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STRAIN MEASUREMENTS AND STRENGTH TESTS OF 25-INCH DIAGONAL-TENSION BEAMS WITH SINGLE UPRIGHTS

By James P. Peterson

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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[redacted] REPORT

STRAIN MEASUREMENTS AND STRENGTH TESTS OF 25-INCH DIAGONAL-TENSION BEAMS WITH SINGLE UPRIGHTS

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SUMMARY

An investigation was made of a series of diagonal-tension beams to determine the accuracy of previously published design charts in predicting the stresses in single uprights. Strain measurements were made on the uprights and webs of the test beams to obtain the stress distribution in the beams and the ultimate stresses that could be developed in the beams. Failures of the beams occurred in both the uprights and the webs. The measured stresses were generally in agreement with the predicted stresses.

INTRODUCTION

A semiempirical theory for use in the design of beams with shear webs in incomplete diagonal tension is given in reference 1 with a design chart to facilitate the use of the theory. More refined design charts are given in reference 2. The empirical coefficients that are incorporated with the theory in the design charts were derived from tests of beams with uprights on both sides of the web. The design charts have been used for predicting the stresses in single uprights without experimental confirmation of the accuracy of the charts. Ample test data from various manufacturers on the ultimate strength of such diagonal-tension beams were analyzed in reference 2, but these data give no clues as to the stresses existing in the uprights at any given load. It was therefore desirable to test beams with single uprights in order to compare the experimental stress distribution with the stresses given by the theory of references 1 and 2. Such tests were made in the Langley structures research laboratory and the results are presented herein. At the same time, the opportunity was taken to obtain more information on the ultimate strength of diagonal-tension beams with single uprights and on the ultimate stresses developed in such beams.

SYMBOLS

A_U	actual cross-sectional area of upright, square inches
C_1, C_2	stress factors
P	applied load, kips
d	spacing of uprights, inches
h	depth of beam, back of top flange to back of bottom flange, inches
h_e	depth of beam between centroids of flanges, inches
k	diagonal-tension factor
t	thickness of web, inches
α	angle between axis of beam and direction of diagonal tension, degrees
ρ	radius of gyration of cross section of upright with respect to centroidal axis parallel to web, inches
σ	normal stress in web, ksi
σ_U	compressive stress in upright caused by diagonal tension, ksi
τ	nominal shear stress in web, ksi
τ_V	shear stress in web perpendicular to beam axis, ksi
ωd	parameter of flange flexibility

Subscripts:

e	effective
all	allowable

cr	critical
cy	compressive yield
ty	tensile yield
ult	ultimate
max	maximum
min	minimum

TEST SPECIMENS AND TEST PROCEDURE

Test Specimens

Nine beams were constructed of the general dimensions shown in figure 1(a). More detailed dimensions of the beams are shown in table I and dimensions of the cross sections of the uprights of each beam are shown in figure 1(b). On all beams, the web was fastened to the flange angles as diagrammed in figure 1(a) with the exception of beams 6 and 9. On these beams, the web was placed between the flange angles, and the uprights were joggled at each flange.

The webs of the test beams were fastened to the uprights by $\frac{1}{8}$-inch A17S-T aluminum-alloy brazier-head rivets spaced 5/8 inch. The rivets were countersunk and flush on the side of the upright so that strain gages could be placed at any station. On beam 1, a preliminary test was made with a 1.25-inch pitch of the upright-to-web rivets; the final test to ultimate load was made after adding intermediate rivets to reduce the pitch to 5/8 inch. The web was fastened to the flange by No. 10 socket-head capscrews of steel alloy spaced 1 inch in two rows. The uprights were fastened to each flange by two No. 10 socket-head capscrews of steel alloy.

Properties of Materials

The beams were made from 24S-T aluminum alloy. Stress-strain curves for the upright material of some of the beams are shown in figure 2. The stress-strain curves for extruded uprights (beams 1 and 6) differ appreciably from the stress-strain curves for the formed uprights (beams 2 and 8), the yield stress being about 41 ksi for extruded and 45 ksi for formed uprights. The stress-strain curves for beams 2 and 8 are considered typical for all the beams except beams 1 and 6 because all the beams except 1 and 6 had formed uprights.

Stress-strain curves for the web material of beams 5 and 9 are shown in figure 3. These curves were obtained from strain measurements on standard tensile specimens tested in the with-grain and cross-grain directions. The average of the ultimate stress in the with-grain and cross-grain directions is about 71 ksi for each beam and is taken as the ultimate stress that might be expected in a direction 45 degrees to the grain, because the difference between the ultimate stress in the with-grain direction and the ultimate stress in the cross-grain direction is small.

Ultimate strength tests were made on special tensile specimens from the web material of beams 5 and 9 to determine the effect of holes on the strength of the web. These specimens had parallel sides and a width equal to the rivet pitch (5/8 inch) of the upright-to-web rivets. A hole equal in diameter to the diameter of the upright-to-web rivets (1/8 inch) was drilled in the center of each specimen. The specimens were tested in the with-grain and cross-grain direction and the stress-concentration factor was found to be 1.13 based on the net section (see table II).

Test Procedure

The specimens were tested as cantilever beams with the load applied to the free end of the beam. In order to prevent lateral deflection or twisting of the beams when load was applied, the beams were fastened with parallel-motion guides to an auxiliary truss work. A typical test beam after failure with wires removed is shown in figure 4, and part of the lateral bracing is shown also.

Strain measurements were taken on the web and the uprights of the test beams at locations indicated by strain gages on the specimen in figure 4. Measurements were made on three uprights on the test beams with a 10-inch upright spacing and on two uprights on the beams with a 20-inch upright spacing. Strain measurements on the web were made in two bays on the beams with a 10-inch upright spacing and in three bays on the beams with a 20-inch upright spacing at similar locations with respect to the bay. The strain gages were placed in pairs on opposite sides of the web and the strains were averaged to cancel local-bending effects. Because this procedure was not possible in measuring strains in the uprights, strain measurements were made at a fairly large number of stations along the upright in an attempt to obtain an average strain that was reasonably free of local-bending effects.

Thicknesses of the webs and uprights were obtained by micrometer measurement and are accurate to about 0.0001 inch. Cross-sectional areas were obtained by weighing and are believed to be accurate to 1 percent. The loads were applied with a hydraulic jack and are accurate to about 1 percent. Strain measurements were made with Baldwin Southwark SR-4 electrical strain gages, types A-1 and R-1, and are believed to be accurate to within 2 percent.

