EFFECTS OF CERTAIN DEFECTS AND STRESS-CONCENTRATING FACTORS ON THE STRENGTH OF TENSION FLANGES OF BOX BEAMS

Information Reviewed and Reaffirmed

May 1953

INFORMATION REVIEWED AND
REAFFIRMED JUNE 1959
DATE OF ORIGINAL REPORT
NOVEMBER 17, 1944

INFORMATION REVIEWED
AND REAFFIRMED
1965

**This Report is One of a Series
Issued in Cooperation with the
AIR FORCE-NAVY-CIVIL SUBCOMMITTEE
on
AIRCRAFT DESIGN CRITERIA
Under the Supervision of the
AIRCRAFT COMMITTEE
of the
MUNITIONS BOARD**

No. 1513

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison 5, Wisconsin
In Cooperation with the University of Wisconsin

EFFECTS OF CERTAIN DEFECTS AND STRESS-CONCENTRATING FACTORS ON THE STRENGTH OF TENSION FLANGES OF BOX BEAMS[1]

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Summary

This report embodies a series of tests arranged to allow the study of effects of bolt holes, various shapes of load blocks, sloping grain, preexisting compression failures, and of compression failures induced by inverted loading on the tension flanges of box or similar built-up beams of wood and plywood.

Bolt holes induced longitudinal shear cracking of the lange material, the cracking first appearing at a stress of about one-half of the modulus of rupture or about one-third of the ultimate tension of minor specimens matched to the flange material. The average load at first crack was about one-third of the ultimate load carried by similar control beams.

The load capacity of the beams was affected but little by differences between two types of load blocks. It is probable that differences in load blocks would have more effect on lighter, more flexible beams.

The presence of a grain slope of 1 in 15 in the tension flange reduced the load-carrying capacity of the beams to about two-thirds of that of similar beams having straight grain in the tension flange.

Preexisting compression failures in the tension flanges reduced the load-carrying capacity of beams with solid flanges to one-third that of control beams. In beams with laminated flanges, such failures reduced the value to three-eights of that of the controls. Beams with tension flanges damaged in compression by inverse loading developed less than one-third of the load-carrying capacity of control beams.

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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. Results here reported are preliminary and may be revised as additional data become available.

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

Notation

The following symbols, ANC[3] whenever possible, are used in this report. All values are in inch and pound units.

C_c = Distance from the neutral axis to the extreme fiber in compression.

C_t = Distance from the neutral axis to the extreme fiber in tension.

E_L = Modulus of elasticity of wood in the direction parallel to the grain as determined from a static bending test.

E_{Lc} = Modulus of elasticity of wood in the direction parallel to the grain as determined from a compression test.

E_{Lt} = Modulus of elasticity of wood in the direction parallel to the grain as determined from a tension test.

F_{bu} = Modulus of rupture of wood in bending for solid wood parallel to grain.

F_{cu} = Ultimate compressive stress parallel to the grain for solid wood.

F_{tu} = Ultimate tensile stress parallel to grain for solid wood.

f_c = Calculated maximum compressive stress in the beam while it is acted upon by the maximum load.

f_{cu} = Calculated maximum stress in compression when compression failures become visible during the testing of the beam in the inverted position.

f_{tcr} = Calculated maximum stress in tension in the beam at the load when visible shear cracks start at the edges of the holes.

f_{tu} = Calculated maximum stress in tension in the beam at ultimate load.

I = Moment of inertia of the section about the neutral axis of the beam.

P = Total load on the beam at critical load, compression failure load, or ultimate load.

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[3]Air Force-Navy-Civil Committee on Aircraft Design Criteria of the Munitions Board Aircraft Committee.

Introduction

The purpose of the series of tests here reported was to study the effects of various defects of design, material, or manufacture upon the strength of tension flanges in wood box beams. Variables, causing concentration of stress or reductions in strength or both, considered in this study were: (1) Holes in the tension flanges, (2) poorly designed load blocks or filler blocks, (3) sloping grain in the tension flanges, (4) preexisting compression failures in solid tension flanges, (5) preexisting compression failures in laminated tension flanges, and (6) tension flanges in the normal position after being loaded in an inverted position until compression failures were visible.

Description of Specimens

These beams were designed to fail in the tension flange. Nominal dimensions were the same for all beams. Figures 1, 2, and 3 show the details of construction.

The tension flanges were Sitka spruce and were nominally 3 inches wide and 2-1/2 inches deep. The compression flanges were made of Douglas-fir in order to have a material of higher compressive strength and to insure final failure of the beam in the tension flange without raising the neutral axis unduly. Compression flanges were made of three approximately equal sections 4 inches deep by 3 inches wide placed one between the webs and one on either side, thus forming a beam of T cross section. The webs were of 5-ply yellow-poplar plywood conforming to Specification AN-NN-P-511b. Nominal veneer thicknesses were 1/16, 1/10, 1/12, 1/10, and 1/16 inch with the grain at 45° to the horizontal axis of the beam. All beams were 15 feet long and were loaded at points 20 inches either side of the center of the beam. The span was 14 feet and 4 inches.

Material for flanges was selected by examination and on the basis of results from minor tests made prior to the construction of the beams. Toughness, static bending, and compression-parallel-to-the-grain tests determined the suitability of material for compression flanges. Toughness, static bending, compression-parallel-to-the-grain, and tension-parallel-to-the-grain tests determined the suitability of the material for tension flanges. Specimens for these tests were prepared from the sides of the flat-sawn planks so that the same growth rings occurred in minor specimens and in the flanges.

Minor specimens were taken from all of the plywood panels used in making the webs, to check the quality of the plywood. Tests were made in panel shear and in tension, compression, and static bending, both parallel and perpendicular to the face grain.

The material for the tension flanges of control beams 1-T-1, 1-T-2, 1-T-2A, and 1-T-3 was carefully selected for straightness of grain and freedom from defects. The flanges were constructed of three vertical laminae to minimize the effects of variation of the properties of the material. These beams served as controls for all others.

The material for the tension flanges of beams 2-T-1, 2-T-1A, 2-T-2, 2-T-2A, and 2-T-3 was selected with the same care and fabricated in the same manner as for the controls. One-half-inch diameter holes were drilled vertically through the middle of the tension flange of beam 2-T-1 at: (1) a point 5 inches from the center of the span; (2) a point 29-1/4 inches from the center of the span thus placing the hole outside of and tangent to the end of the load block; and (3) a point midway between the load point and the reaction. Beam 2-T-1A had a 1/2-inch diameter horizontal hole at middepth of the tension flanges 4 inches from the center of the span. The plywood webs were routed out around the hole to expose the flange for observation during test. Beams 2-T-2, 2-T-2A, and 2-T-3 each had a 1/2-inch diameter vertical hole centered on the width of the tension flange 4 inches from the center of the span.

Beams 3-T-1, 3-T-2, and 3-T-3 were constructed similarily to the control beams 1-T-1, 1-T-2, and 1-T-3 except that a much shorter, stiffer load block was used to accentuate the effects of poorly designed load blocks upon the tension flange.

Beams 4-T-1, 4-T-2, and 4-T-3 differed from the control beams only in that the tension flanges consisted of three vertical laminae so cut that the grain had a slope in the vertical plane of 1 in 15.

Beams 5-T-1, 5-T-2, and 5-T-3 differed from the control beams only in that the tension flanges were of one piece construction and were selected from stock known to contain compression failures.

Beams 6-T-1, 6-T-2, and 6-T-3 differed from the control beams only in that the tension flanges were formed of three vertical laminae selected from stock known to contain compression failures.

Beams 7-T-1, 7-T-2, and 7-T-3 (for test in the normal position following overstress in the inverted position) were in all respects similar to the control beams.

The minor specimens for flange material were as follows:

Toughness.--Specimens 5/8 by 5/8 by 10 inches loaded on a tangential face at the center of an 8-inch span.

Static bending.--Specimens 1 by 1 by 16 inches loaded on a tangential face at the center of a 14-inch span.

Compression parallel to the grain.--Specimens 1 by 1 by 4 inches loaded on end.

Tension parallel to the grain.--Specimens 3/4 by 1 by 29 inches shaped to a uniform section 1/4 by 1/2 by 5 inches long at the center, the transition being made by a circular curve, tangent to the ends of the center section, of 90 inches radius and leaving a full sized portion at either end 5-1/4 inches long.

Methods of Testing

The beams were tested in a 200,000-pound, screw-type testing machine by loading at points 20 inches on either side of the center of a 14-foot 4-inch span. Figure 4 shows a beam in the testing machine ready for test with the dials, strain gages, and deflection-measuring instruments in place. The discolored area in the center part of the beam near the tension flange is a "brittle lacquer" applied to the critical tension area of the beam as an aid in discovering regions of early stress concentration. The lacquer was also helpful in locating defects and areas of partial failure. The lacquer was applied to each beam the evening preceding test in order to allow time for proper setting but not sufficient time for cracking of the lacquer by moisture and temperature changes.

The beams, except 7-T-1, 7-T-2, and 7-T-3, were loaded in predetermined increments up to the load at which the dials and gages were removed. These increments were so chosen that a minimum of 10 sets of readings were obtained before the dials and gages were removed. Dials and gages were removed soon after the proportional limit of the beam, as measured by deflection, was passed. Deflection was applied at the rate of 0.21 inch per minute corresponding to the rate of strain prescribed by A.S.T.M.[4] standards for beams of this type.

Beams 7-T-1, 7-T-2, and 7-T-3 were first placed in the machine in inverted position with all dials and gages in place. Increments of load were then applied at the rate of 0.21 inch of deflection per minute. Loading was stopped while readings were taken. This procedure was continued until compression wrinkles appeared in the flange designed for tension but, in this position, taking compression stress. The beam was then removed from the machine and the tension flange was coated with brittle lacquer. After a rest period for the curing of the lacquer, the beam was again placed in the machine, but in normal position and tested in accordance with the procedure outlined for the other beams.

