NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1177

EFFECT OF RIVET OR BOLT HOLES ON THE ULTIMATE STRENGTH DEVELOPED BY 24S-T AND ALCLAD 75S-T SHEET IN INCOMPLETE DIAGONAL TENSION

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EFFECT OF RIVET OR BOLT HOLES ON THE ULTIMATE STRENGTH DEVELOPED BY 24S-T AND ALCLAD 75S-T SHEET IN INCOMPLETE DIAGONAL TENSION

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SUMMARY

Strength tests were made of a number of 24S-T and Alclad 75S-T aluminum-alloy shear webs to determine the effect of rivet or bolt holes on the shear strength. Data were obtained for webs which approached a condition of pure shear stress as well as for webs with well-developed diagonal tension. The rivet factor, (pitch minus diameter) divided by pitch, was varied from approximately 0.81 to 0.62. These tests indicated that the shear stresses on the gross section were nearly constant for all values of the rivet factor investigated if the other properties of the web were not changed.

INTRODUCTION

The strength of a shear web is sometimes computed on the assumption that failure will take place when the shear stress on the net section between rivet or bolt holes reaches the ultimate shear stress of the material. This practice is analagous to the method used for computing the strength of tension members with holes, except that many of the light alloys used in aircraft structures are known to show stress-concentration effects of holes at ultimate load. These effects must be taken into account when computing the strength of tension members. Similar stress-concentration effects may be expected in shear webs. Another difficulty involved in computing the strength of shear webs is that no really satisfactory method of determining the ultimate shear stress of a thin sheet has been devised.

Because of these difficulties the most expedient method of determining the allowable stress for shear webs with rivet or bolt holes is by direct tests on shear webs fastened with rivets or bolts and subjected to pure shear load, while the ratio of pitch to diameter is varied to evaluate the combined effect of reduction in section and stress concentration around holes. The stiffening of the webs should also be varied in order to determine the effect of changing from the nearly shear-resistant web (failure occurs soon after buckling takes place) to the partly diagonal-tension web (failure occurs long after buckling takes place). The results of such tests made on 24S-T and Alclad 75S-T aluminum-alloy sheets are given herein.

SYMBOLS

C_r	rivet factor $\left(\frac{p - d}{p} \text{ or } \frac{\text{net area along line of holes}}{\text{gross area along line of holes}}\right)$
L	length along one side of shear panel between corner bolts, inches
P	load required to fail panel, kips
d	diameter of rivet or bolt holes, inches
p	pitch of rivet or bolt holes in one row, inches
t	thickness of sheet, inches
σ_{ult}	ultimate tensile stress, ksi
σ_{perf}	ultimate tensile stress on net section of perforated tensile specimen, ksi
τ	shear stress on web, ksi
τ_g	shear stress on gross section of web, ksi
τ_n	shear stress on net section of web between rivet holes, ksi
$\tau_{g_{av}}$	average measured gross shear stress at failure for one type of specimen, ksi
τ_{ult}	ultimate shear stress of material, ksi

TEST SPECIMENS AND PROCEDURE

The test specimens used in the present investigation were made from 24S-T or Alclad 75S-T aluminum alloy of 0.040-inch thickness. In order to have specimens fail at different stages of incomplete diagonal tension some specimens were tested as flat sheets without stiffeners; these specimens gave fairly well-developed diagonal tension. The other specimens, tested with closely spaced stiffeners (fig. 1), approached a condition of pure shear stress. Most of the specimens, which had an effective length of $51\frac{1}{4}$ inches and an effective width of 5 inches, were tested in the rectangular frame shown in figure 2. A few of the specimens were panels 10 inches square and were tested in the square frame shown in figure 3. The specimens were fastened into the square and rectangular frames with one or two rows of bolts which were tight fits in the holes. All but two of the tests in the rectangular frame were made with washers under the heads of the bolts; these two were made with the heads of the bolts bearing directly on the sheet. The tests in the square frame were made with the sheet between the angles and also with the sheet on the outside of the angles so that the bolt heads were bearing directly on the sheet.

In all tests the pitch of the holes was 1 inch and the hole diameters, used to obtain a variation in pitch-to-diameter ratio, were 3/16, 1/4, 5/16, and 3/8 inch.

The test specimens were cut from several different sheets of material. Ultimate tensile strengths of each sheet of material were determined from the following groups of control specimens:

(a) Two standard tensile specimens cut parallel to the grain

(b) Two standard tensile specimens cut perpendicular to the grain

(c) Two perforated tensile specimens cut parallel to the grain for each size of hole used in the shear webs (eight specimens)

(d) Two perforated tensile specimens cut perpendicular to the grain for each size of hole used in the shear webs (eight specimens)

The perforated tensile specimens mentioned under (c) and (d) were strips with a width equal to the pitch of the holes in the shear webs and with a hole in the middle of each corresponding to one of the sizes used in the shear webs. These perforated specimens were used to evaluate the stress-concentration effects at ultimate load under simple tension loading.