TEST RESULTS AND DISCUSSION

Upright Stresses below Failure Loads

Single uprights are in eccentric compression because the load is applied to them in the plane of the web. The maximum stress in the upright occurs in the fibers adjacent to the web, that is, on the outside face of the leg attached to the web. This stress is given by the design charts of reference 2 when applied to beams with single uprights. For comparison with the test results, the stresses given by the design charts were corrected to the plane in which the stresses were measured - that is, to the inside face of the leg attached to the web - with linear stress distribution assumed in the upright. In order to obtain a stress that could be compared with the stress obtained from the design charts, all the upright stresses that were measured on the leg of the upright adjacent to the web at a given load were averaged. Figure 4 shows a few strain gages on the outstanding leg of the uprights, but the stresses obtained from these gages were not considered sufficiently informative to warrant their inclusion in this report. The stress-strain curves shown in figure 2 were used to convert the measured strains to stresses. An average of the stress-strain curves for beams 2 and 8 was used for the beams for which a stress-strain curve is not shown.

Load-stress plots for the uprights of each test beam are given in figure 5. The calculated stresses are generally in good agreement with the experimental stresses or are slightly conservative at loads that do not cause stresses above the elastic limit of the material in the upright. The only exception is beam 7; on this beam, the measured stresses are higher than the calculated stresses. The low calculated stresses on this beam are attributed to the degree of refinement of the design charts of reference 2. According to the theory of incomplete diagonal tension, the stress in the uprights is given by the formula

$$\sigma_U = \frac{k\tau dt}{A_{U_e} + (1 - k)dt} \tan \alpha \qquad (1)$$

In reference 2, the angle α was assumed to be defined by the formula

$$\tan^2 \alpha = \frac{1}{1 + \frac{\sigma_U}{2\tau}} \qquad (2)$$

In preparing the design charts of reference 2, a first approximation to σ_U was found from formula (1) by assuming that tan α was equal to unity. A value of tan α was calculated from formula (2) by using the value for σ_U obtained from formula (1). Then, a second approximation for σ_U was obtained by multiplying the first approximation of σ_U by the value obtained for tan α. This second approximation is the value for σ_U that is incorporated in the design charts of reference 2. If tan α is quite different from unity, the second approximation for σ_U will be somewhat optimistic; hence, a third approximation should be used. Tan α is quite different from unity if the value of A_{U_e}/dt is small as in beam 7 (see table I). If used on beam 7, therefore, a third approximation for σ_U would change the calculated stress to give good agreement between calculated and experimental stresses.

For some of the beams, the measured stress in the uprights at high loads is considerably more than the calculated stress. This effect is prominent for beams 4, 5, and 6 (see fig. 5). At these high loads, the maximum stress in the uprights is above the proportional limit of the upright material; and since the elementary theory of eccentric loading is not valid at stations where the proportional limit of the material in the upright has been exceeded, a quantitative comparison between calculated and experimental stresses is hardly warranted. A qualitative comparison is of some interest, however, because it indicates that the difference between calculated and experimental stresses might be removed by applying the theory of plastic bending to the uprights. The stress at the plane of maximum stress was not much above the proportional limit of the material for most of the stations along the length of the upright, and the stress was measured at a plane somewhat removed from the plane of maximum stress. Thus, when the plastic range was reached in the fibers of maximum stress, an increase in load on the upright forced more load upon the fibers in the plane of measured stress than is indicated by the assumption of linear distribution of stress. As a result, the experimental stresses are greater than the calculated stresses.

The range of measured stresses in the uprights at a given load is given in figure 5. The measured stresses at different stations along the upright vary considerably, which indicates that the upright tended to wave with the buckles in the web. This effect can be seen by inspection of the uprights on the test beam in figure 4. The load has been removed from the beam shown in figure 4; the effect was considerably more noticeable when the beam was under load.

Failure of Uprights

Failures of the uprights were caused by twisting forced upon the uprights by folds in the web. Two empirical formulas (formulas (14) and (14a)) are given in reference 2. These formulas are used to determine the stress at which uprights may be expected to fail by forced twisting. Formula (14), which is representative of average test results, was used to predict upright failures for the present beams. Inspection of table III shows that the present test results agree with calculations based on formula (14), the ratio of test load to predicted load ranging from 0.92 (beams 2 and 4) to 1.10 (beam 8). Formula (14a) was intended to be sufficiently conservative to serve as a design formula and is about 19 percent more conservative than formula (14); consequently, use of formula (14a) would have resulted in conservative predictions in all cases.

Empirical formulas for calculating the loads at which beams with single uprights will fail are given in references 3 and 4. The ratios of test ultimate load to the ultimate load as calculated with these formulas are given in table IV. The ratios calculated with formula (14) of reference 2 are also given.

The moment of inertia of the upright about the axis of its cross section parallel to the web is a parameter of upright design in the formula of reference 3, but the use of this parameter is questionable because observation of upright failures indicates that single uprights do not usually fail as columns. The tests of beams 2 and 7 are of interest because the moments of inertia of the uprights of the two beams are approximately equal, and the nominal dimensions of the two beams are the same; consequently, the formula of reference 3 predicts a failing load of 12 kips for both beams. The uprights of beam 2 failed, however, at a load of 11.4 kips and the uprights of beam 7 failed at a load of 6.7 kips.

The torsional stiffness of the upright is the main factor used in predicting upright failures by the formula of reference 4. Observation of upright failures on single uprights having Z cross sections indicates, however, that such sections do not fail by pure twisting without distortion of the cross section. The edge between the web of the Z-section and the free leg of the Z-section tends to remain straight because the free leg is in tension, and the cross section distorts instead of twisting. The same phenomenon is present in angles when used as single uprights but is probably not so pronounced as in Z-sections. The use of the torsional stiffness as the main factor for predicting the failing loads for uprights consequently appears to be somewhat objectionable and leads to rather unconservative predictions.

Web Stresses below Failure Loads

The strain measurements obtained from the rosettes on the webs were used to compute the shear stresses in the web on faces parallel and perpendicular to the longitudinal axis of the beam and to compute the principal stresses in the web. Because the strains measured at similar locations in different bays were nearly equal, the stresses obtained from these strains were averaged. The average stresses are shown in figure 6.