Methods of Calculation

For the determination of maximum tension and compression stresses due to flexure the section moduli of the beams were calculated using the appropriate modulus of elasticity for each flange as determined from minor test data. The modulus of elasticity of the plywood was assumed as one-fourth that of the material composing the tension flange. Thus, the recommendation of section 3.1151 of ANC Bulletin 18, "The Design of Wood Aircraft Structures," was followed as closely as practicable for beams with flanges of different materials.

Section moduli for beams in the 2-T group were calculated under two further assumptions made necessary by the fact that these beams had holes in the tension flanges. During the early stages of loading prior to the development

[4]American Society for Testing Materials, Standard D198-27.

of shear cracks located by the holes, bending was assumed to take place about a neutral axis determined by the gross area of the cross section but with all stress carried by the net section. After cracking, the neutral axis was assumed to shift to a new position located by the net section. Accordingly, two sets of section moduli were computed for these beams, the first based upon the moment of inertia of the net section taken about a neutral axis determined by the gross section, the second based upon the moment of inertia of the net section taken about a neutral axis determined by the net section.

Description of Tests and Results

Table 1 shows the results and other pertinent data from the tests of the individual beams of this series. Table 2 summarizes the data obtained from tests of minor specimens of flange material. Table 3 compares the average ultimate loads and stresses, for each of the variables studied, with the average of the control beams.

Control beams.--A total of four beams were tested as controls. Beam 1-T-2 did not carry so large a load as others in the group and examination after failure revealed a steep slope of grain at the point of failure despite original careful inspection. The results from this beam, though shown in table 1, are not included in the averages. The three other beams failed at an average load of 44,050 pounds, corresponding to an average maximum stress in the tension flange of 14,490 pounds per square inch. This stress was 1.239 times the average modulus of rupture and 0.886 times the average ultimate tension for minors taken from the tension flange material.

Figure 5 shows the crack patterns in the brittle lacquer at the center-line of beam 1-T-3 at loads of 9,000 and 21,000 pounds. These cracks always form at right angles to the principal tensile deformation and those shown in this figure are typical for the control beams. The cracks are uniformly distributed and, in general, at right angles to the axis of the beam, indicating freedom from stress concentrations and uniformity of stress distribution.

Beams with rigid load blocks.--Beams 3-T-1, 3-T-2, and 3-T-3 were designed with short heavy load blocks (fig. 3) to accentuate any stress concentrations which could be attributed to this type. No stress concentration, however, was evidenced by observation of the brittle lacquer coating or by other behavior characteristics of the beam during test.

In a previous series of tests of box beams designed to fail in the tension flange, the results of which have not been published, one beam was built with a solid Sitka spruce tension flange and with solid Sitka spruce load blocks of a modified "fish-tail" type. This beam failed in tension in the flange, apparently due to the concentration of stress at the outer end of the fairly rigid load block. The flange of this beam was 2-1/2 inches wide and 3/4 inch thick; the webs were nominally 1/8 inch thick. The failure of the flange in tension started at the end of the load block with a square break that included about one-third of the area of the flange. The calculated maximum stress in tension at failure was 13,660 pounds per square inch and was 75 percent of the ultimate tensile strength of the minors representative of the flange material. This percentage is less than that for the control beams of this series. It indicates that beams with thin flanges and webs are more susceptible to concentrations of stress at filler blocks than beams with the proportions used in this series.

The average load carried by the beams with rigid load blocks in the present series was 46,870 pounds and the average maximum stress in the tension flange was 15,600 pounds per square inch. This is somewhat greater than the corresponding values as previously stated for the beams primarily intended as controls. Accordingly, these beams were considered as additional controls and the results were averaged with the other controls for the comparisons in table 3. The average load for the six beams was 45,460 pounds and the average maximum tension stress was 15,050 pounds per square inch.

Figure 6 is a photograph of beam 3-T-1 after test and shows a typical failure of a straight-grained tension flange.

Beams with bolt holes in tension flanges.--The beams of this group developed longitudinal shear cracks approximately tangent to the sides of the bolt holes and parallel to the grain of the wood. Shear failures were first visible at an average calculated tensile stress of 5,610 pounds per square inch of net area of the flange. This value is 49 percent of the modulus of rupture and 37 percent of the ultimate tensile strength shown by tests of specimens representing the tension flanges. Shear failures were progressive, starting at the holes and becoming longer as the load increased until, at failure of the beams, they were often more than 2 feet in length. The holes were stress risers that caused the first cracking. The point of stress concentration then moved along with the crack causing a continuation of the cracking.

A mathematical analysis[2] of stresses around a hole shows that for the conditions here encountered there is a concentration of shearing stress which is a maximum at the ends of radii which are approximately 78° from the direction of applied stress. Figure 7 shows the shear failures at the edges of the horizontal hole in beam 2-T-1A; figure 8 the shear failures at the edge of a vertical hole in beam 2-T-2; and figure 9 the extent of shear cracking in the tension flange of beam 2-T-1 at the failure of the beam. The progression of the shear cracking can also be seen in these figures. These photographs show that the beams acted in agreement with theory.

Because beam 2-T-1 failed by shear in the web due to defective gluing and beam 2-T-3 had sloping grain in the tension flange at point of failure, their ultimate strength values have not been included in the averages. The average failing load for the remainder of the beams was 32,500 pounds with an average maximum tension stress on the net section of 12,800 pounds

[2]The Effect of Elliptic or Circular Holes on the Stress Distribution in Plates of Wood or Plywood Considered as Orthotropic Materials, by C. B. Smith. Forest Products Laboratory Report No. 1510.

per square inch. This was 113 percent of the modulus of rupture and 85 percent of the ultimate tension of minors from the tension flange material.

Beams with grain at a slope of 1 in 15 in the tension flanges.--The beams of this group developed an average calculated stress at failure in the tension flange of 10,500 pounds per square inch, which is 97 percent of the average modulus of rupture and 68 percent of the average ultimate tension stress from tests of minor specimens cut so that the grain was parallel to the axis of the specimens. These results serve as further substantiation of the relations used in establishing the rule that the ultimate tensile strength of wood is adequately represented by the modulus of rupture for slopes of grain as great as 1 in 15.

The average tensile strength of the minor specimens was 15,470 pounds per square inch. Substituting this value in equation 2:53 of ANC Bulletin 18, "Design of Wood Aircraft Structures," June 1951, together with assumed values for tension strength perpendicular to the grain and shear strength parallel to the grain of[6] 370 and 1,150 pounds per square inch respectively, the tensile strength of the wood with a slope of grain of 1 in 15 was computed as 11,430 pounds per square inch. The ratio of the average stress in the tension flanges at ultimate to the unit tensile strength so computed was 0.92 whereas the corresponding ratio for beams in this series with straight-grained tension flanges is 0.94.

The failures in the tension flanges of the beams with 1 in 15 sloping grain in the tension flanges occurred suddenly without any previous signs of distress. They were complete after which the flanges were incapable of carrying any load. Figure 10 is a photograph of beam 4-T-1 showing the typical failure of a tension flange with a grain slope of 1 in 15 in the vertical plane.

Beams with preexisting compression failures in the tension flanges.--There were two groups of these beams: those with solid tension flanges and those with vertically laminated tension flanges. The preexisting compression failures in the tension flanges of these beams were of a magnitude not easily detected by ordinary inspection methods. They were usually of a microscopic nature and were found by microscopic examination and toughness tests. The appearance of the saw cuts[7] at the ends of the planks sometimes gave evidence of the presence of compression failures.

The two groups of beams exhibited essentially the same behavior during loading. The brittle lacquer cracked early and spalled off at some of the preexisting compression failures but showed normal behavior at other points. Final failure was sudden in all beams and occurred at an average maximum stress of 5,215 pounds per square inch for the solid flanges and at an average maximum stress of 5,760 pounds per square inch for the laminated flanges. The tensile strength of wood containing compression

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[6] These values were obtained from table 1, U. S. Department of Agriculture Technical Bulletin No. 479, "Strength and Related Properties of Wood Grown in the United States," by L. J. Markwardt and T.R.C. Wilson.

[7] This is further described in Forest Products Laboratory Report No. 1588, "Detection of Compression Failures in Wood," by Eric A. Anderson.

failures is so low that the use of such material in airplane construction is inadvisable. The necessity of taking every possible care to eliminate compression failures is emphasized by these tests.

Beam 5-T-3 after failure is shown in figure 11. The compression flange was cut in two for this photograph to show the brash character of a tension flange failure when preexisting compression failures are present. A comparison of this figure with figure 6 shows the difference in the appearance of tension breaks of straight-grained good quality Sitka spruce and Sitka spruce with preexisting compression failures.

Beams subjected to reverse loading.--Beams 7-T-1, 7-T-2, and 7-T-3 were first loaded in an inverted position until visible failures developed in the flange then in compression. This occurred at an average load of 21,170 pounds or on an average maximum compressive stress of 7,070 pounds per square inch. This calculated stress at which compression wrinkling became visible was 2.6 percent greater than the average maximum compressive strength value obtained from the corresponding minor specimens.

Following the test in the inverted position, the tension flange of the beam was coated with brittle lacquer and the beam was tested to failure in the normal position. Failure occurred at an average load of 14,280 pounds or an average maximum stress of 4,770 pounds per square inch. This is lower than the corresponding values for beams fabricated of material with preexisting compression failures. It seems probable that the lower stress is due to the wood fibers being damaged to a greater extent when compressed to failure in a dry condition than when the material is green.

Conclusions

Holes in the tension flanges of box beams induce longitudinal shear failures in the flanges. The failures start at the holes, are approximately tangent to them, and become progressively longer as the loads increase. The shear failures were first visible in the flanges of the beams in this series at loads approximately one-third of the ultimate of comparable beams without holes. Flanges in these beams were straight grained and the ultimate loads were close to those expected from the net section. When cross grain is present, there is grave danger of complete failure of the flange at a low load because shear failures follow the grain of wood.

