_a$	Number of specimens	Moisture content	$(F_{cu})_b$	Number of specimens	Moisture content	$(F_{tu})_a$	Number of specimens	Moisture content	$(F_{tu})_b$	For -grain using $(F_{cu})_a$ $(F_{tu})_b$	For +grain using $(F_{cu})_b$ $(F_{tu})_a$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
	In.		Percent	1,000 lb. per sq. in.		Percent	1,000 lb. per sq. in.	1,000 lb. per sq. in.		Percent	Lb. per sq. in.		Percent	Lb. per sq. in.		Percent	Lb. per sq. in.		Percent	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.
1- HP	1/4	6	3.1	1,686	6	3.0	325	....	6	3.0	5,020	6	3.0	5,180	6	3.8	7,460	6	3.2	9,000	....	....
4- HP	1/4	6	3.1	1,427	6	3.3	303	....	6	3.2	4,080	6	3.1	4,670	6	3.8	7,190	6	3.7	7,470	....	....
2- HV	1/4	6	3.6	1,106	6	3.7	282	....	6	3.2	3,940	6	3.2	4,860	4	3.5	6,124	5	3.6	7,620	....	....
2-HVA	1/4	6	5.1	1,121	6	5.3	291	....	12	5.2	2,980	12	5.1	4,220	6	5.3	5,230	5	5.9	7,980	....	....
2-HVB	1/4	6	5.6	2,035	6	5.1	339	....	6	5.7	4,310	6	5.8	3,660	1	6.2	9,240	6	5.9	9,520	....	....
Average for 1/4-inch plywood			4.1	1,475	....	4.1	308	1,720	....	4.2	3,890	....	4.2	4,470	....	4.2	6,650	....	4.4	8,360	3,530	3,710
2- HP	1/8	6	3.2	1,131	6	3.2	317	....	6	3.2	3,810	6	3.1	4,520	5	4.0	5,280	6	3.0	8,890	....	....
2-HPA	1/8	6	3.7	1,128	6	4.6	239	....	6	3.2	3,890	6	3.6	3,850	6	3.5	5,670	6	3.5	7,720	....	....
2-HPB	1/8	6	4.7	1,492	6	4.9	312	....	6	4.2	4,080	6	4.3	4,930	5	5.4	7,060	6	4.8	9,980	....	....
3- HP	1/8	6	3.8	873	6	3.8	324	....	6	3.2	3,400	6	3.2	4,310	5	4.2	4,720	6	3.7	8,500	....	....
1- HV	1/8	6	3.2	1,045	6	3.7	328	....	6	3.3	3,400	3	3.2	4,140	6	3.9	5,290	6	3.2	8,900	....	....
Average for 1/8-inch plywood			3.7	1,134	....	4.0	304	1,381	....	3.4	3,720	....	3.5	4,370	....	4.2	5,650	....	3.6	8,800	3,330	3,460
5- HP	1/12	6	3.4	1,238	6	3.8	216	....	6	4.8	3,820	6	3.9	3,200	6	3.5	5,160	5	4.0	7,020	....	....
3- HV	1/12	6	5.7	1,271	6	6.3	232	....	6	3.0	4,180	5	3.3	3,600	6	3.6	6,840	6	3.0	6,020	....	....
Average for 1/12-inch plywood			4.6	1,254	....	5.0	224	1,425	....	3.9	4,000	....	3.6	3,380	....	3.6	6,000	....	3.5	6,520	3,410	2,950

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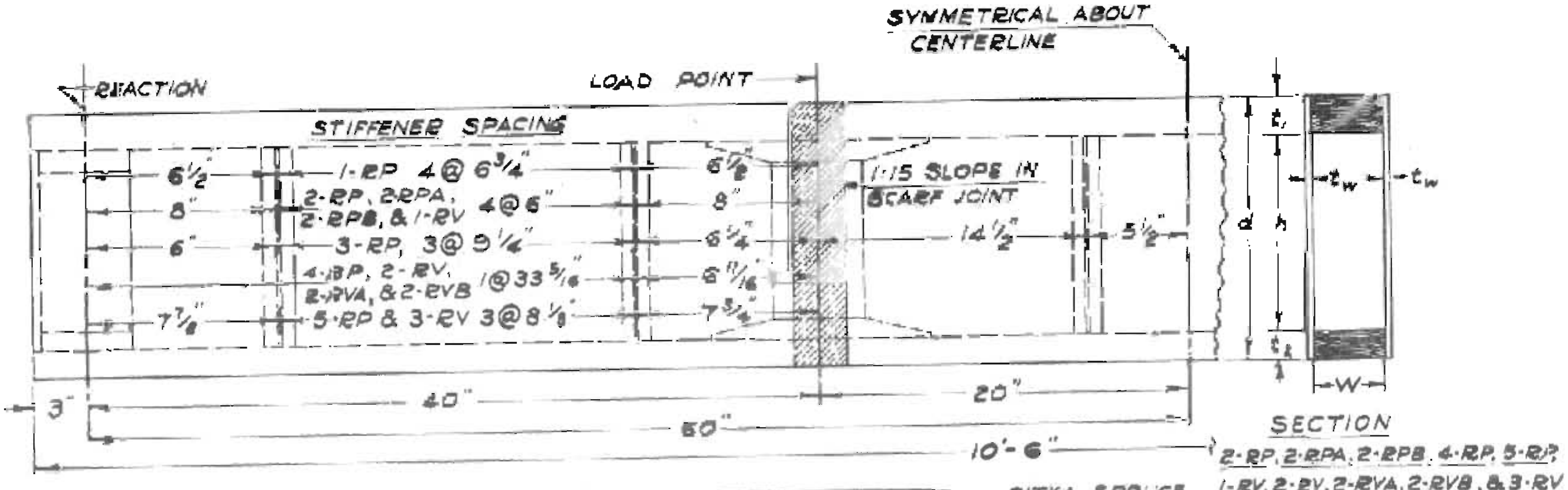
[1] Plywood was yellow-poplar with a 1:2:1 veneer thickness ratio and was bonded with a phenolic-resin film glue.