Under the assumptions underlying the theory of incomplete diagonal tension as presented in reference 2, the maximum principal stress at stations removed from rivet holes is calculated by the formula

$$\sigma_{max} = \frac{P(1 + k)}{h_e t} (1 + kC_2)(1 + kC_1)$$

For the beams with a 10-inch upright spacing (beams 3, 4, 5, 8, and 9), figure 6 shows that the maximum principal stress measured at the center of the panel agrees well with the calculated maximum stress in the web. For the beams with a 20-inch upright spacing (beams 1, 2, 6, and 7), the calculated stress is conservative. The stress-concentration factor due to the flexibility of the flanges is large for these beams. As suggested in reference 2, the theoretical value of this factor is probably too high, so that the calculated stresses are conservative.

The maximum principal stresses measured by the gages in the corners of the bays are somewhat greater than the maximum stresses measured at the center of the bays (see fig. 6). As a result, the stresses measured in the corners of the bays are greater than the calculated stresses for the beams with a 10-inch upright spacing and are in fair agreement with the calculated stresses for the beams with a 20-inch upright spacing.

Figure 6 shows that the compressive stress (minimum principal stress) in the web continues in most cases to increase after buckling of the web and does not remain constant and equal to the critical shear stress, as is assumed in some diagonal-tension theories. For each beam, the calculated critical shear stress is less than 0.5 ksi (see table III). Compressive stresses were measured as high as

7 ksi at the center gage (beam 5) and as high as 15 ksi at the gages in the corners of the panels (beam 8).

The shear stresses τ_V parallel and perpendicular to the beam axis computed from the rosette readings are compared in figure 6 with calculated shear stresses based on the formula

$$\tau_V = \tau(1 + kC_2)$$

The coefficient C_2 is a theoretical factor of stress concentration caused by flexibility of the flanges and is valid for pure diagonal tension. The factor $(1 + kC_2)$ was suggested in reference 2 as a means of adapting the coefficient C_2 to webs in incomplete diagonal tension. For the beams with an upright spacing of 10 inches (beams 3, 4, 5, 8, and 9), the calculated shear stress agrees well with the shear stress measured at the center of the panel. For the beams with a 20-inch upright spacing (beams 1, 2, 6, and 7), the calculated shear stress is somewhat more than the measured shear stress, presumably because of the previously mentioned inaccuracy of the stress-concentration factor. The shear stress measured in the corners of the panels is in most instances greater than the calculated shear stress.

Failure of the Webs

The maximum stresses developed in the webs of the test beams were estimated by linear extrapolation to ultimate load of the maximum stresses given in figure 6. In this extrapolation, only test data representing stresses less than 30 ksi were used because strains greater than the strain at the proportional limit were used in calculating higher stresses and the formulas used to calculate stresses from strains do not apply strictly in the plastic range. Linear extrapolation probably gives values of developed stresses that are low, but the error is expected to be small, especially for the beams with a 10-inch upright spacing. The developed stress at the center gage was found to be about 49 or 50 ksi for all the beams that had web failures with the exception of beam 1, for which the developed stress was found to be about 47 ksi. The low value for beam 1 is due to damage suffered in the preliminary test with the 1.25-inch pitch of upright-to-web rivets (see section "Test Specimens"). This large rivet pitch proved inadequate; severe diagonal-tension folds developed and, as a result, one of the rivets pulled through the sheet. The test was discontinued and intermediate rivets were added, but no attempt was made to reinforce the hole in the sheet for the final test.

Extrapolation in figure 6 of the data in the corners of the panels gives maximum stresses at failure of about 70 ksi in some instances. These stresses are local and probably not restricted appreciably by the rivet factor and the stress concentration due to holes because the stresses are not much below the ultimate tensile stress of the material.

The loads at which web failures would occur were estimated by the method used in reference 2. Formula (8) of reference 2 was used to calculate an "equivalent" shear stress in the web, and formula (12) of reference 2 was used to calculate the allowable "equivalent" shear stress. Minimum guaranteed properties taken from reference 5 were used in formula (12) of reference 2, and the resulting allowable stress was corrected to actual material properties by multiplying the stress by the ratio of the actual tensile strength of the web with holes $\left(\frac{71}{1.13}\text{ ksi}\right)$ to the value of σ_{ult} taken from reference 5. The values of 71 ksi for the ultimate tensile strength and of 1.13 for the stress-concentration factor due to holes were obtained from tests on the web material of beams 5 and 9 (see section "Properties of Materials") but were also considered to be representative of the other beams that had web failures.

The predictions of the loads at which web failures would occur were within 6 percent of the failing load for the beams with a 10-inch upright spacing (beams 3, 5, and 9; see table III). On the beams with 20-inch upright spacing, the prediction was much less accurate, presumably because - as mentioned before - the factor of stress concentration C_2 is too high. The failing load of beam 6 was predicted 32 percent too low and that of beam 1 was predicted 21 percent too low. Beam 1, however, failed at a low load because of faulty rivet spacing. A comparison of the maximum stresses developed in beam 1 with those developed in beam 6, which was of similar construction, led to the conclusion that the predicted failing load of beam 1 would have been about 29 percent too low if a suitable rivet spacing had been used throughout the test.

Effect of Joggling Uprights

The uprights on beams 6 and 9 were joggled at the flanges and the webs of these beams were placed between the flange angles. With the exception of this change, beams 6 and 9 were of the same nominal dimensions as beams 1 and 3, respectively. No significant difference appears in the stress distribution in the uprights of the similar beams. The stresses in the webs of similar beams at given loads cannot be compared directly, since the thicknesses of the webs were somewhat different even though the nominal thicknesses were the same. A comparison of the strength of the similar beams can be made by comparing the nominal shear stresses developed in the webs of the beams at failure. The nominal shear stress developed in the similar beams 3 and 9 was about 25.5 ksi for each beam. The developed nominal shear stress in beam 1 was 20.5 ksi as compared with 22.6 ksi in beam 6. The low developed stress in beam 1, as mentioned before, was due to previous damage caused by a rivet head pulling through the web at a load less than the ultimate load.

CONCLUSIONS

For the tests on nine beams described herein, the stresses in the uprights throughout the load range were predicted with fair accuracy unless the stresses exceeded the elastic limit of the material used in the uprights. The loads at which the uprights failed were predicted with a maximum error of 10 percent.