Concentrations of stress in the tension flanges due to short stocky load blocks were negligible in the beams tested. The strength values achieved in the beams with the two quite different types of load blocks were practically the same, indicating that for beams with proportions as in this series, either type of load block is satisfactory. It appears that beams with thinner flanges and webs, however, would probably be more susceptible to concentrations of stress due to rigid load blocks.

Shear failures along the glue lines between flanges and tapering load blocks have been observed. The concentration of shearing stress and subsequent failure is similar to that observed in the tension flanges with holes. When cross grain is present in the tension flange, there is danger of the beam failing at a low load. If sloping grain is not present, however, no harm appears to result from the use of tapering load blocks.

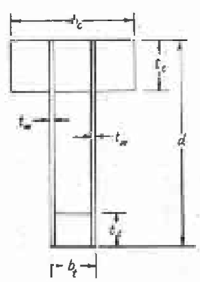
Beams with grain sloping 1 in 15 in the vertical plane in the tension flange developed strength values about two-thirds those of comparable beams with straight-grained tension flanges free from defects. The calculated maximum stresses in the tension flanges of these beams were approximately two-thirds the ultimate tension values of the minor test material representing these flanges. These tests emphasize the necessity for suitably correcting the allowable tension stress when slope of grain is permitted.

Preexisting compression failures in the tension flanges of beams in this series, compared with loads achieved in control beams with straight grain and no defects, reduced the ultimate loads to about one-third for solid flanges and to three-eighths for flanges with three vertical laminations. That the strength values in these beams were low emphasizes the care that should be exercised in selecting and inspecting material for aircraft to eliminate the possibility of preexisting compression failures in parts that will be stressed in tension.

Beams loaded in reverse to induce compression failures in the tension flanges were less than one-third as strong, when loaded in the normal position, as the comparable beams in the control series. These tests indicate the magnitude of the damage that may take place when tension members are overstressed in compression.

Table 1.--Results of tests of individual beams and related information[1]

Beam No.	Dimensions[2] b_c	t_c	b_t	t_t	$2t_w$	d	Moisture content at test: Compression flange	Tension flange	Webs	Data for load causing final failure: $\frac{I}{c_c}$	$\frac{I}{c_t}$	P ultimate	f_c	f_{tu}	Data at first shear failure[3]: $\frac{I}{c_c}$	$\frac{I}{c_t}$	P critical	f_{tcr}	Data for inverted beams[4]: P at compression failure	f_{cu}	Minor test information for tension flanges[5]: F_{cu}	F_{bu}	F_{tu}	Ratios between majors and minors: $\frac{f_{tcr}}{F_{bu}}$	$\frac{f_{tcr}}{F_{tu}}$	$\frac{f_{cu}}{F_{cu}}$	$\frac{f_{tu}}{F_{bu}}$	$\frac{f_{tu}}{F_{tu}}$	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
	Inches	Inches	Inches	Inches	Inch	Inches	Percent	Percent	Percent	Inches³	Inches³	Pounds	Lb. per sq. in.	Lb. per sq. in.	Inches³	Inches³	Pounds	Lb. per sq. in.	Pounds	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.						
1-T-1	9.822	3.997	3.779	2.494	0.788	16.030	11.0	10.8	5.7	272.5	100.7	40,100	4,860	13,140								10,630	16,300				1.236	0.806	
1-T-2	9.630	3.980	3.742	2.510	.768	16.000	11.2	10.6	4.3	275.5	99.4	[6]33,420	4,000	[6]21,090								11,900	17,500				[6].932	[6].634	Local slope of grain in center lamina. Results not used.
1-T-2A	9.690	3.964	3.757	2.496	.768	15.984	11.5	10.6	5.4	264.5	100.2	42,320	5,280	13,940								11,780	15,400				1.183	.905	
1-T-3	9.722	3.980	3.772	2.506	.772	16.010	11.6	11.0	4.9	281.2	100.1	49,740	5,840	16,400								12,640	17,330				1.297	.946	
Average for control beams												44,050		14,490													1.239	.886	
2-T-1	9.752	3.906	3.754	2.484	.784	15.892	11.5	9.8	....	[7]241.5	[7]85.4	[6]33,860	4,630	[6]13,080	[8]226.7	[8]87.9	14,500	5,450				12,740	17,000	0.428	.381		[6]1.027	[6].769	Tension flange did not fail. Not used for results at ultimate.
2-T-1A	9.628	3.990	3.695	2.497	.776	15.955	12.7	10.1	4.0	[7]247.1	[7]80.5	31,430	4,200	12,880	[8]230.4	[8]84.7	15,000	5,850				10,340	15,660	.566	.374		1.246	.822	
2-T-2	9.710	3.934	3.748	2.490	.780	15.960	11.6	10.4	4.2	[7]246.8	[7]85.6	33,960	4,500	13,100	[8]233.4	[8]88.1	14,500	5,430				12,120	15,200	.448	.357		1.081	.862	
2-T-2A	9.692	3.924	3.727	2.510	.782	15.846	12.1	10.6	4.1	[7]233.7	[7]85.2	32,100	4,530	12,430	[8]219.4	[8]87.6	15,000	6,030				11,600	14,550	.520	.414		1.072	.854	
2-T-3	9.450	3.944	3.734	2.490	.782	15.874	11.6	9.6	4.0	[7]223.5	[7]85.5	[6]28,000	4,130	[6]10,810	[8]210.0	[8]87.7	14,000	5,270				11,320	15,400	.466	.342		[6].955	[6].702	Slight local slope of grain at failure. Not used for results at ultimate.
Average for beams with holes in tension flange												32,500		12,800			14,800	5,610						.486	.362		1.133	.848	
3-T-1	9.690	3.959	3.783	2.484	.786	15.935	10.5	10.5	5.6	279.9	98.8	48,300	5,760	16,330								12,840	15,800				1.272	1.034	
3-T-2	9.760	3.983	3.754	2.486	.782	15.843	12.5	11.3	5.2	258.8	98.7	46,400	5,920	15,520								12,520	16,270				1.240	.954	
3-T-3	9.605	3.954	3.747	2.504	.766	15.944	12.5	10.6	4.6	259.8	99.5	45,320	5,760	14,960								11,880	15,200				1.259	.984	
Average for beams with poorly designed load blocks												46,670		15,600													1.257	.991	
4-T-1	9.668	3.896	3.714	2.434	.772	15.922	11.8	10.1	3.6	257.1	98.7	31,440	4,040	10,520								11,310	15,920				.930	.661	
4-T-2	9.485	3.869	3.732	2.468	.762	15.794	10.2	10.2	3.6	248.9	97.8	[6]25,210	3,740	[6]8,560								11,880	16,550				[6].721	[6].517	Reinforcing of tension flange at load block caused premature failure because of stress concentration. Results not used.
4-T-3	9.580	3.909	3.716	2.470	.780	15.850	10.2	9.4	3.6	228.4	99.0	31,440	4,540	10,480								10,310	14,960				1.016	.701	
Average for beams with 1 in 15 sloping grain												31,440		10,500													.973	.681	
5-T-1	9.020	3.961	3.476	2.520	.778	15.970	11.4	9.4	3.8	253.8	90.6	16,000	2,040	5,810								13,400	12,660				.434	.459	
5-T-2	9.560	3.954	3.683	2.514	.776	15.975	12.4	11.1	3.4	266.8	98.7	15,270	1,900	5,130								12,090	8,090				.424	.634	
5-T-3	9.710	3.983	3.285	2.506	.790	15.979	12.0	10.6	3.2	274.5	98.2	14,000	1,680	4,705								11,910	11,660				.395	.404	
Average for beams with preexisting compression failures in solid tension flanges												15,090		5,215													.418	.499	
6-T-1	9.660	3.934	3.680	2.492	.786	15.893	12.4	11.7	3.0	266.1	96.4	22,280	2,760	7,620								10,820	13,620				.704	.559	
6-T-2	9.560	3.946	3.666	2.510	.788	15.981	11.4	10.5	3.3	256.7	97.8	14,630	1,880	4,940								10,550	10,780				.468	.458	
6-T-3	9.569	3.972	3.713	2.532	.786	16.024	11.7	8.0	3.4	268.2	99.5	14,220	1,750	4,720								11,070	10,420				.426	.453	
Average for beams with preexisting compression failures in laminated tension flanges												17,040		5,760													.533	.490	
7-T-1	9.730	3.937	3.749	2.490	.780	15.947	11.5	10.4	4.5	277.6	98.8	17,000	2,060	5,680					21,000	7,020	6,860	12,210	14,220			1.023	.465	.399	
7-T-2	9.660	3.954	3.727	2.500	.778	15.934	11.8	10.0	4.4	254.3	99.4	14,000	1,820	4,650					20,500	6,810	6,690	12,080	14,300			1.018	.385	.325	
7-T-3	9.685	3.989	3.735	2.494	.780	15.958	11.2	9.2	4.6	274.9	98.3	11,850	1,420	3,980					22,000	7,380	7,110	12,490	16,880			1.038	.319	.236	
Average for beams with induced compression failures in tension flanges												14,280		4,770					21,170	7,070						1.026	.390	.320	



[1]Beams were tested by loading at points 20 inches each side of the center of a 14-foot 4-inch span. Tension flanges were Sitka spruce, compression flanges were Douglas-fir, and webs were 5-ply yellow-poplar plywood with the grain of the plies at 45° to the direction of the span.

[2]Headings of these columns refer to the sketch of the beam cross section at left.

[3]Visible shear failure parallel to the grain of the wood at the edge of hole in the tension flange.

[4]Beams were tested in an inverted position until compression failures were visible in what would normally be the tension flange, before being tested to destruction in the normal position.

[5]See table 2 for complete information from minor tests.

[6]Not included in average.

[7]Section properties calculated using net section for locating neutral axis and computing I.