[2] E_L was calculated from average values of E_1 and E_2.

[3] (-) grain indicates that the diagonal tensile stress was perpendicular to the grain in the face plies. (+) grain indicates that the diagonal tensile stress was parallel to the grain in the face plies.



BEAM NO.	d	h	W	t_1	t_2	t_3	t_w
1-RP	13 1/2"	7 1/2"	4"	2 1/4"	2 1/4"	1 1/2"	1/4"
2-RP, 2-RPA, 2-RPB, & 1-RV	12"	9 1/8"	4"	1 3/4"	1 1/8"	-	1/8"
3-RP	12"	8 3/8"	4"	1 1/4"	1 1/8"	1 1/4"	1/8"
4-RP, 2-RV, 2-RVA, & 2-RVB	18"	13 1/4"	5"	2 3/4"	2"	-	1/4"
5-RP & 3-RV	9"	7 1/4"	4"	1 1/8"	5/8"	-	1/12"

SITKA SPRUCE
LAMINATED FLANGES.
1:2:1 YELLOW-
POPLAR PLYWOOD
WEBS WITH FACE
GRAIN SLOPING 45°
DOWNWARD TOWARD
THE REACTIONS IN
THE OUTER PANELS

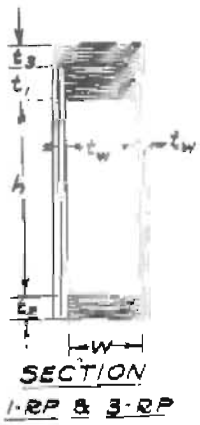


Figure 43.--Construction details (beam assemblies) of box beams for reneated and reversed loading.

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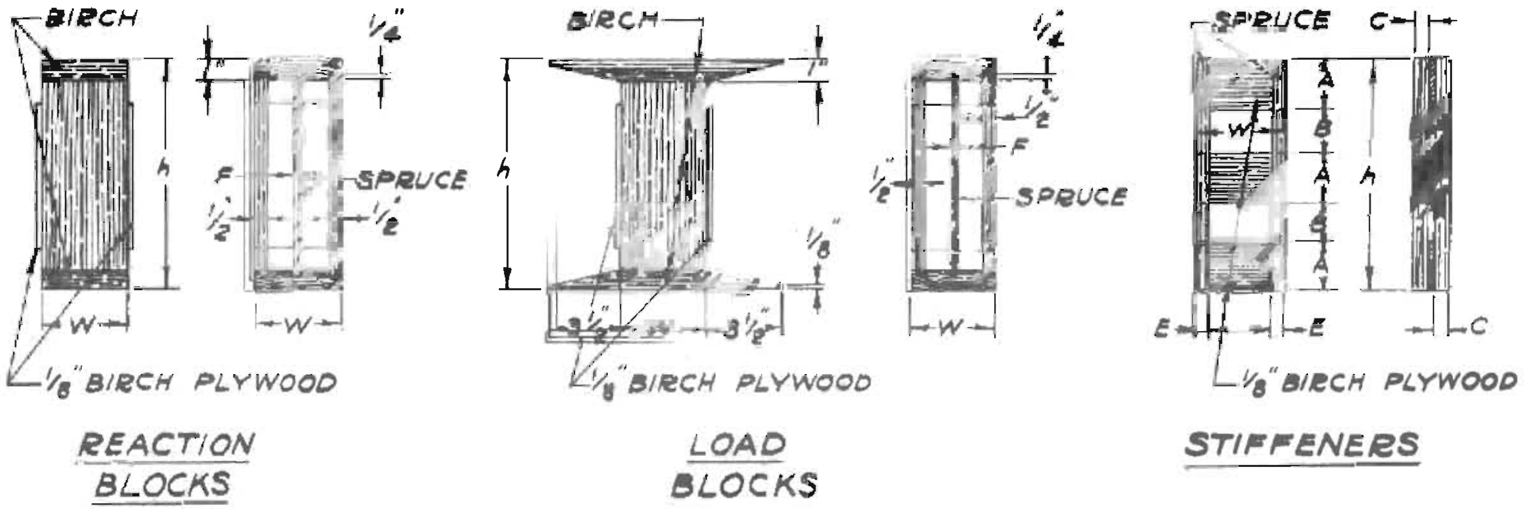