TEST RESULTS

The shear stress at failure was computed for both the gross section and the net section along the line of holes and reduced to the minimum guaranteed properties of the material. The shear stress at failure on the gross section of each specimen tested in the rectangular frame was computed by

$$\tau_g = \frac{P}{Lt} \tag{1}$$

For the specimens tested in the square frame with diagonal loading the formula for shear stress on the gross section becomes

$$\tau_g = \frac{0.707P}{Lt} \tag{2}$$

The shear stress at failure on the net section along the line of holes was computed for each specimen by

$$\tau_n = \frac{\tau_g}{C_r} \tag{3}$$

In order to make possible a comparison of specimens cut from different sheets of the same material, all shear stresses computed by formulas (1), (2), and (3) were reduced to the minimum guaranteed properties of the material as given in references 1 and 2 (62 ksi for 24S-T aluminum alloy and 72 ksi for Alclad 75S-T aluminum alloy). This reduction was made by multiplying the values obtained from formulas (1), (2), and (3) by $62/\sigma_{ult}$ for 24S-T aluminum alloy and $72/\sigma_{ult}$ for Alclad 75S-T aluminum alloy, where σ_{ult} is the actual ultimate tensile stress of a particular sheet obtained from standard tensile specimens cut perpendicular to the grain of the sheet. Standard tensile specimens cut perpendicular to the grain were used to obtain σ_{ult} because reference 1 states that a specimen cut from the sheet in any direction shall possess the certain minimum guaranteed properties given in this reference paper. For the standard cross-grain specimens, σ_{ult} was generally from 2.2 to 3.4 percent less than for the standard with-grain specimens. (See table 1.)

The reduced values of τ_g and τ_n are shown in figures 4 and 5 from which, apparently, τ_g is nearly constant while τ_n decreases as C_r increases. Figures 4 and 5 show the average values of gross shear stress at failure $\tau_{g_{av}}$ for the webs with edges clamped between a heavy plate and stiff washers or between two heavy plates. The value of $\tau_{g_{av}}$ was 36.9 ksi for the stiffened Alclad 75S-T webs, 31.9 ksi for the unstiffened Alclad 75S-T webs, 30.3 ksi for the stiffened 24S-T webs, and 25.8 ksi for the unstiffened 24S-T webs. The individual values of τ_g in any group did not vary more than 9 percent from these values of $\tau_{g_{av}}$ and most of the panels fell within 5 percent of the average. Figure 6 shows these variations between $\tau_{g_{av}}$ and individual values of τ_g for the webs with edges clamped between a heavy plate and stiff washers.

Table 1 gives the ultimate stresses for the net section of the perforated tensile specimens as well as for the standard tensile specimens. This table also gives the stress-concentration factors $\sigma_{ult}/\sigma_{perf}$ for the perforated specimens, where σ_{ult} is the average ultimate stress of two standard tensile specimens and σ_{perf} is the ultimate tensile stress on the net section of a perforated specimen cut in the same direction as the standard specimens. Inspection of table 1 indicates a slight tendency for σ_{perf} to decrease as C_r increases.

DISCUSSION OF TEST RESULTS

In aircraft structures the shear stress τ_g on the gross section of a shear web is sometimes computed by formula (1), and the shear stress τ_n on the net section along the rivet or bolt line, by dividing τ_g by C_r as indicated by formula (3). Failure is assumed to occur in a straight line along the center line of the holes when τ_n becomes equal to the allowable shear stress of the material. This allowable stress is assumed to be independent of changes in the pitch-to-diameter ratio of the holes. The present tests, however, seem to indicate that this method is not correct. These tests show that failure tends to be in a zigzag line between holes rather than in a straight line. The tests also indicate that the shear stresses on the net section τ_n at failure were not constant as usually assumed but decreased as C_r increased.

Variations in shear stress at failure.- Figures 4 and 5 and table 1 indicate that the decrease in τ_n at failure as C_r increased was large compared with the decrease in σ_{perf} on the tensile specimens. Computations showed that for shear webs with C_r approximately equal to 0.81, τ_n at failure was from 20 to 30 percent less than for the shear webs with C_r approximately equal to 0.62. Table 1 indicates that the stress-concentration factor $\sigma_{ult}/\sigma_{perf}$ varied from 1.038 to 1.088 for the Alclad 75S-T aluminum alloy and from 1.044 to 1.202 for 24S-T aluminum alloy as C_r varied from 0.828 to 0.606. These facts, then, indicate that the variation in τ_n can be partly accounted for by the stress-concentration effects noted in the tension tests.

Part of the decrease in τ_n at failure as C_r increased may have been because large bearing stresses as well as large shear stresses were at the same point on the edge of a hole in the shear webs; whereas, no bearing stresses were around the edge of a hole in the perforated tensile specimens. These bearing stresses increased as C_r increased; apparently, this increase in bearing stress decreased the ability of the sheet to carry shear stress. The data available are insufficient to determine the exact interaction effects.

Gross shear stresses at failure.- Figures 4 and 5 show that τ_g is almost constant over the range of C_r from about 0.81 to about 0.62. The average values of gross shear stress at failure $\tau_{g_{av}}$ are given for shear webs with the edges clamped between two heavy plates or between a heavy plate and stiff washers. These values of $\tau_{g_{av}}$, however, should be used only for the range of C_r values covered in the present tests. As C_r continues to decrease, τ_n will become nearly constant because it is approaching a maximum value somewhat less than τ_{ult} for the material; when this value is reached, τ_g will no longer be constant but will decrease at about the same rate as C_r (the ratio of net area along the line of holes to gross area along the line of holes) decreases.