[8]Section properties calculated using gross section for locating neutral axis and net section for computing I.

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Table 2.--Summary of minor tests for flanges

Beam No.	Douglas-fir compression-flange material								Sitka spruce tension-flange material										
	Compression parallel to the grain				Static bending				Compression parallel to the grain				Static bending				Tension parallel to the grain		
	Moisture content	Specific gravity[1]	F_{cu}	E_{Lc}	Moisture content	Specific gravity[1]	F_{bu}	E_L	Moisture content	Specific gravity[1]	F_{cu}	E_{Lc}	Moisture content	Specific gravity[1]	F_{bu}	E_L	Moisture content	F_{tu}	E_{Lt}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
	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.	Percent	Lb. per sq. in.	1,000 lb. per sq. in.
1-T-1	9.9	0.432	7,240	1,974	10.6	0.430	12,360	1,772	8.4	0.362	6,580	1,837	9.8	0.362	10,630	1,631	9.2	16,300	2,168
1-T-2	9.8	.477	7,190	1,856	9.9	.478	13,330	1,740	9.3	.389	6,870	1,902	10.1	.390	11,900	1,722	9.5	17,500	2,231
1-T-2A	9.7	.488	7,460	1,841	9.7	.485	13,260	1,777	8.7	.384	6,730	1,822	8.8	.380	11,780	1,742	7.7	15,400	1,936
1-T-3	9.7	.479	7,440	1,810	10.0	.479	13,380	1,709	9.6	.408	7,040	1,956	10.3	.408	12,640	1,773	9.5	17,330	2,246
2-T-1	9.9	.461	7,310	1,961	9.9	.459	13,000	1,794	8.8	.395	7,160	1,868	8.5	.395	12,740	1,838	8.5	17,000	1,934
2-T-1A	8.5	.442	7,320	1,758	8.6	.439	11,900	1,544	8.8	.363	6,380	1,759	8.5	.362	10,340	1,485	8.2	15,660	1,959
2-T-2	9.9	.470	7,420	1,909	10.2	.471	12,710	1,704	8.6	.391	6,600	1,820	8.8	.386	12,120	1,711	8.6	15,200	2,013
2-T-2A	10.1	.488	7,870	2,141	9.9	.488	13,170	1,854	8.7	.389	6,980	1,817	9.2	.385	11,600	1,592	7.3	14,550	1,988
2-T-3	10.0	.490	8,140	2,185	10.5	.490	13,100	1,890	8.7	.363	6,240	1,728	8.5	.364	11,320	1,671	9.3	15,400	1,878
3-T-1	9.6	.442	7,020	1,730	9.8	.446	12,630	1,625	9.5	.417	7,080	1,999	10.4	.416	12,840	1,783	9.3	15,800	2,212
3-T-2	10.0	.510	8,010	2,102	9.9	.508	13,770	1,921	8.6	.407	6,990	1,942	9.1	.403	12,520	1,809	7.9	16,270	2,150
3-T-3	10.3	.501	7,810	2,036	10.1	.501	13,510	1,927	8.9	.380	6,800	1,862	9.0	.379	11,880	1,761	7.8	15,200	2,098
4-T-1	9.4	.476	7,590	1,953	9.6	.471	12,620	1,707	8.7	.385	6,820	1,833	9.5	.379	11,310	1,597	8.1	15,920	1,976
4-T-2	9.1	.455	7,710	2,033	9.4	.455	12,420	1,811	8.4	.398	7,070	1,919	10.0	.391	11,880	1,639	8.9	16,550	2,040
4-T-3	8.7	.479	8,330	2,261	9.0	.476	13,390	1,909	8.9	.363	6,210	1,667	9.5	.361	10,310	1,541	8.8	14,960	1,737
5-T-1	9.9	.460	7,500	1,799	10.1	.459	12,570	1,635	8.1	.454	8,220	2,413	8.0	.453	13,400	2,169	8.1	12,660	2,292
5-T-2	9.2	.488	8,860	2,237	9.8	.485	14,240	1,992	9.6	.489	8,800	2,330	9.8	.485	12,090	2,172	8.6	8,090	2,527
5-T-3	9.2	.462	7,720	1,848	9.4	.460	12,840	1,714	9.0	.403	7,250	1,916	8.4	.399	11,910	1,769	8.4	11,660	2,216
6-T-1	9.4	.464	7,770	1,860	10.3	.461	12,390	1,668	9.2	.472	8,270	2,421	10.9	.470	10,820	2,002	8.1	13,620	2,137
6-T-2	8.4	.469	8,370	2,026	9.3	.468	13,210	1,812	8.2	.405	7,510	2,124	8.8	.412	10,550	1,876	6.9	10,780	2,079
6-T-3	8.2	.445	7,500	1,706	10.1	.441	11,550	1,527	8.1	.372	6,720	1,711	9.0	.371	11,070	1,640	7.9	10,420	1,922
7-T-1	10.0	.495	7,180	1,805	10.2	.490	13,240	1,598	8.5	.397	6,860	1,950	8.8	.396	12,210	1,812	9.0	14,220	2,109
7-T-2	9.5	.464	7,770	2,107	9.8	.465	12,970	1,865	8.5	.395	6,690	1,873	8.6	.394	12,080	1,820	9.2	14,300	2,047
7-T-3	8.9	.427	7,140	1,810	9.1	.425	11,930	1,608	8.5	.408	7,110	2,087	9.2	.406	12,490	1,860	7.2	16,880	2,180

[1] Specific gravity based on volume at test and oven-dry weight.

Z M 56762 F

Table 3.--Comparison of the average ultimates of test beams, by groups, with the average ultimates of the control beams[1]

Beam groups	Phase of study	Ratio of average ultimate load of group to average ultimate load of controls	Ratio of average f_{tu} of group to average f_{tu} of controls
(1)	(2)	(3)	(4)
2-T-1A, 2-T-2, and 2-T-2A	Beams with holes in the tension flanges	0.715	0.850
4-T-1, and 4-T-3	Beams with 1 in 15 sloping grain in the tension flanges	.692	.698
5-T-1, 5-T-2, and 5-T-3	Beams with preexisting compression failures in solid tension flanges	.332	.347
6-T-1, 6-T-2, and 6-T-3	Beams with preexisting compression failure in laminated tension flanges	.375	.383
7-T-1, 7-T-2, and 7-T-3	Beams with induced compression failures in the tension flanges	.314	.317

[1] The average control values are the mean strengths of beams 1-T-1, 1-T-2A, 1-T-3, 3-T-1, 3-T-2, and 3-T-3, and are 45,460 pounds for the load at ultimate and 15,050 pounds per square inch for the ultimate tensile stress. The test values for the beams in the 3-T series are included in the averages for the controls because the concentrations of stress introduced by the poorly designed load blocks were negligible.

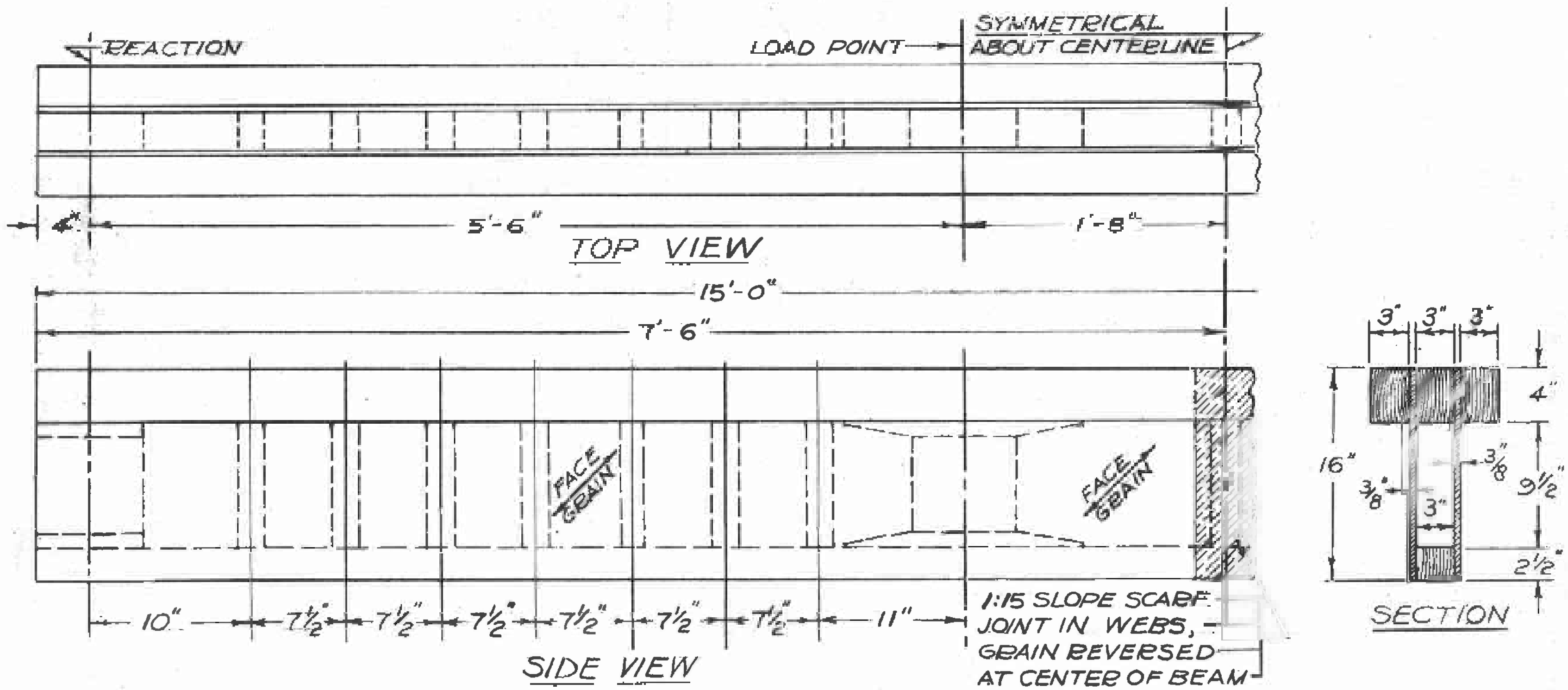

Figure 1.--Details of construction of beams. Webs were 5-ply yellow-poplar plywood as specified in table 2 of Specification AN-NN-P-511-b. Grain of plywood was at an angle of 45° with the axis of the beam. Compression flanges were Douglas-fir, with annual growth rings vertical. Tension flanges were Sitka spruce, with annual growth rings vertical.