BEAM NO.	h	W	A	B	C	E	F
1-RP	7 1/2"	4"	1 1/4"	1 7/8"	3/4"	1/2"	1/4"
2-RP, 2-RPA, 2-RPB, & 1-RV	9 1/8	4"	2"	1 9/16"	1/2"	3/8"	1/4"
3-RP	8 3/8"	4"	1 1/4"	2 5/16"	3/8"	3/8"	1/4"
4-RP, 2-RV, 2-RVA, & 2-RVB	13 1/4"	5"	2"	3 5/8"	3/4"	1/2"	3/8"
5-RP & 3-RV	7 1/4"	4"	1 1/8"	1 13/16"	3/8"	3/8"	1/4"

Figure 44.--Construction details (reaction blocks, load blocks, and stiffeners) of box beams for repeated and reversed loading.

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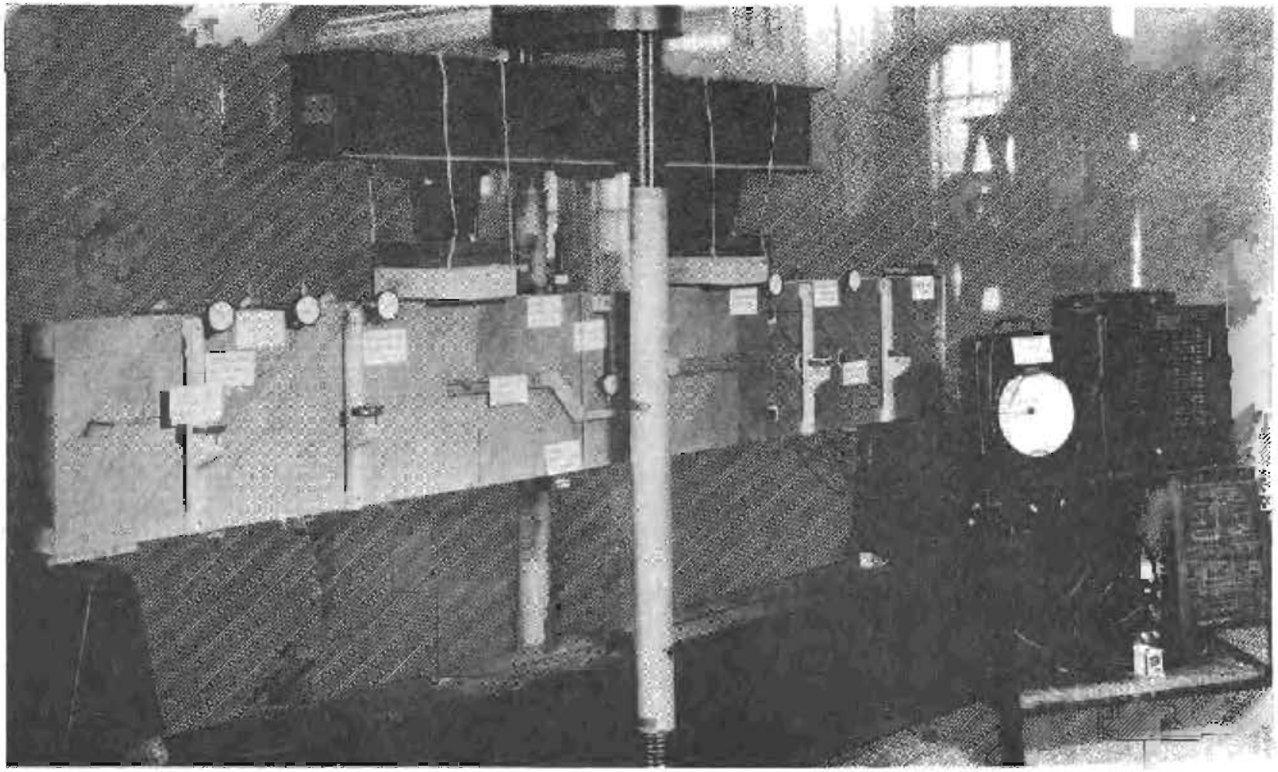

Figure 45.--Beam in testing machine ready for test with strain and deflection-measuring instruments in place showing buckle deflection dials and metalectric strain recorder.