Effect of method of attachment on shear stresses.- The average gross shear stresses shown in figures 4 and 5 are the result of tests on specimens with the heavy attachment plate of the rectangular frame on one side of the web and stiff washers on the other. Two tests were also made with the sheet clamped between the faces of the heavy angles in the square frame shown in figure 3. The results of both methods are shown in figure 5 and no apparent difference is noted in the shear strength obtained by the two methods of fastening. Two tests were made in each frame with the heads of the bolts bearing directly on the sheet of the specimens, which were duplicates of those specimens that had heavy plates on both sides or a heavy plate on one side and stiff washers under the heads of bolts. The results of these tests are also shown in figure 5. When the heads of the bolts were bearing directly on the sheet the shear strength was apparently lower than when the sheet was clamped between a heavy plate and stiff washers or between two heavy plates. The shear strength obtained when the bolt heads were bearing directly on the sheet was about 11 percent less than when the edges were well supported on both sides. Previous tests described in reference 3 indicated that specimens which were riveted to one side of a plate without washers under the heads of the rivets would have a strength about 15 percent less than the strength of a similar specimen bolted or riveted between heavy plates.

Two factors may contribute to this difference in strength between webs that are clamped between a heavy plate and washers and webs that are fastened to a plate on one side but have the heads of the bolts or rivets bearing directly on the opposite side of the sheet. When the web is tightly clamped between a plate and washers or between two plates, friction may transmit some of the load and reduce the stress before reaching the net section along the rivet line. In the present tests, however, the bolts were drawn just tight enough to make certain that the parts were drawn together so that very little opportunity existed for any load to be transmitted in friction. The parts are usually clamped more tightly than they are in these tests; therefore, if any load is transmitted in friction, the present tests are probably conservative. Another explanation for the difference in strength may be that when the web is fastened to a plate or angle with only the head of a rivet or bolt for support on the opposite side, the buckles which develop in the sheet extend very close to the edges of the holes. When this buckling occurs there is a local increase in stress caused by the folds as well as by the reduction in net section along the rivet line. When the sheet is supported on both sides the buckles do not extend very close to the holes; therefore, no local increase in stress from this source is added to the local increase in stress caused by the reduction in the net section along the line of holes.

Number of rows of rivets required.- Figures 4 and 5 show that in both 24S-T and in Alclad 75S-T webs no consistent difference was noted in strength between the specimens fastened with one and two rows of bolts for values of C_r from 0.75 to 0.62. For C_r of about 0.81 $\left(\frac{3}{16}\text{-in. holes}\right)$, however, the 24S-T specimens with one row of bolts consistently carried smaller loads than the specimens with two rows of bolts. No tests were made on Alclad 75S-T webs with one row of $\frac{3}{16}$-inch bolts. The bearing stresses on the 24S-T panels with one row of $\frac{3}{16}$-inch holes exceeded the allowable bearing stresses; on all others the bearing stresses were below the allowable values (reference 4). If one row of bolts is sufficient to reduce the bearing stresses below the allowable values given in reference 4, then, the addition of the second row in an attempt to decrease the bearing stresses at each hole appears to have very little or no effect on the strength of the joint. Of course, if one row of rivets does not furnish sufficient shear strength in the rivets then the addition of a second row would increase the strength of the joint.

CONCLUSIONS

Strength tests were made of shear webs of 24S-T and Alclad 75S-T aluminum alloy to determine the effect of rivet or bolt holes on the allowable shear stress of these materials. In order to obtain data on specimens that failed at different stages of incomplete diagonal tension, one type of specimen - a flat sheet without stiffeners - gave well-developed diagonal tension; the other type of specimen - a flat sheet with closely spaced stiffeners - approached a condition of pure shear stress. The rivet factor C_r, (pitch minus diameter) divided by pitch, was varied from about 0.81 to about 0.62 by using a constant pitch and changing the size of the holes. These shear web tests indicated that:

1. The shear stresses on the gross section at failure were almost constant for all values of C_r investigated if the other properties of the web were not changed.

2. For webs with the edges clamped between two heavy plates and stiff washers, the average shear stress on the gross section at failure was 36.9 ksi for the stiffened Alclad 75S-T webs, 31.9 ksi for the unstiffened Alclad 75S-T webs, 30.3 ksi for the stiffened 24S-T webs, and 25.8 ksi for the unstiffened 24S-T webs.

3. When the webs were fastened with a heavy plate along one side with the heads of the rivets or bolts bearing directly on the sheet on the opposite side, the shear strength of the webs was about 11 percent less than when the edges were well supported on both sides.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., September 18, 1946

REFERENCES

1. Anon.: Federal Specification for Aluminum-Alloy (AL-24), (Aluminum-Copper-Magnesium (1.5 percent) - Manganese); Plates, Sheets, and Strips. Federal Standard Stock Catalog, Sec. IV, (pt.5) QQ-A-355a, Nov. 28, 1941.

2. Anon.: Army-Navy Aeronautical Specification, Aluminum Alloy, Clad (AL-XB75C2); Sheet and Strip. AN-A-10a, Dec. 14, 1943.

3. Kuhn, Paul: Ultimate Stresses Developed by 24S-T Sheet in Incomplete Diagonal Tension. NACA TN No. 833, 1941.

4. Anon.: Strength of Aircraft Elements. ANC-5, Army-Navy-Civil Committee on Aircraft Design Criteria. Revised ed., Dec. 1942; Amendment 1, Oct. 22, 1943.