The theoretical stress concentration in the webs caused by the flexibility of the flanges was too high for the beams with a 20-inch upright spacing and the strength predictions for these beams were therefore up to 32 percent conservative. The strength of the webs of beams with a 10-inch upright spacing were predicted with a maximum error of 6 percent.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

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TABLE I.- PROPERTIES OF TEST BEAMS

$[h = 25.5 \text{ in.}, h_e = 24.3 \text{ in.}]$

Beam	d (in.)	$\frac{d}{h}$	t (in.)	Uprights		A_U (sq in.)	$\frac{A_U}{dt}$	$\frac{A_{U_e}}{dt}$	ρ (in.)	Flanges (2∠s) (in.)	ωd
				Cross section	Nominal size (in.)						
1	20	0.78	0.0265	∠	$1 \times \frac{3}{4} \times \frac{1}{8}$	0.212	0.400	0.183	0.309	$2 \times 2 \times \frac{3}{16}$	3.21
2	20	.78	.0265	Z	$1 \times 1 \times 1 \times 0.072$	.195	.368	.144	.407	$2 \times 2 \times \frac{1}{4}$	3.00
3	10	.39	.0224	∠	$1\frac{1}{8} \times 1 \times 0.081$	.153	.684	.352	.357	$2 \times 2 \times \frac{3}{16}$	1.53
4	10	.39	.0257	∠	$1 \times 1 \times 0.064$	.121	.471	.254	.314	$2 \times 2 \times \frac{1}{4}$	1.49
5	10	.39	.0249	Z	$\frac{15}{16} \times \frac{15}{16} \times \frac{15}{16} \times 0.081$	.194	.778	.302	.377	$2 \times 2 \times \frac{3}{16}$	1.58
6	20	.78	.0248	∠	$1 \times \frac{3}{4} \times \frac{1}{8}$	.212	.427	.196	.309	$2 \times 2 \times \frac{3}{16}$	3.12
7	20	.78	.0248	Z	$\frac{3}{4} \times 1\frac{1}{2} \times \frac{3}{4} \times 0.040$	.108	.217	.0831	.582	$2 \times 2 \times \frac{1}{4}$	2.95
8	10	.39	.0248	Z	$\frac{3}{4} \times 1\frac{1}{2} \times \frac{3}{4} \times 0.040$	.109	.439	.174	.611	$2 \times 2 \times \frac{1}{4}$	1.47
9	10	.39	.0245	∠	$1\frac{1}{8} \times 1 \times 0.081$	.156	.637	.331	.358	$2 \times 2 \times \frac{3}{16}$	1.57

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TABLE II.- STRENGTH OF WEB MATERIALS

Specimen	σ_{ult} (no holes) (a)	σ_{ult} (holes) (b)	$\frac{\sigma_{ult} \text{ (no holes)}}{\sigma_{ult} \text{ (holes)}}$
Beam 5; with-grain	71.5	63.0	1.13
Beam 5; cross-grain	70.2	62.0	1.13
Beam 9; with-grain	72.9	64.2	1.13
Beam 9; cross-grain	69.9	61.4	1.14

[a] From standard tensile specimens.

[b] From parallel-sided tensile specimens with central hole. Stress is based on net area. See text for details. Strengths given are average for two specimens; maximum deviation from average was 3 percent.

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TABLE III.- SUMMARY OF CALCULATED AND EXPERIMENTAL RESULTS

Beam	Calc. τ_{cr} (ksi)	P_{ult} (kips)	Calc. P_{ult} (kips) (a)	$\frac{P_{ult}}{h_e t}$ (ksi)	Failure (actual and predicted)	$\frac{P_{ult}}{\text{Calc. } P_{ult}}$	Alternate margin (percent) (b)
1	0.19	13.2	10.9	20.5	[c]Web	1.21	66
2	.19	11.4	12.4	17.7	Upright	.92	4
3	.37	13.9	13.5	25.4	Web	1.03	28
4	.48	13.5	14.7	21.6	Upright	.92	14
5	.45	15.5	14.9	25.6	Web	1.04	13
6	.17	13.6	10.3	22.6	Web	1.32	81
7	.17	6.7	6.5	11.1	Upright	1.03	92
8	.44	10.2	9.3	16.9	Upright	1.10	73
9	.43	15.4	14.5	25.8	Web	1.06	17

[a] Ultimate loads on beams with upright failures are based on formula (14) of reference 2. Formula (14a) of reference 2, which is recommended for design, is 19 percent more conservative.

[b] Predicted margin against web failure on beams where uprights failed, or against upright failure where webs failed.

[c] Premature failure due to excessive rivet spacing (upright to web).

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TABLE IV.- RATIOS OF TEST ULTIMATE LOAD TO CALCULATED ULTIMATE LOAD FOR THE TEST BEAMS WITH UPRIGHT FAILURES

Beam	$\frac{P_{ult}}{\text{Calc. } P_{ult}}$		
	Reference 2	Reference 3	Reference 4
2	0.92	0.95	0.73
4	.92	.99	.85
7	1.03	.56	.81
8	1.10	.54	.91