Z M 57778 F

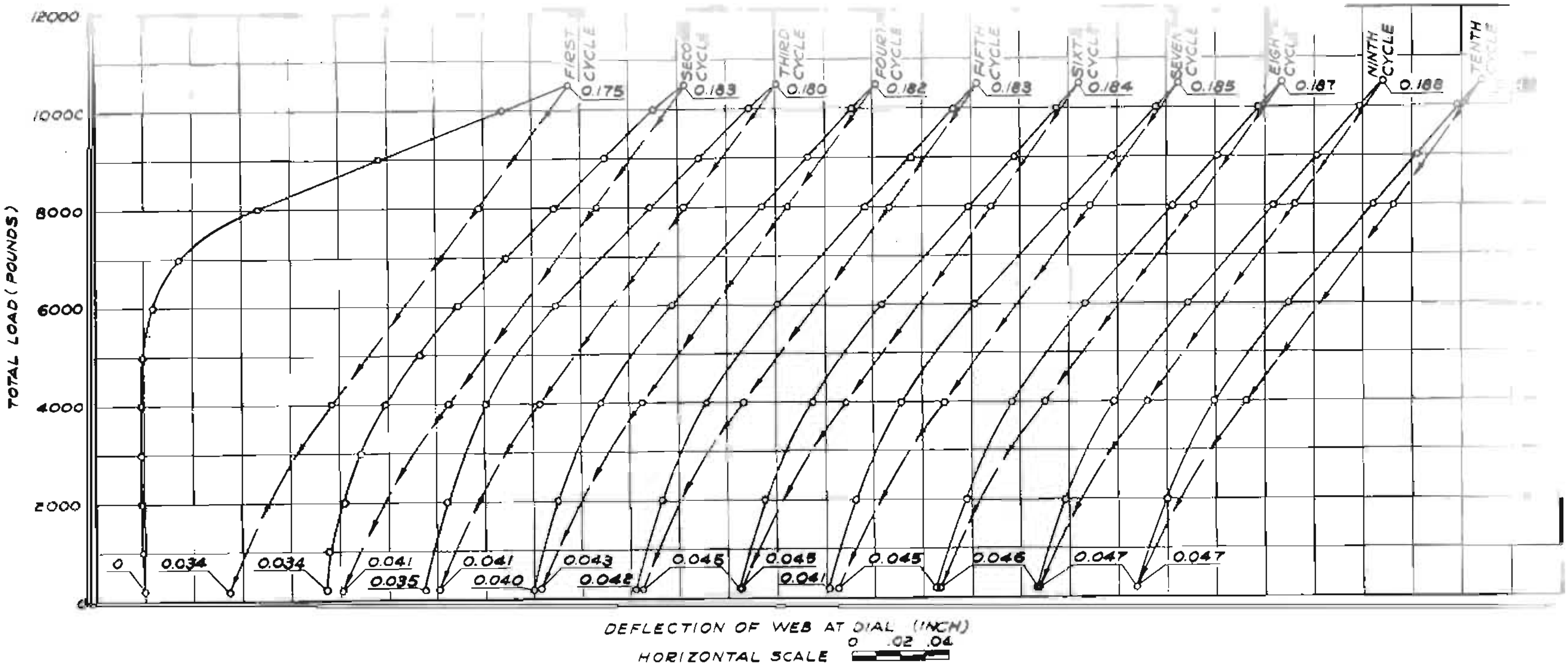

Figure 46.--Load-deflection-of-web curves for one panel of beam 3-RP for the first ten cycles of loading. Compression failure was visible in the valley of the buckle in this panel after nine repetitions of loading. The buckle dial was located at the center of the panel.