TABLE I

TENSILE STRENGTHS OF CONTROL SPECIMENS

Specimen	Nominal diameter (in.)	$\frac{\text{Net area}}{\text{Gross area}}$, C_r	σ_{perf} (ksi)	$\frac{\sigma_{ult}}{\sigma_{perf}}$	Specimen	Nominal diameter (in.)	$\frac{\text{Net area}}{\text{Gross area}}$, C_r	σ_{perf} (ksi)	$\frac{\sigma_{ult}}{\sigma_{perf}}$
24S-T sheet 1									
With grain (σ_{ult} = 71.62)					Cross grain (σ_{ult} = 70.07)				
1	3/16	0.812	59.6	1.202	25	3/16	0.803	60.4	1.159
2	3/16	.792	64.5	1.110	26	3/16	.798	61.9	1.132
3	1/4	.753	63.2	1.133	27	1/4	.748	61.1	1.148
4	1/4	.750	64.3	1.131	28	1/4	.752	60.3	1.162
5	5/16	.682	64.7	1.106	29	5/16	.679	60.7	1.155
6	5/16	.672	63.8	1.122	30	5/16	.676	61.2	1.145
7	3/8	.613	64.7	1.106	31	3/8	.606	61.7	1.136
8	3/8	.632	64.8	1.104	32	3/8	.613	64.3	1.089
24S-T sheet 2									
With grain (σ_{ult} = 71.84)					Cross grain (σ_{ult} = 69.60)				
9	3/16	0.800	63.7	1.128	33	3/16	0.802	62.1	1.121
10	3/16	.813	63.9	1.124	34	3/16	.794	63.0	1.103
11	1/4	.751	67.0	1.072	35	1/4	.744	63.4	1.097
12	1/4	.752	67.0	1.072	36	1/4	.745	63.9	1.088
13	5/16	.688	66.5	1.080	37	5/16	.681	65.9	1.055
14	5/16	.691	66.6	1.079	38	5/16	.686	64.5	1.078
15	3/8	.625	68.0	1.056	39	3/8	.626	65.1	1.069
16	3/8	.624	68.8	1.044	40	3/8	.621	66.2	1.051
Alclad 75S-T sheet									
With grain (σ_{ult} = 81.34)					Cross grain (σ_{ult} = 78.56)				
17	3/16	0.828	74.8	1.088	41	3/16	0.807	75.3	1.043
18	3/16	.798	78.2	1.039	42	3/16	.802	74.3	1.068
19	1/4	.739	78.3	1.038	43	1/4	.752	73.2	1.073
20	1/4	.767	75.0	1.083	44	1/4	.744	74.7	1.052
21	5/16	.682	77.1	1.055	45	5/16	.682	75.2	1.045
22	5/16	.677	77.4	1.051	46	5/16	.690	73.8	1.064
23	3/8	.618	77.3	1.052	47	3/8	.620	75.5	1.041
24	3/8	.618	76.3	1.064	48	3/8	.624	74.7	1.052