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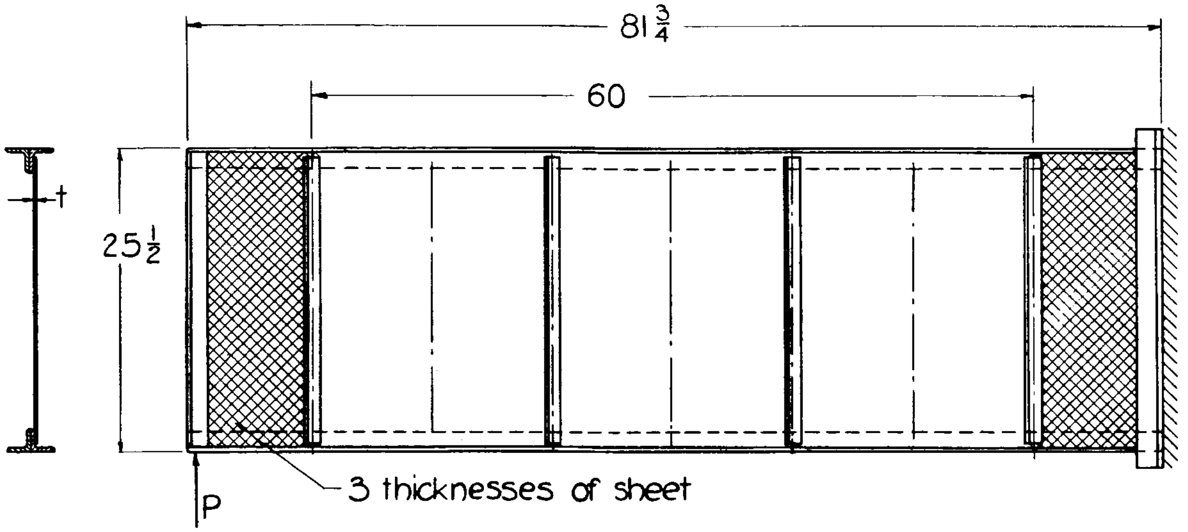
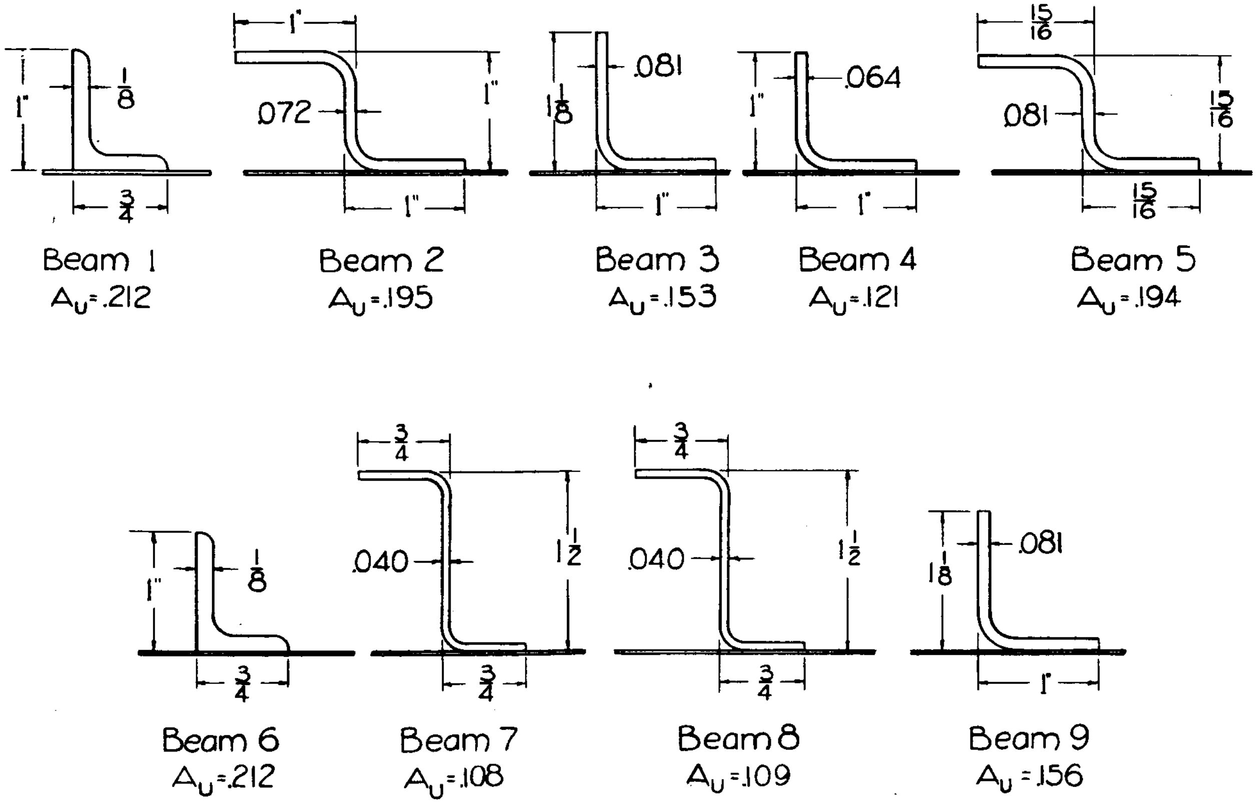


(a) General dimensions of test beams.



(b) Nominal dimensions of uprights.

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Figure 1.- Dimensions of test beams and uprights.

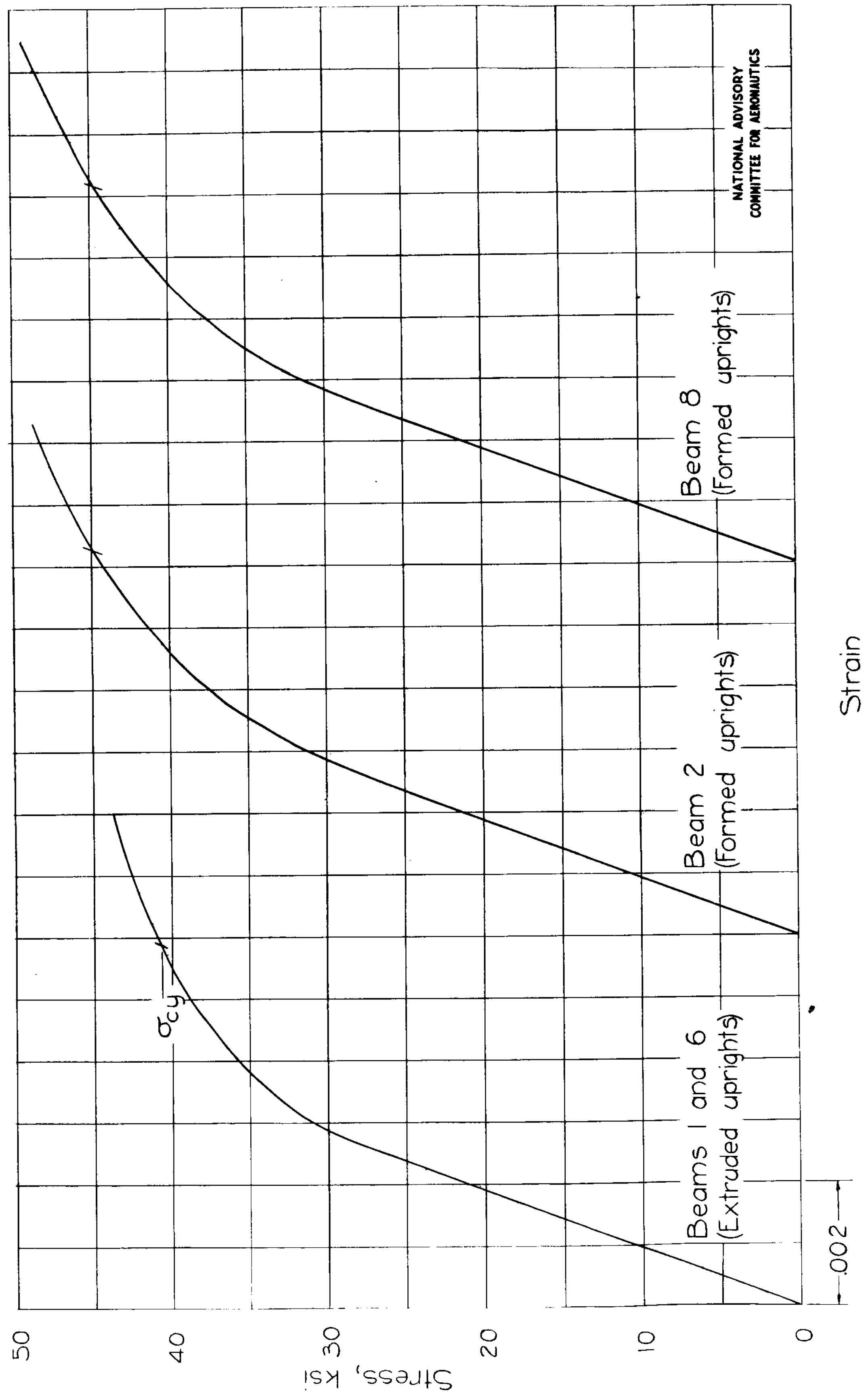

Figure 2.- Compressive stress-strain curves for 24S-T aluminum alloy used in uprights of beams 1, 2, 6, and 8.