Z M 56744 F

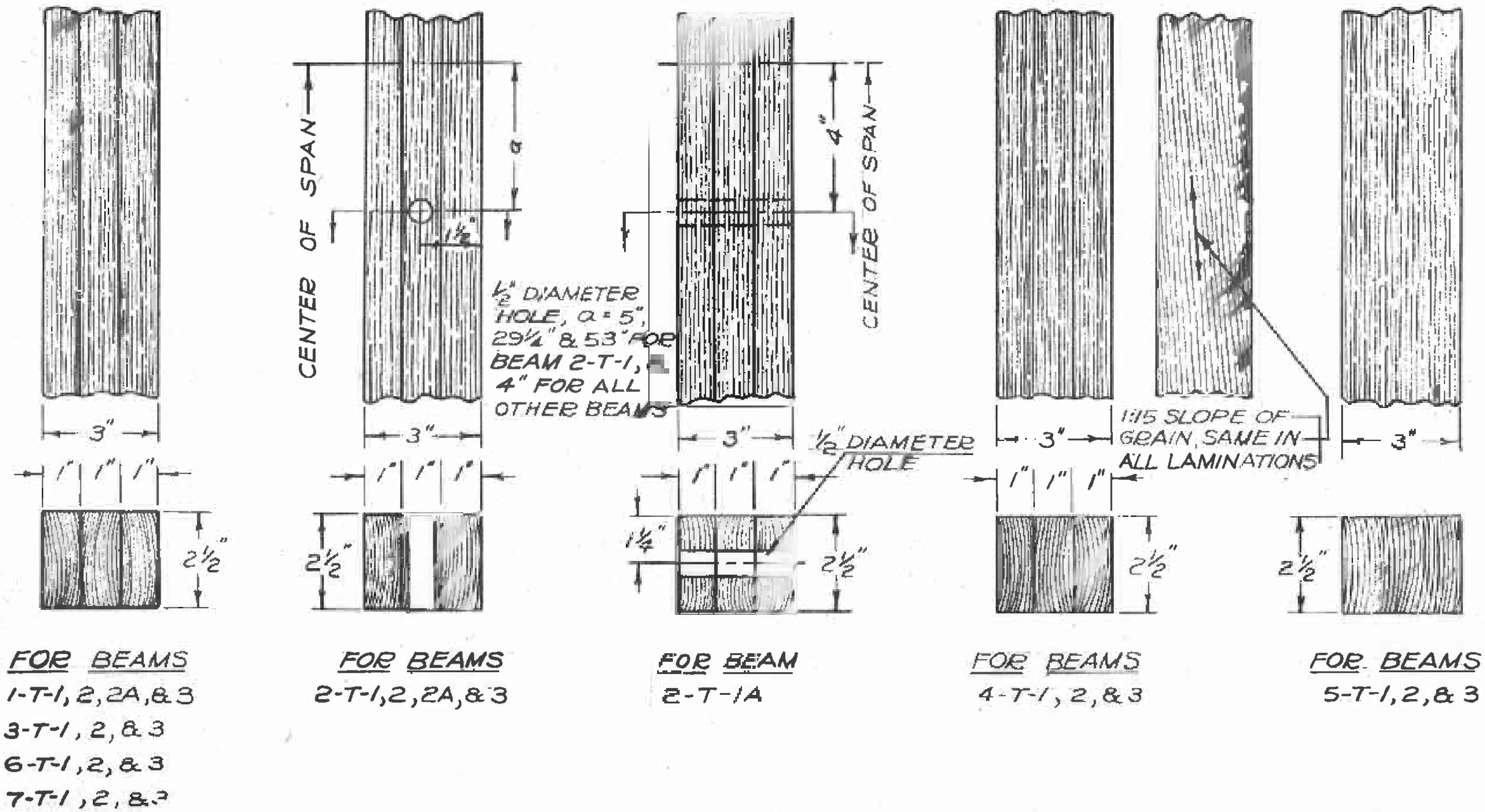

Figure 2.--Details of construction of tension flanges of beams.

Z M 56745 F

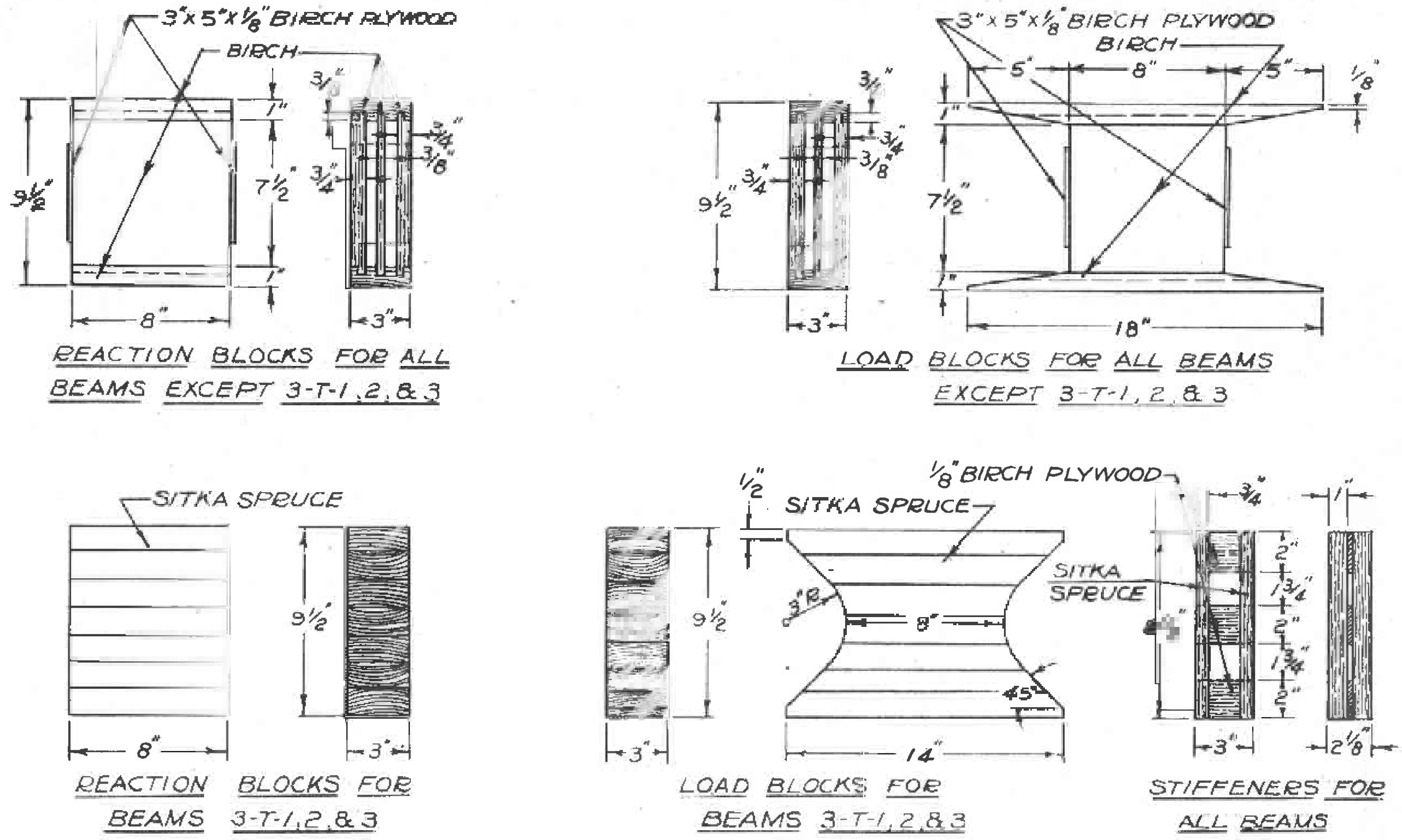

Figure 3.--Details of construction of load blocks, reaction blocks, and stiffeners of beams.