Z M 57779 F

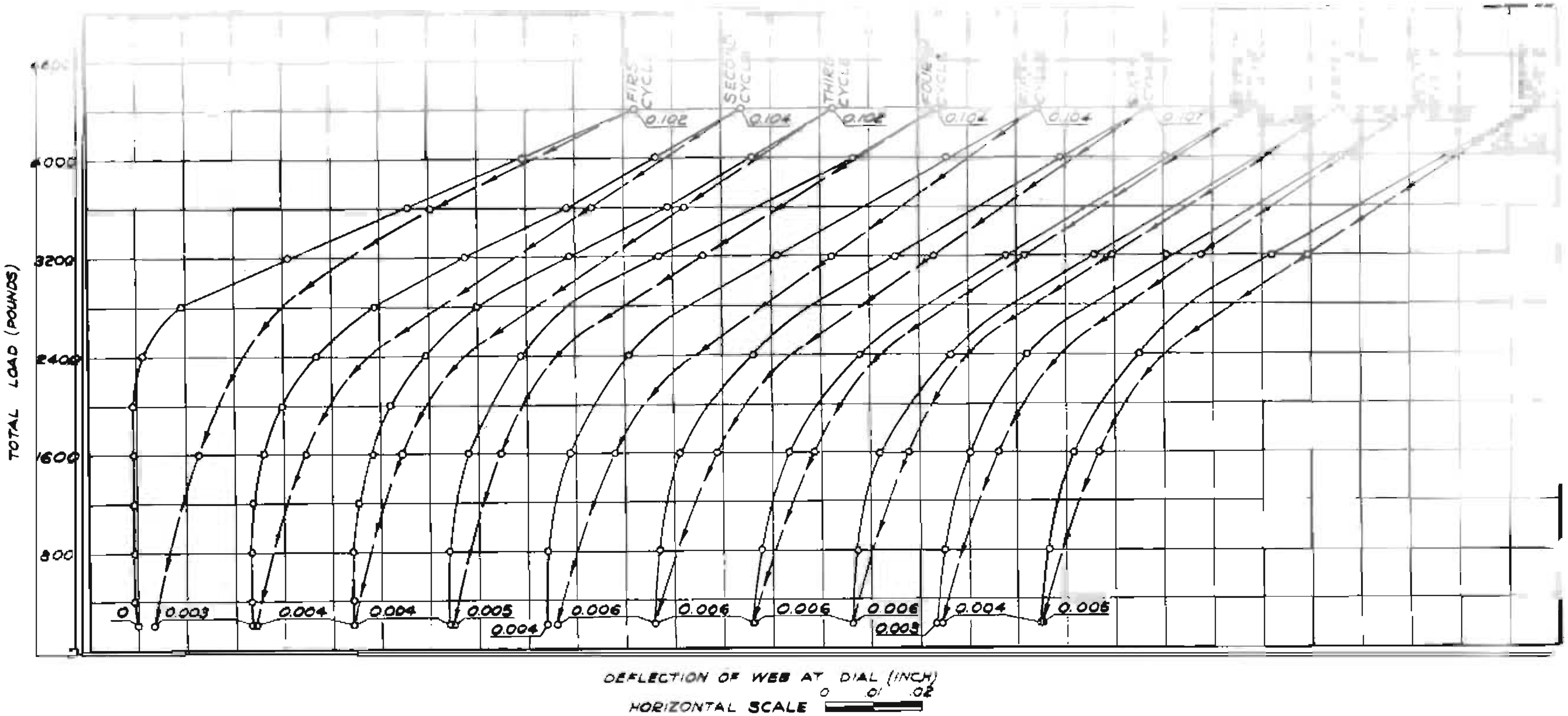

Figure 47.--Load-deflection-of-web curves for one panel of beam R-RV for first ten cycles of loading. Curves show that most of the damage to the web occurred during the first cycle. The buckle dial was located at the center of the panel.