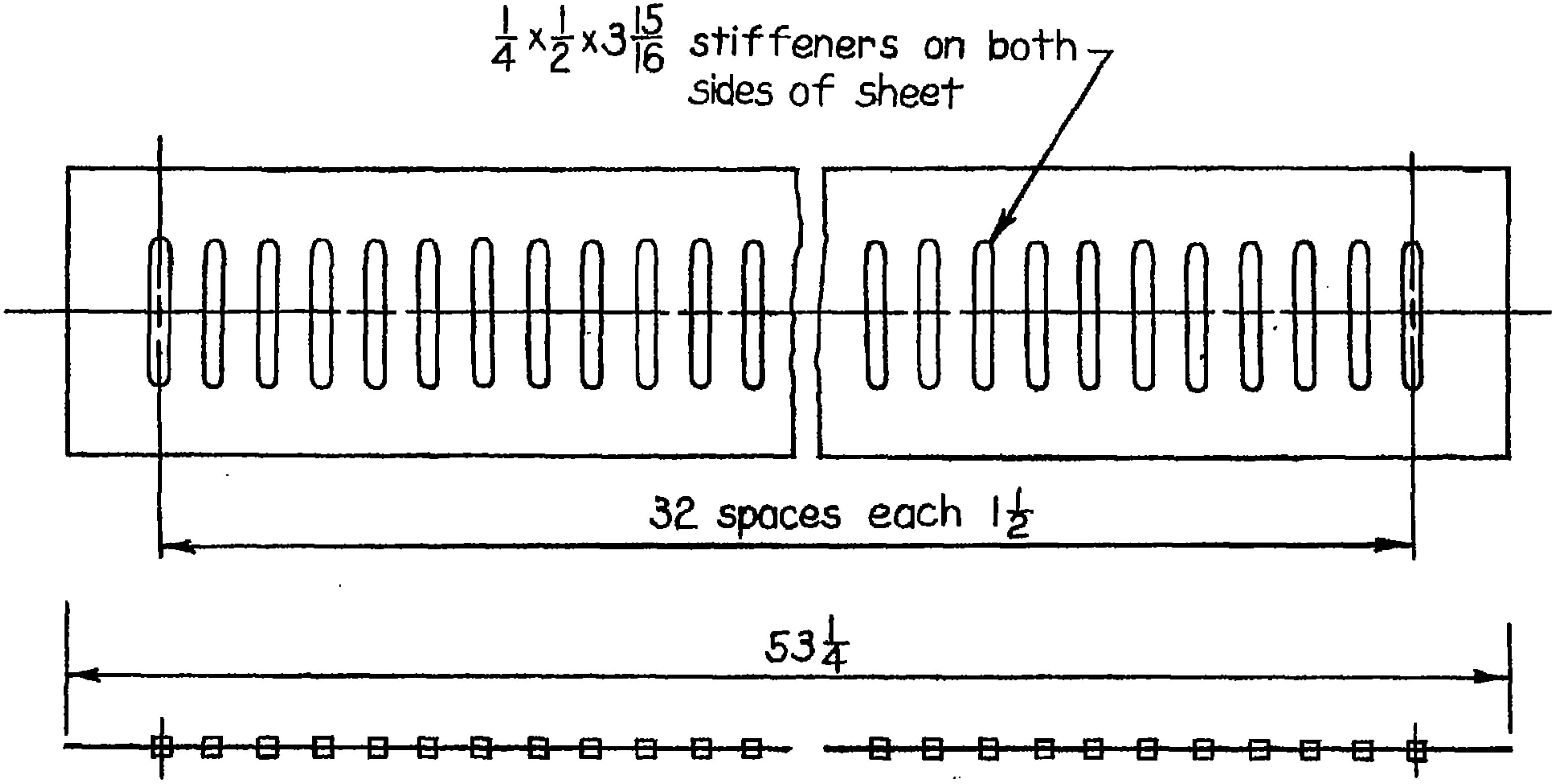

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Figure 1.- Stiffened shear web. Sheet thickness, 0.040 inch.

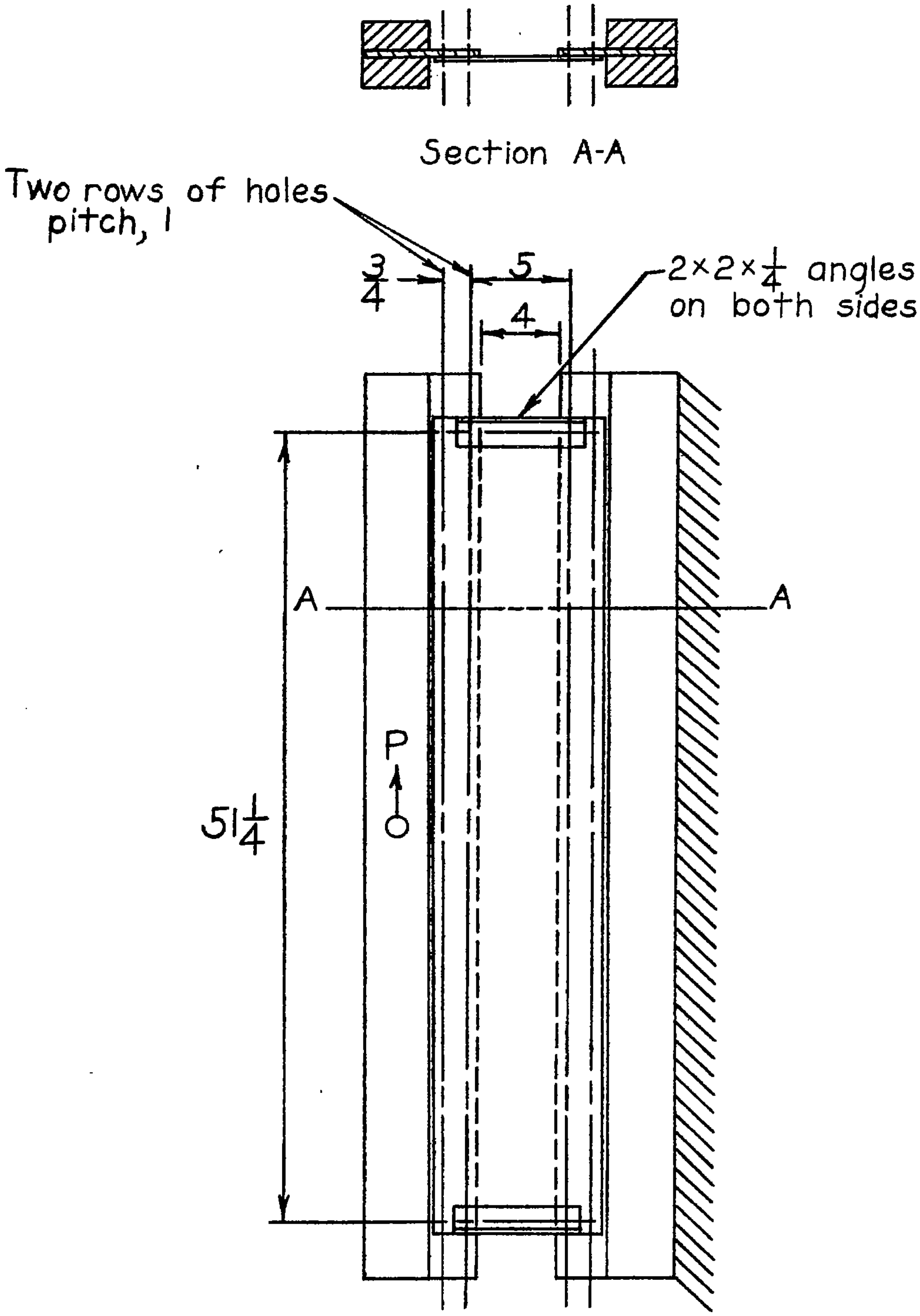

Figure 2.- Rectangular frame.