Z M 56746 F

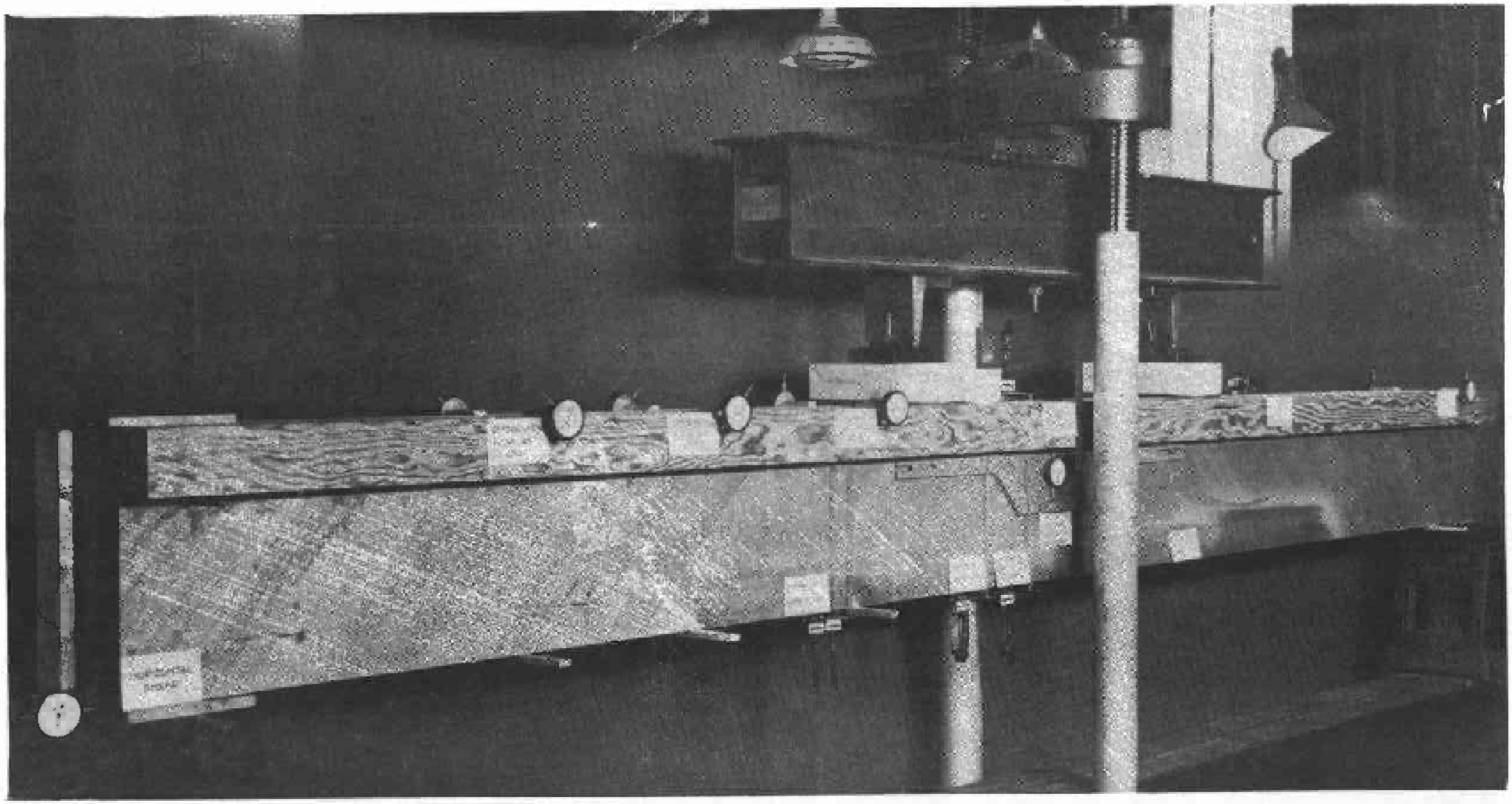

Figure 4.--A beam in the testing machine ready for test with deflection and strain measuring instruments attached.

Z M 56747 F

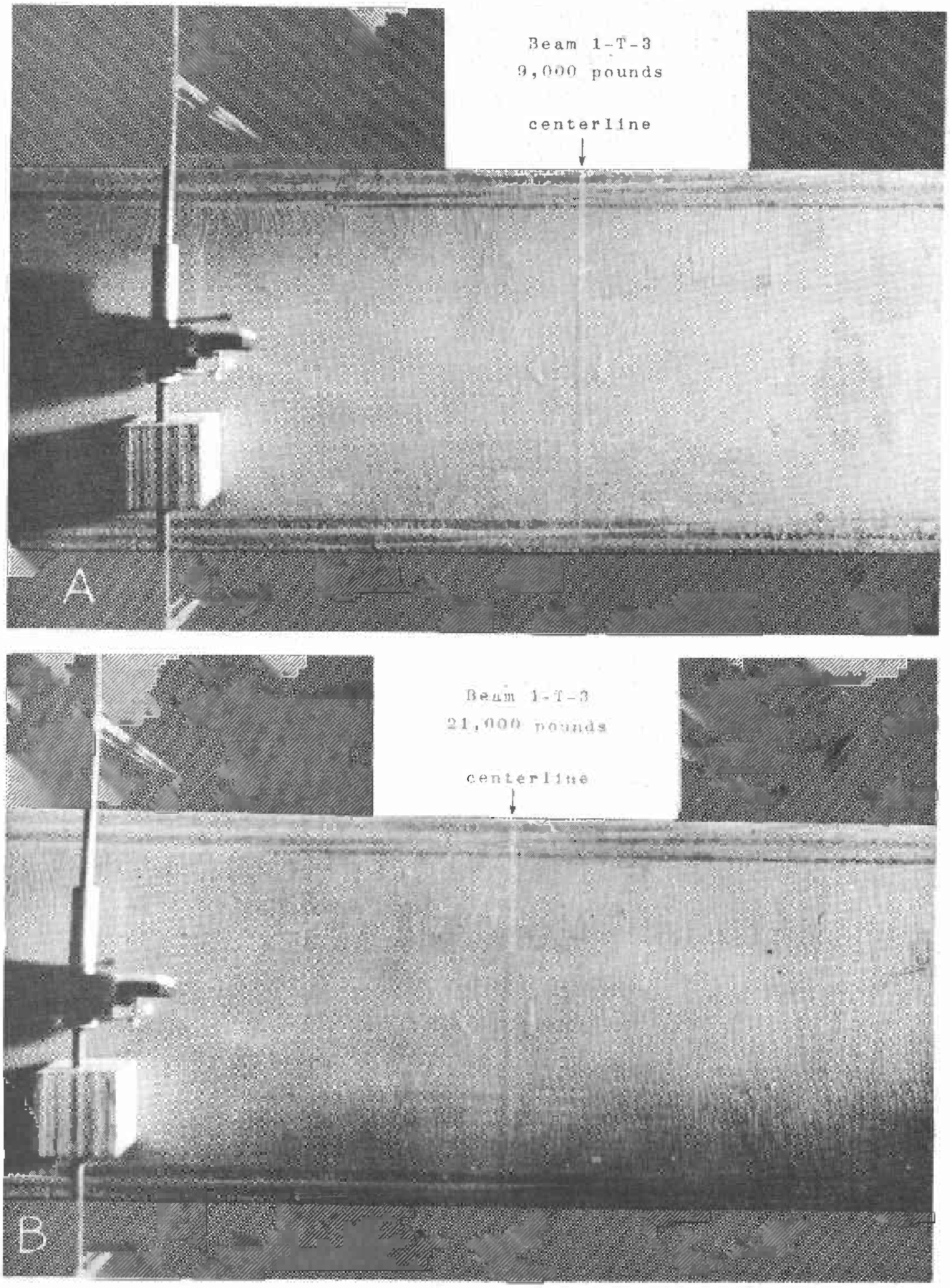

Figure 5.--Cracking of brittle lacquer at the center of the tension flange of box beam 1-T-3: A, at 9,000 pounds total load shortly after cracking was first visible; B, at 21,000 pounds total load, showing fully developed stress cracking pattern.

Z M 55712 F

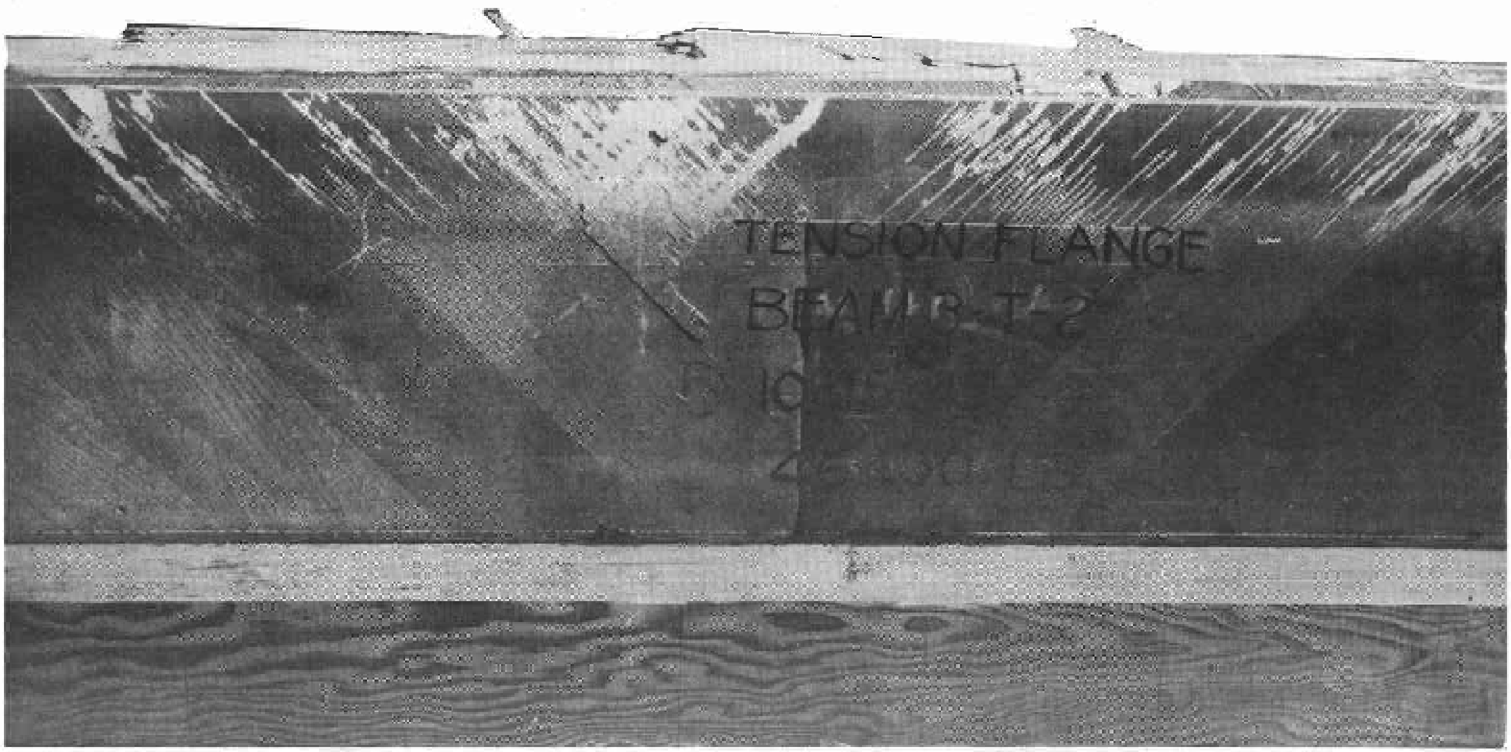

Figure 6.--Beam 3-T-1 after failure, showing typical straight-grained tension-flange failure.