Z M 57780 F

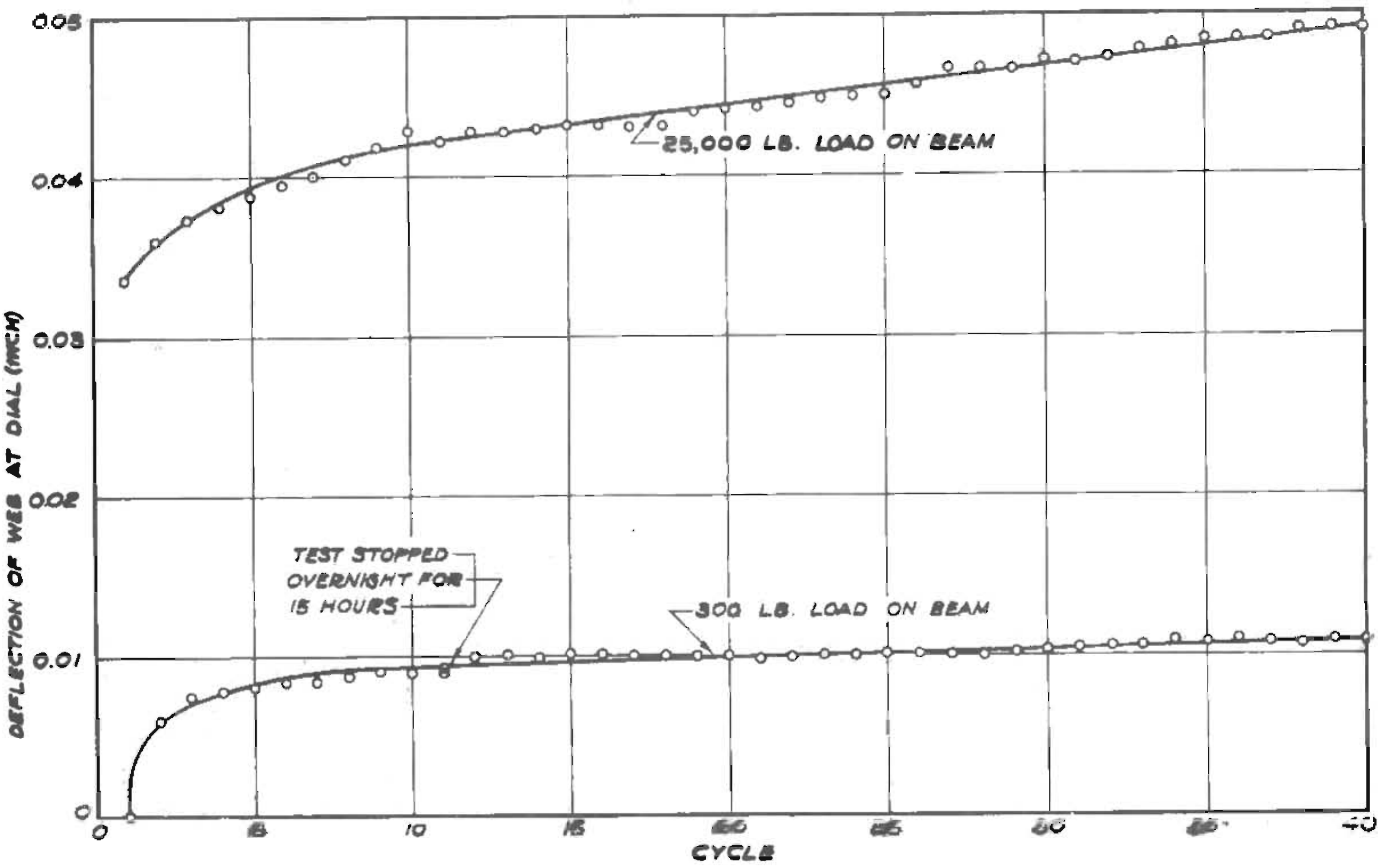

Figure 48.--Deflection of plywood web at buckle dial of beam 2-RVB at 300 and 25,000 pounds load for each cycle of repeated loading, showing typical increase in total buckle deflection of the web with repetition of load. The dial was located at mid-height of panel at the intersection of 45° lines drawn from two corners of the panel.