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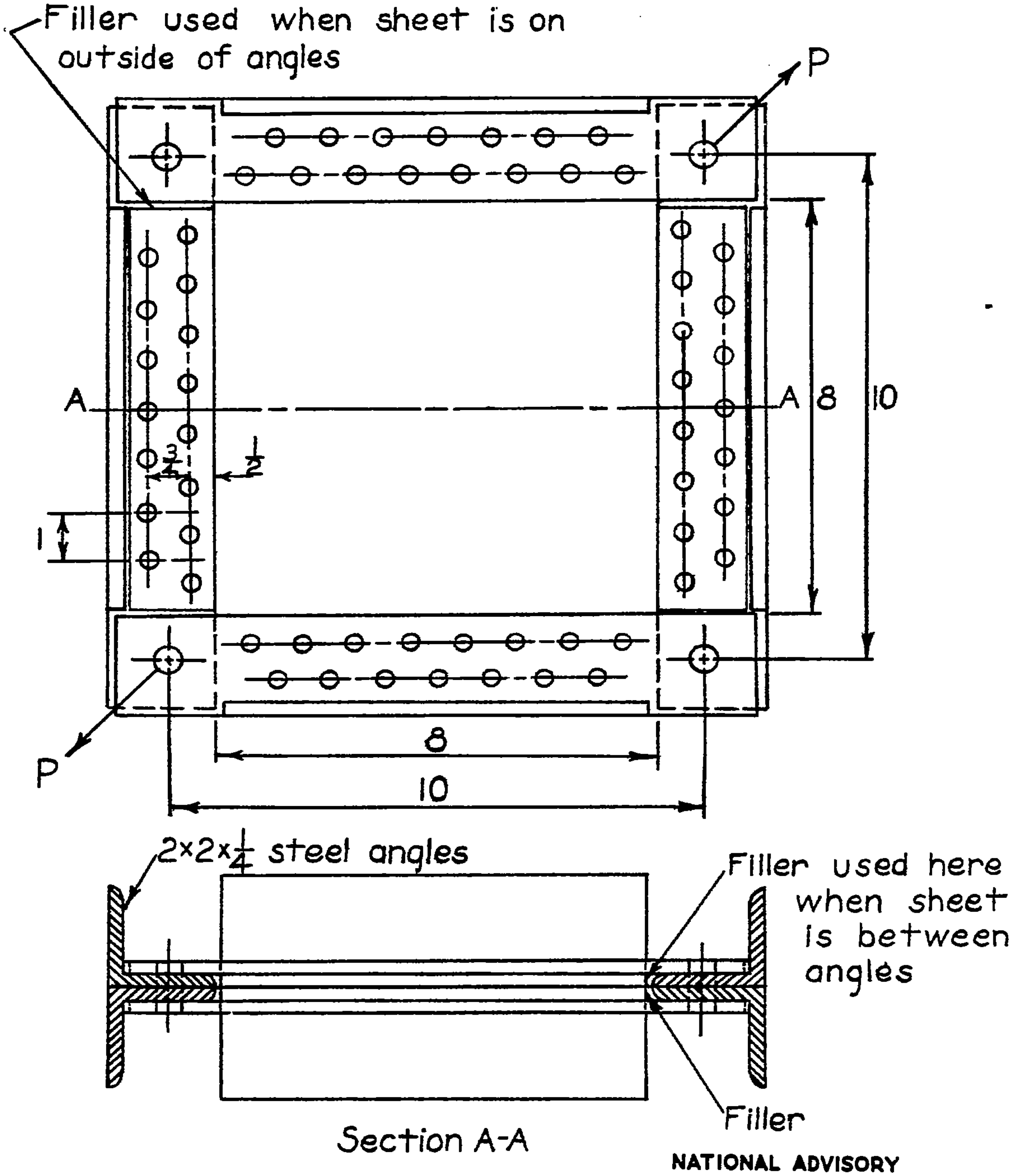