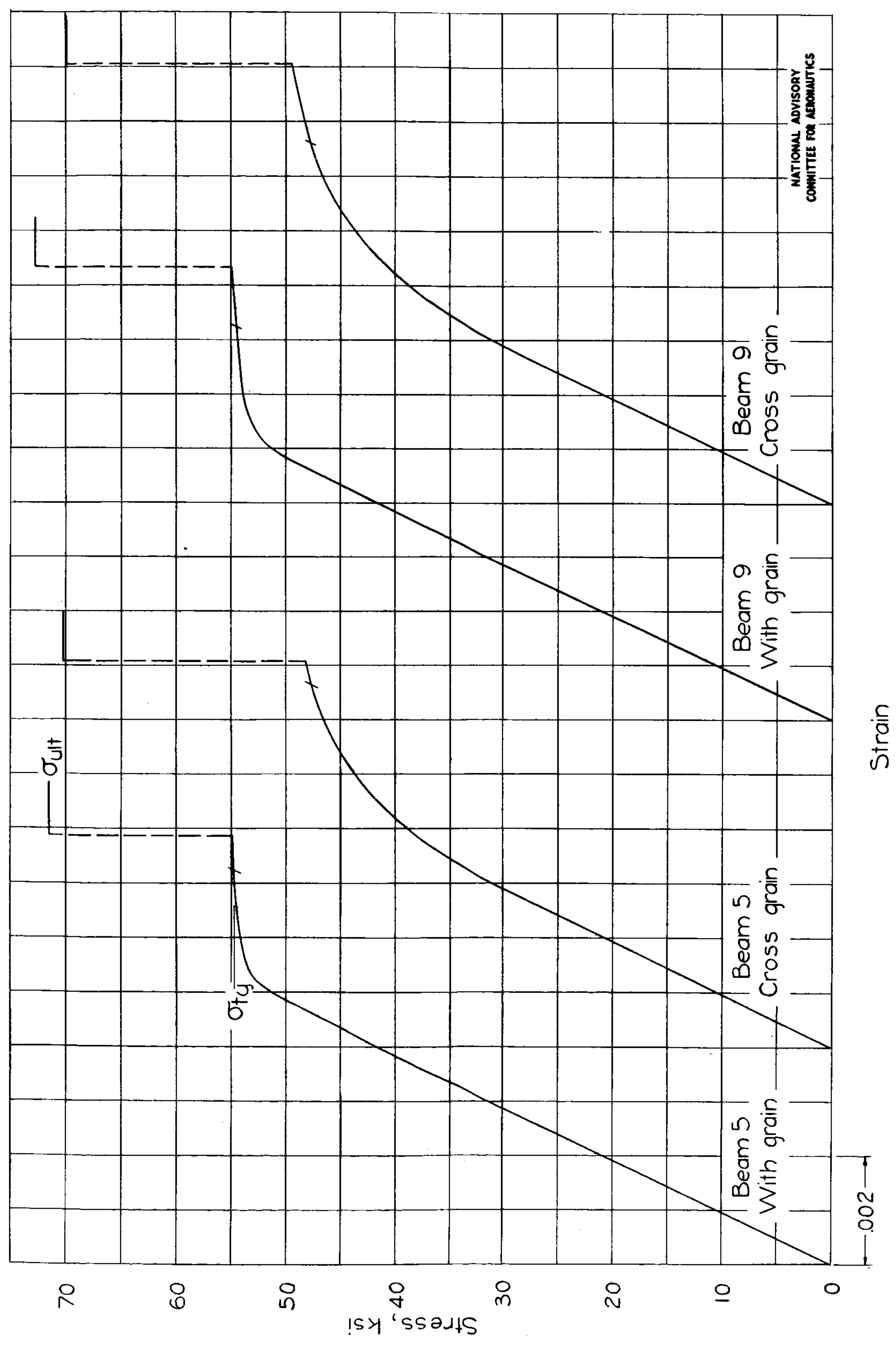

Figure 3- Tensile stress-strain curves for 24S-T aluminum alloy used in webs of beams 5 and 9.