Z M 57781 F

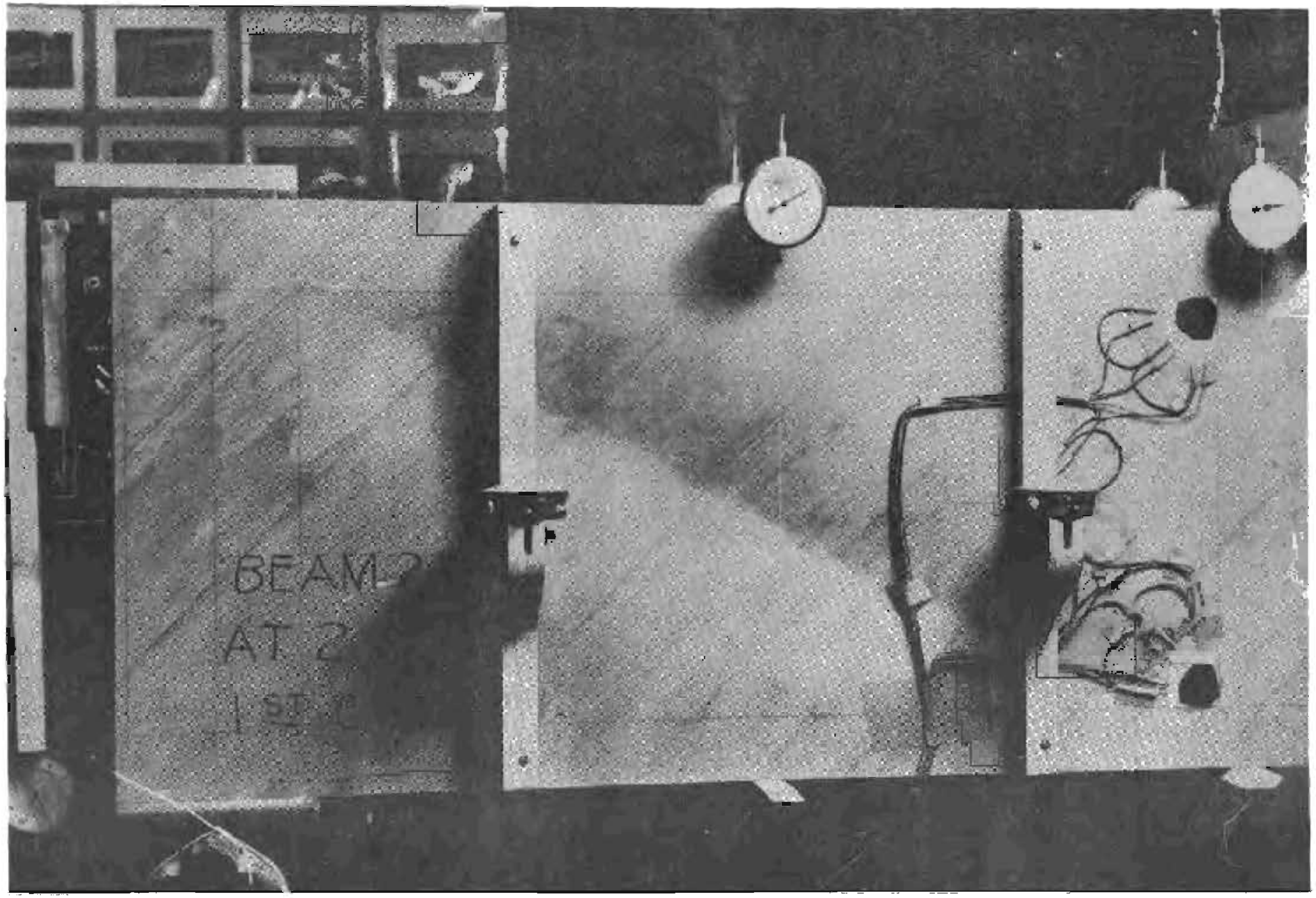

Figure 49.--Compression failure in the valley of buckle in the web of beam 2-RVA at 24,200 pounds total load on the beam, during the first cycle of loading.