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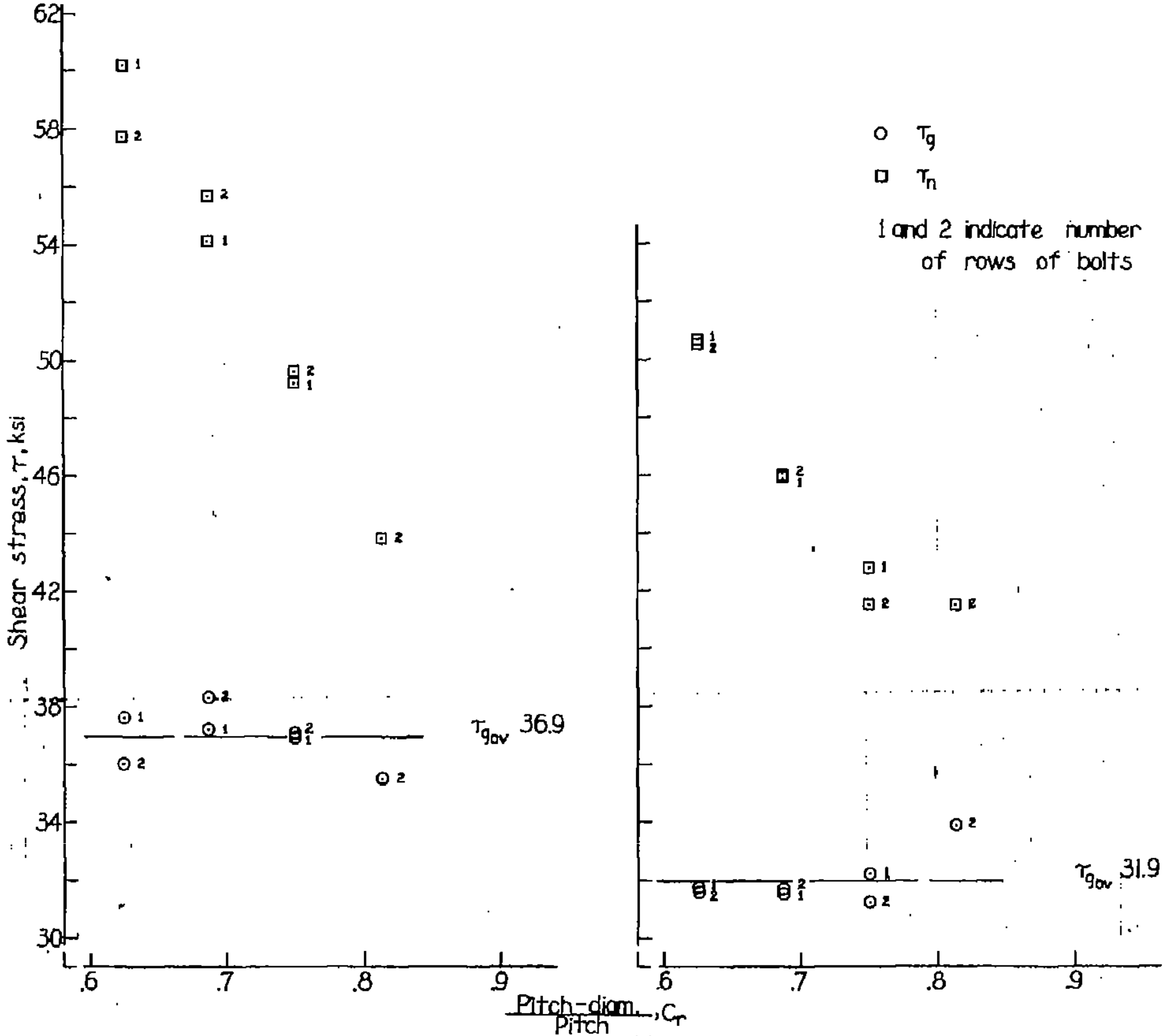
Figure 3.- Square frame.



(a) Stiffened shear webs.

(b) Unstiffened shear webs.

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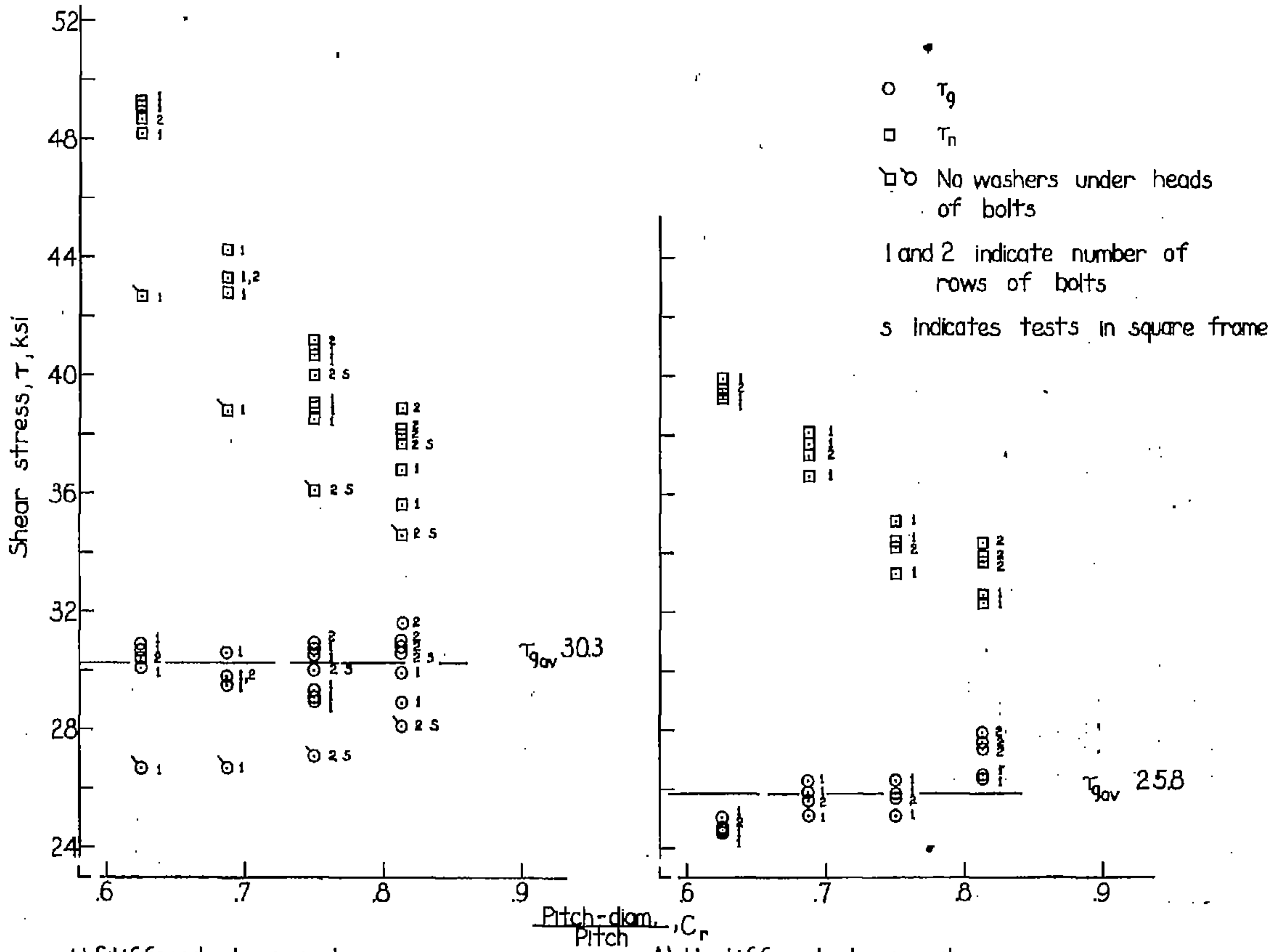
Figure 4.- Ultimate shear stresses on Alcad 75S-T webs. All stresses reduced to minimum guaranteed properties. Web thickness, 0.040 inch.