Z M 56748 F

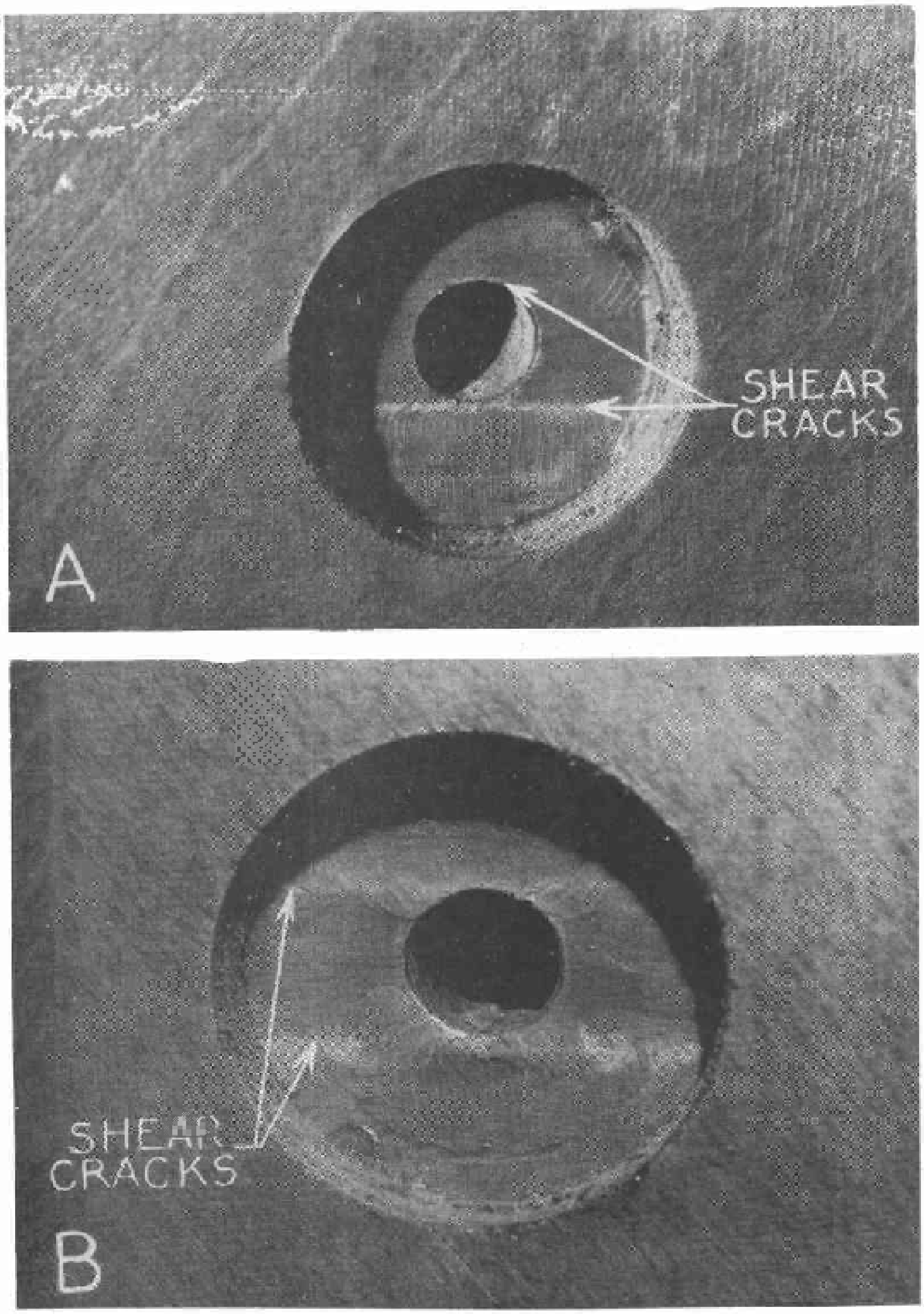

Figure 7.--Horizontal hole in tension flange of beam 2-T-1A. A, one end of hole soon after shear cracking started. Load on beam was 15,000 pounds. B, other end of hole after shear failures had progressed beyond routed-out portion of the web. Load on beam was 24,000 pounds.

2 M 56749 F

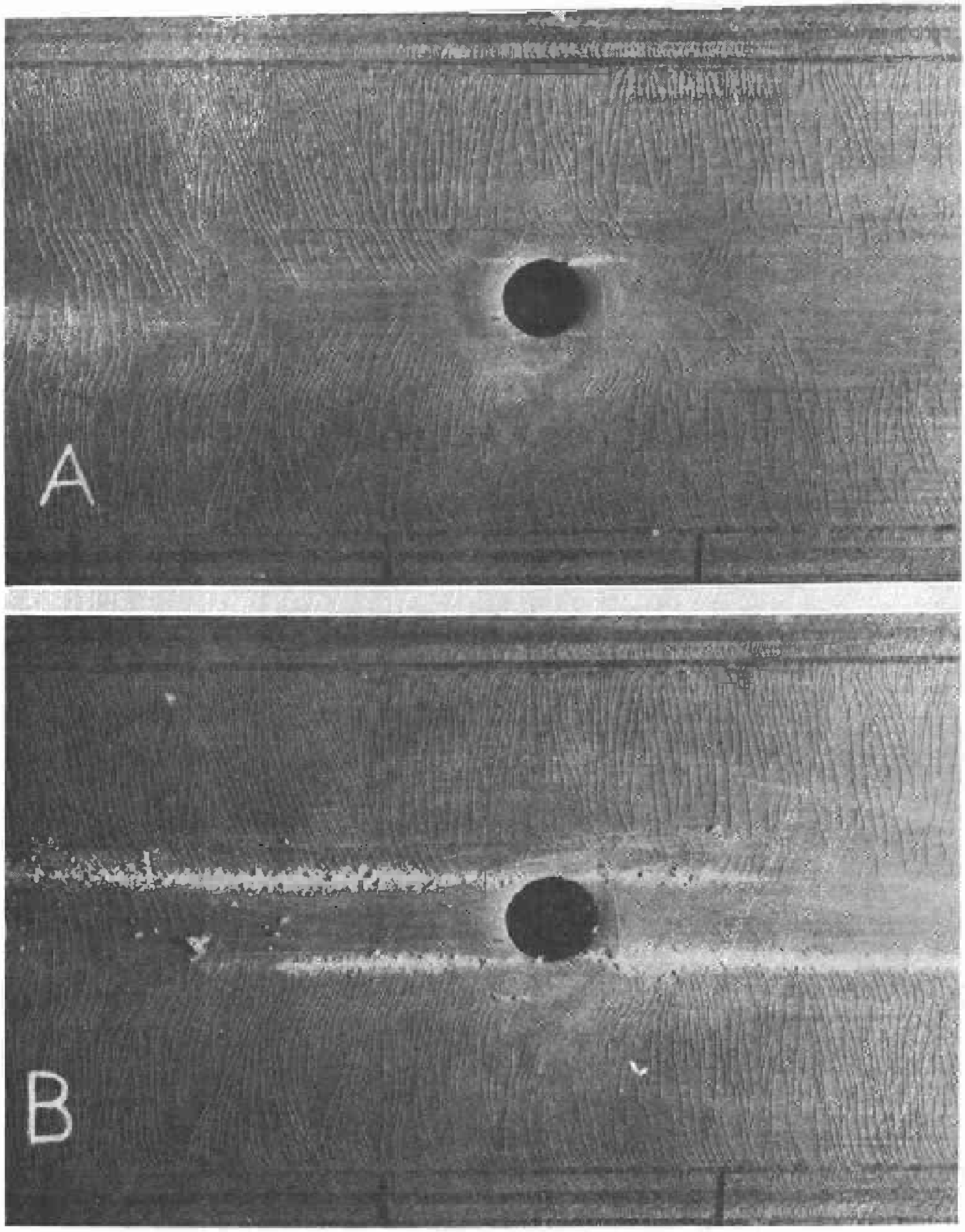

Figure 8.--Vertical hole in tension flange of beam 2-T-2. A, brittle-lacquer stress pattern and start of shear failures at edge of hole. Load on beam was 16,500 pounds. B, increased length of shear cracks due to increase of load. Load on beam was 20,500 pounds.