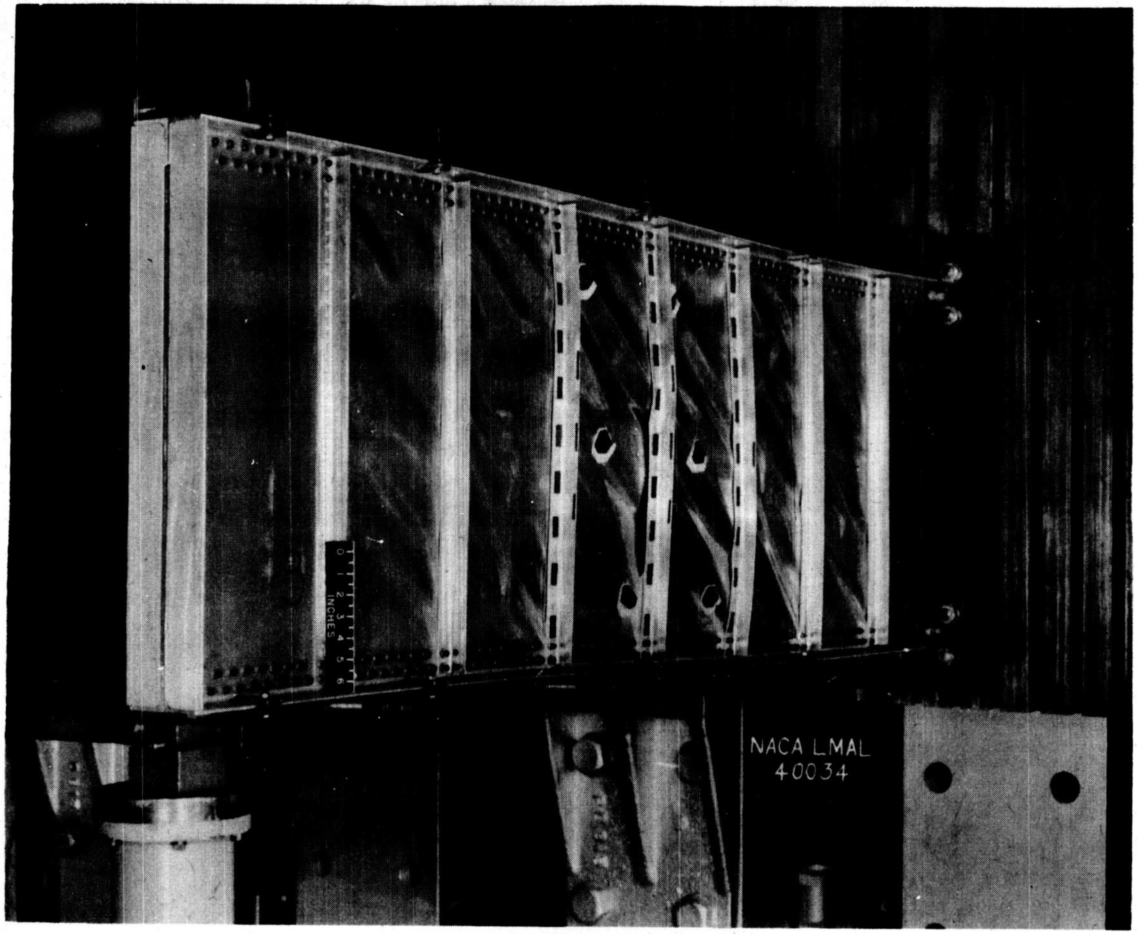

Figure 4.- A typical test beam after failure.