Z M 57782 F

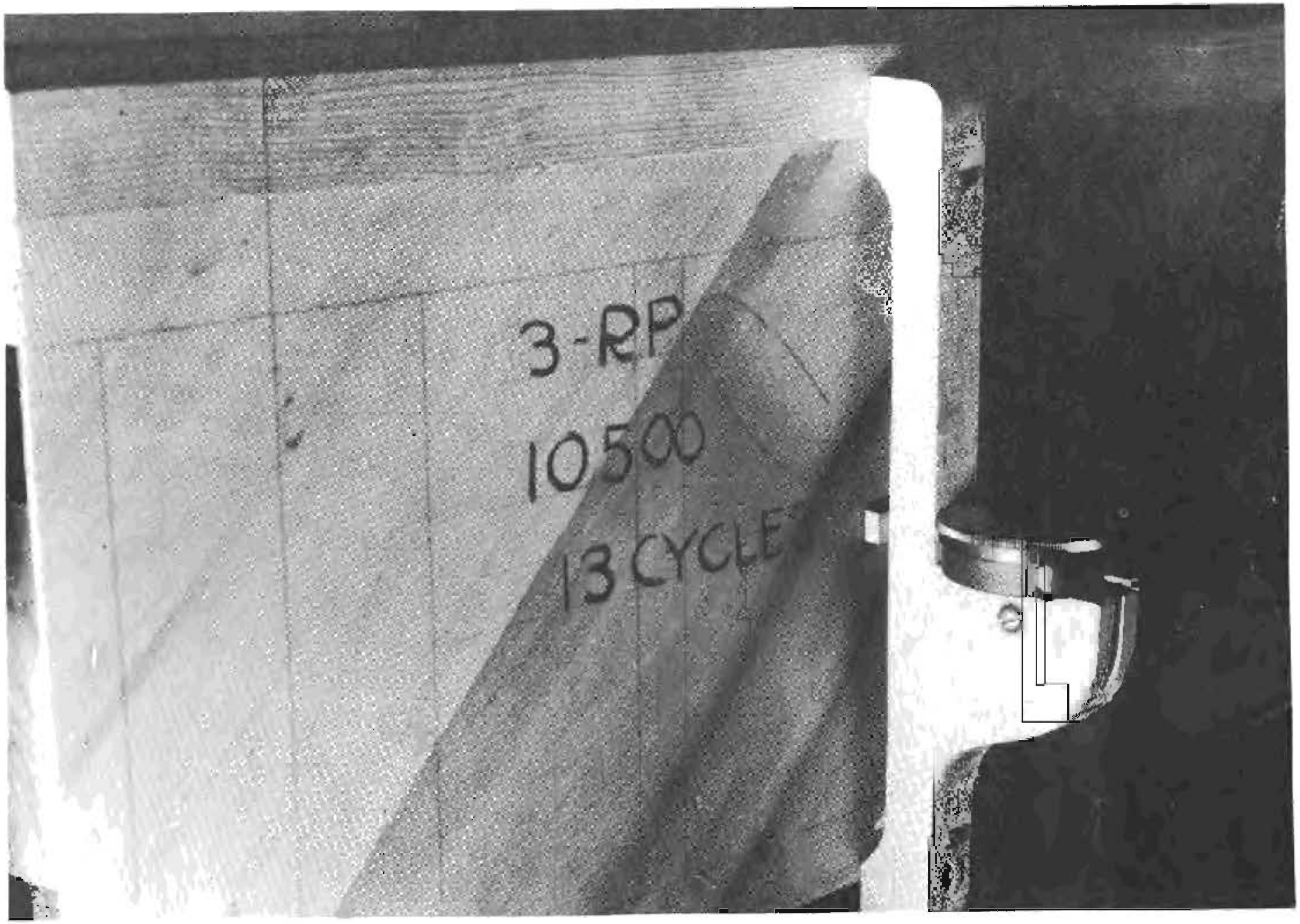

Figure 50.--Compression failure in the valley of buckle in the web of beam 3-RP after 13 cycles of repeated load of 10,500 pounds on beam, showing the dial used to measure the deflection of the web.

Z M 57783 F

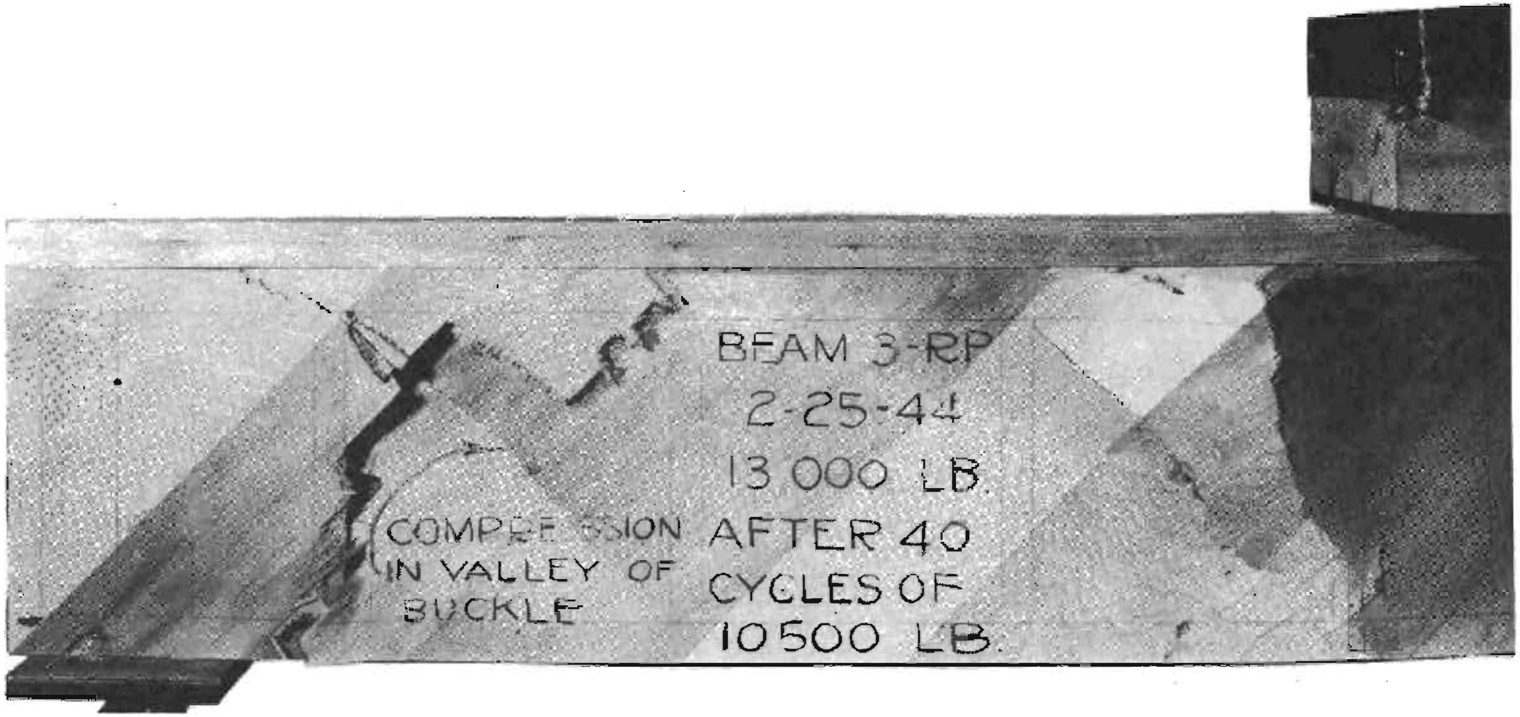

Figure 51.--Box beam 3-RP after failure showing the compression failures in the valleys of buckles and the diagonal tension failure that followed these failures of the web due to excessive buckling.

Z M 57784 F

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