Z M 56750 F

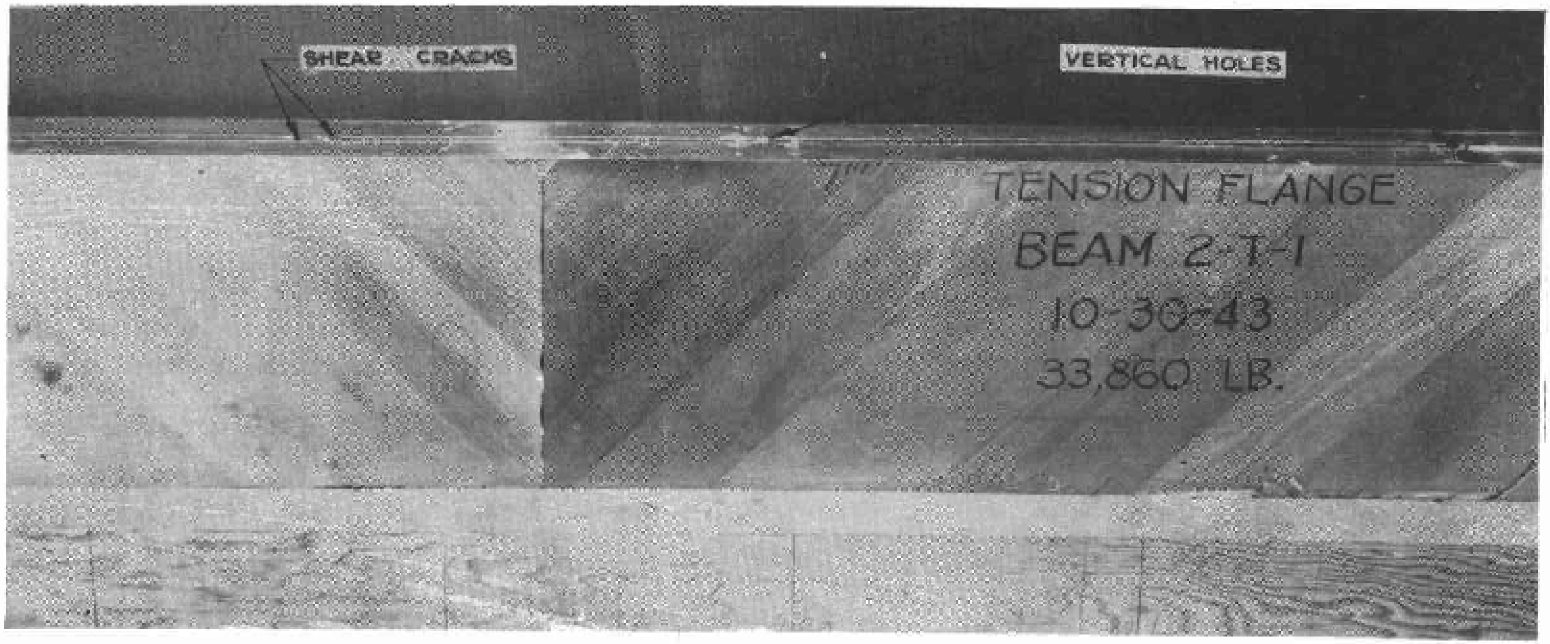

Figure 9.--Beam 2-T-1 after failure, showing lengths of the shear cracks that started at edges of holes.

Z M 56751 F

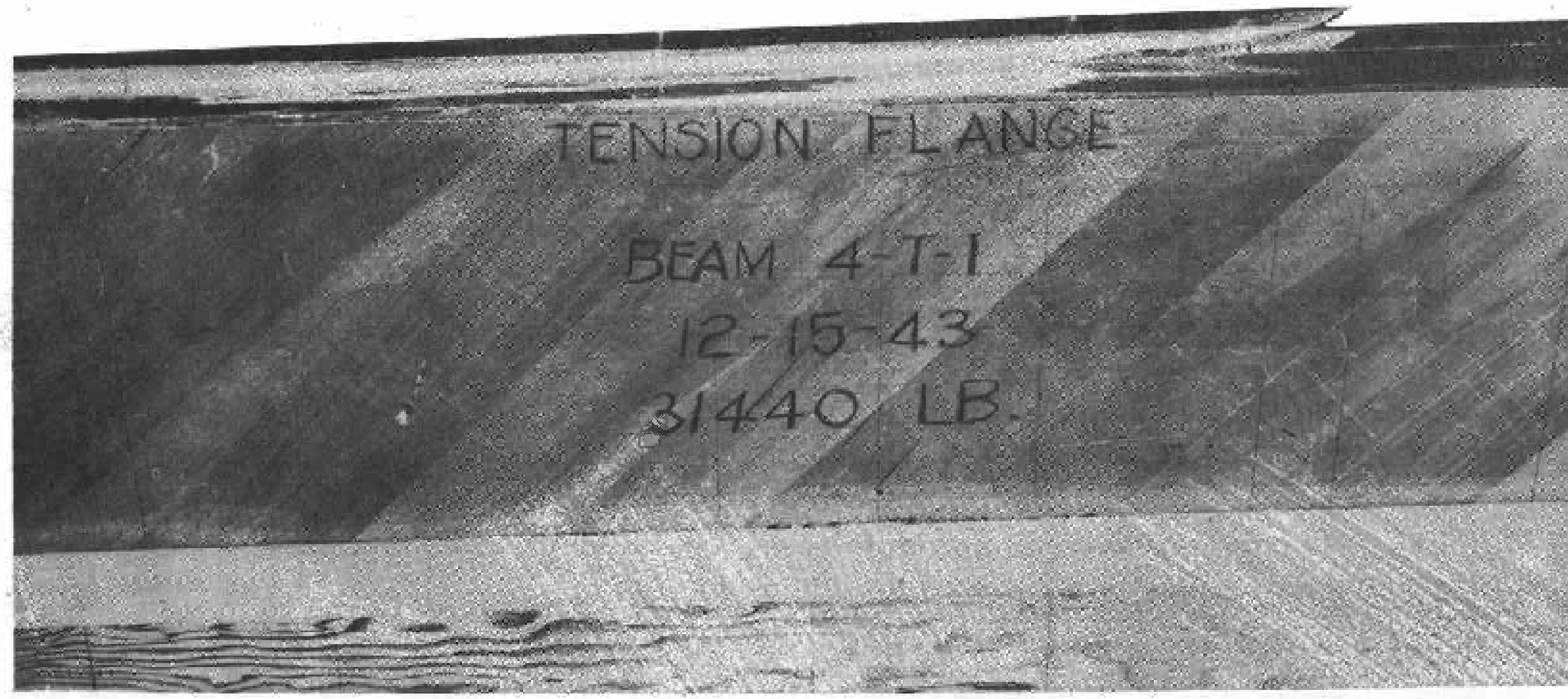

Figure 10.--Beam 4-T-1 after failure, showing typical failure of tension flange when grain slope is 1 in 15 in the vertical plane.

2 M 56752 F

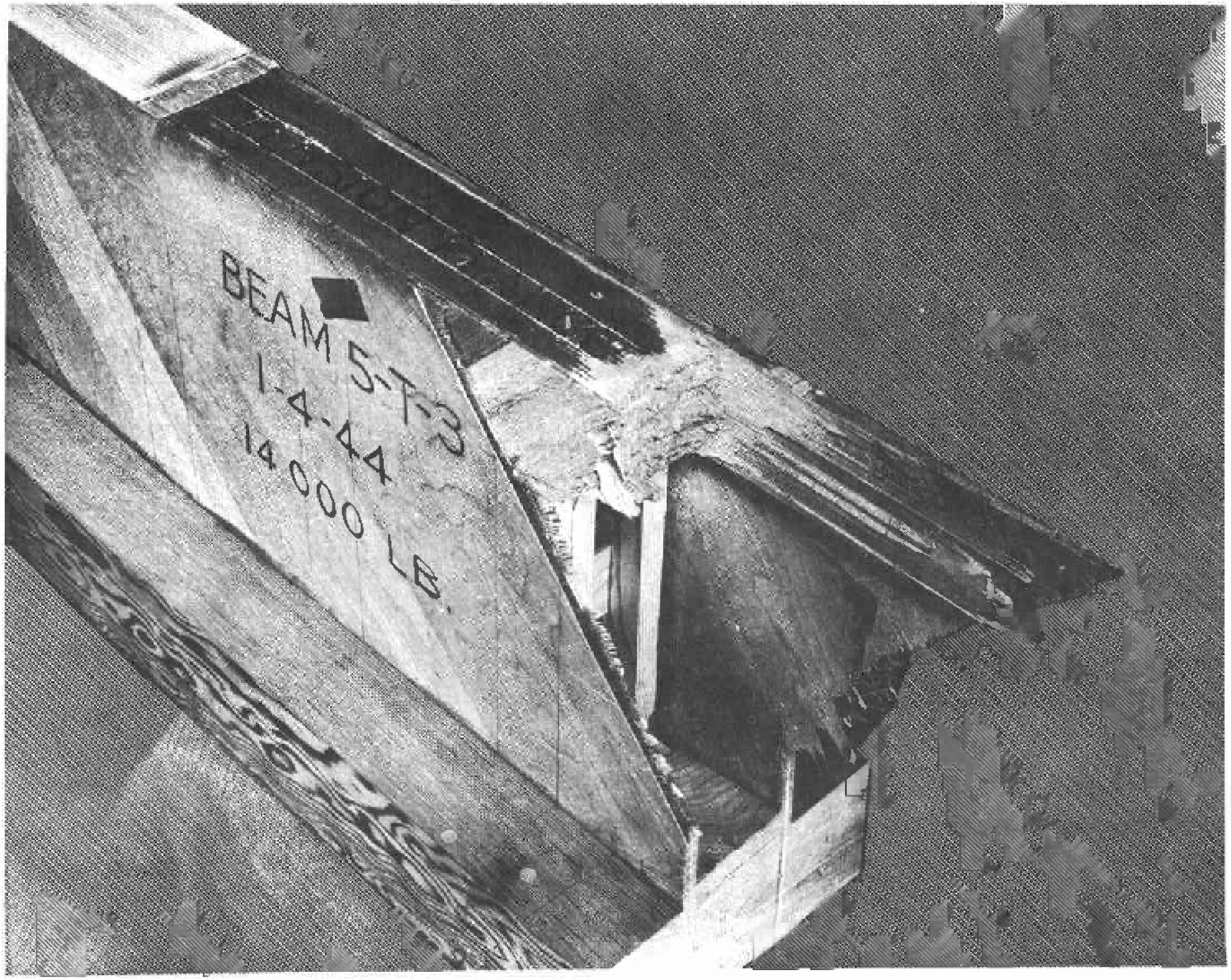

Figure 11.--Beam 5-T-3 after failure, showing brash character of tension flange failure when preexisting compression failures are present. (Part of compression flange removed).

Z M 56753 F