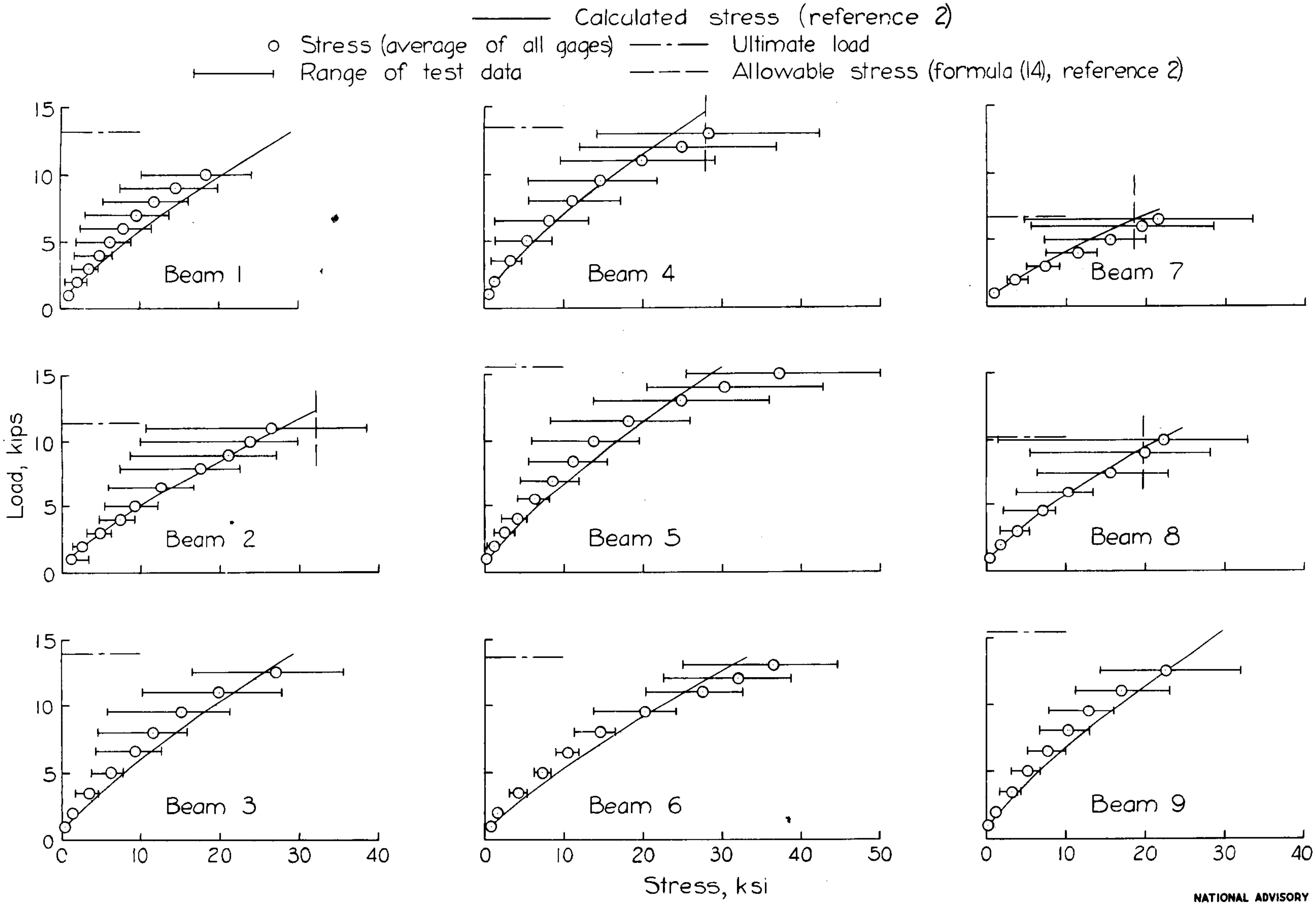

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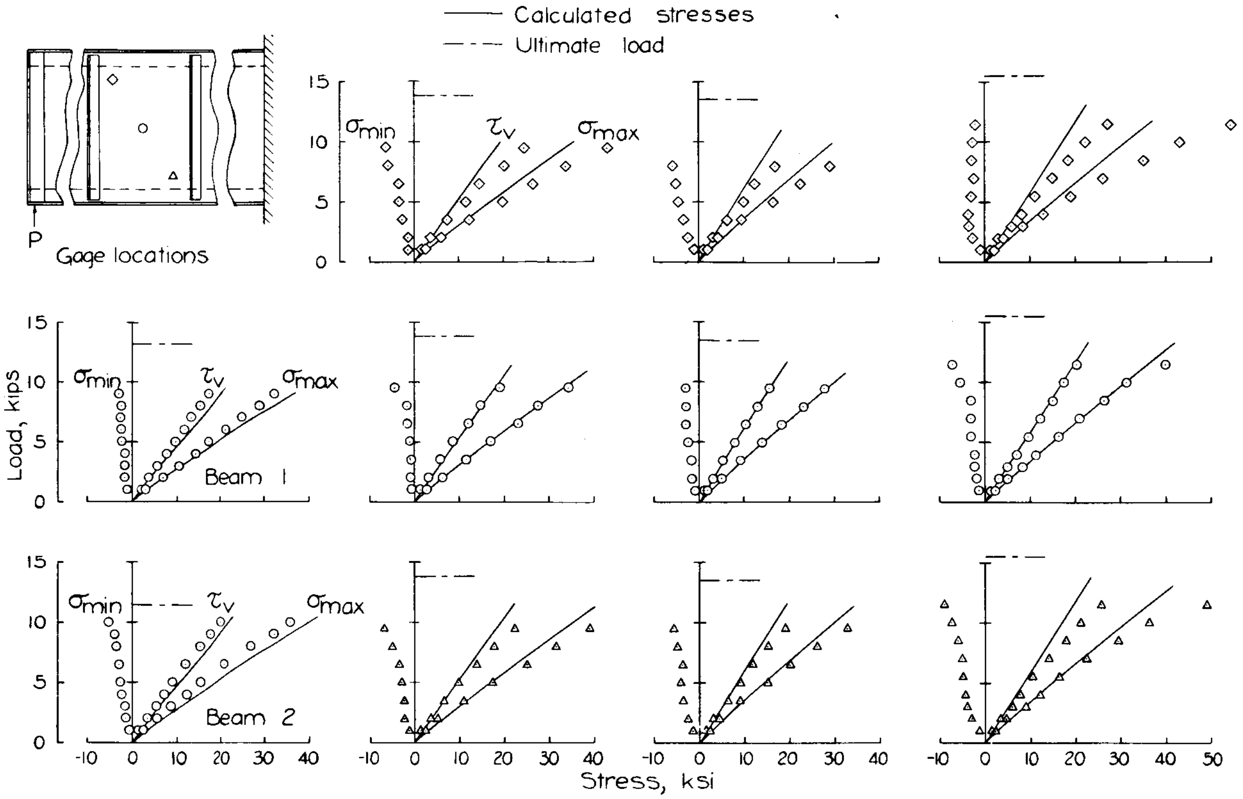
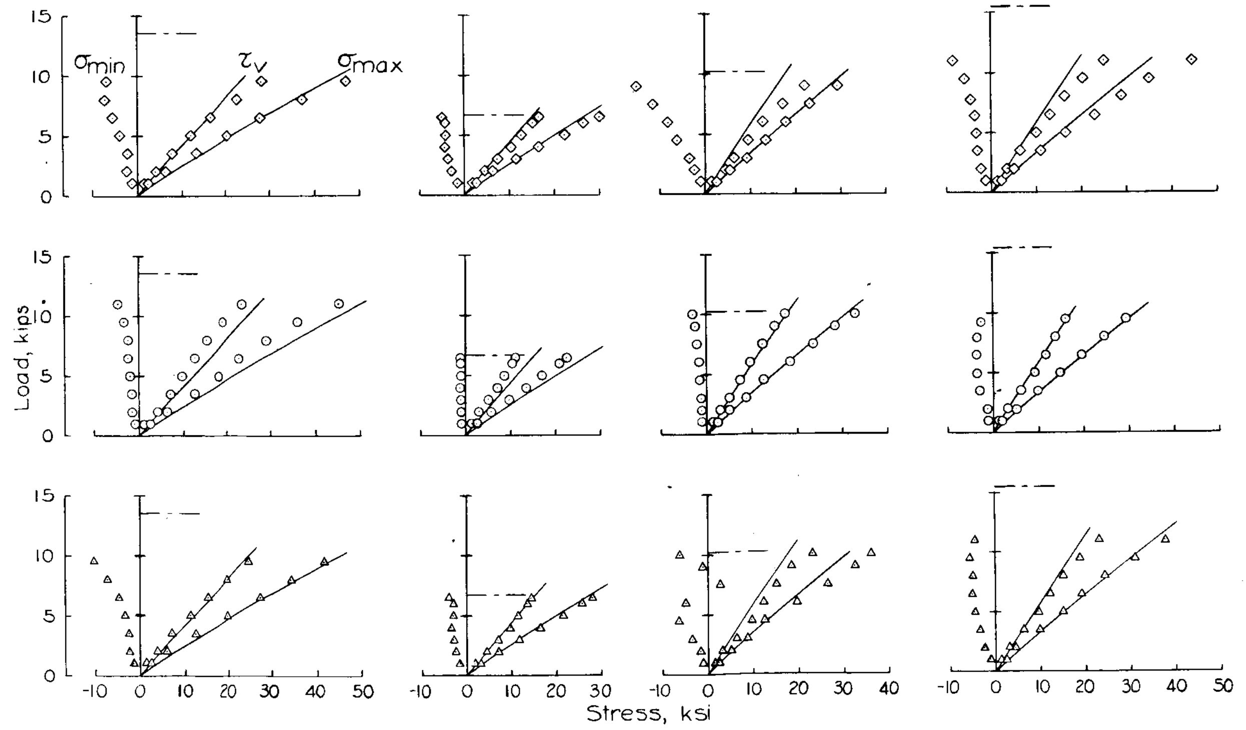
Figure 5.- Stresses in the uprights of test beams. (Allowable stress is shown only for beams having upright failures).



Beams 1 and 2 Beam 3 Beam 4 Beam 5



Beam 6 Beam 7 Beam 8 Beam 9

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Figure 6.- Stresses in the webs of test beams.

TITLE: Strain Measurements and Strength Tests of 25 Inch Diagonal Tension Beams with Single Uprights
AUTHOR(S): Peterson, J. P.
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ABSTRACT:

An investigation was made of diagonal tension beams to determine the accuracy of previously published design charts for predicting stresses in single uprights. Stresses in uprights throughout the load range were predicted with fair accuracy. The loads at which the uprights failed were predicted with a maximum error of 10%. Because of the flexibility of the flanges, the strength of the beams with 20 in. upright spacing was predicted with a maximum error of 32% while the strength of the beams with 10 in. spacing had only 6% error.

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Wright-Patterson Air Force Base
Dayton, Ohio