(a) Stiffened shear webs.

(b) Unstiffened shear webs.

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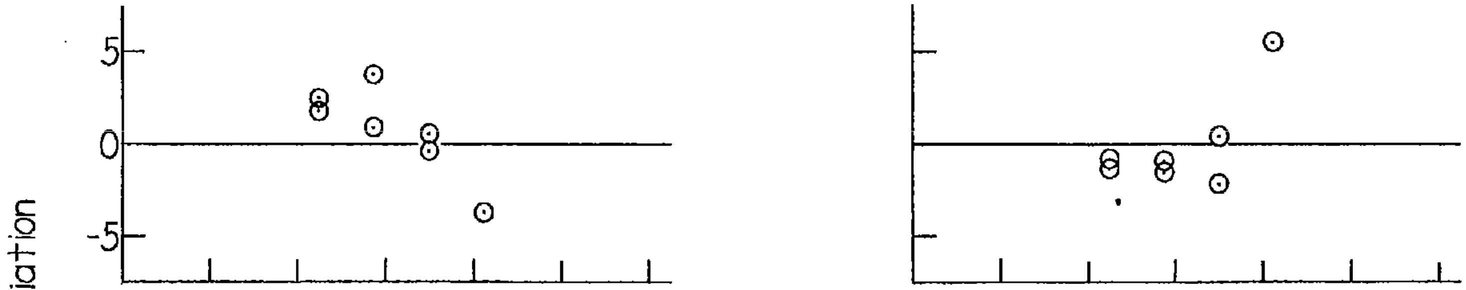
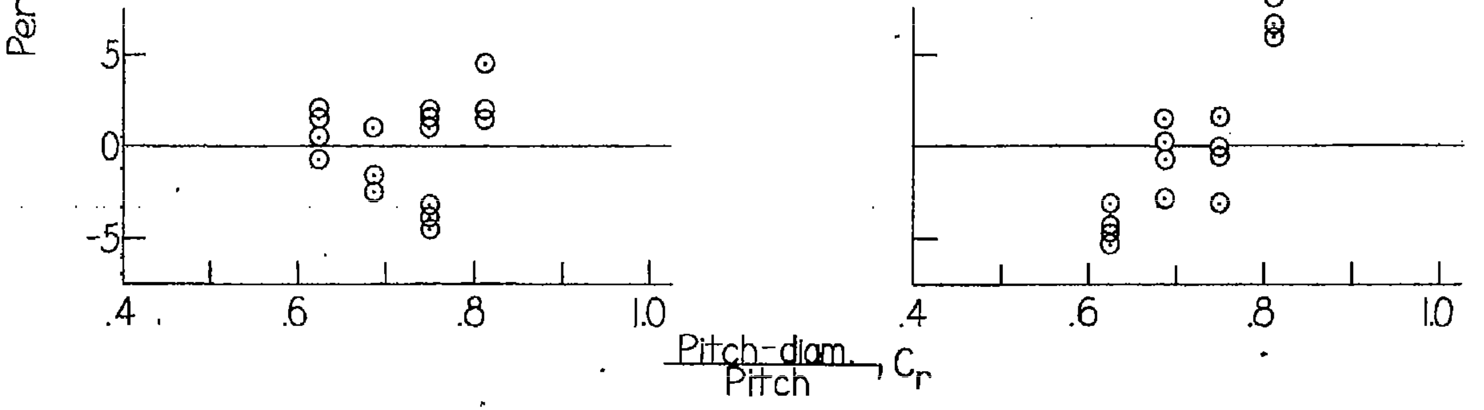
Figure 5.- Ultimate shear stresses on 24S-T webs. All stresses reduced to minimum guaranteed properties. Web thickness, 0.040 inch.



(a) Stiffened 75S-T webs.

(b) Unstiffened 75S-T webs.



(c) Stiffened 24S-T webs.

(d) Unstiffened 24S-T webs.

Figure 6.- Variations of individual gross shear stresses from average measured gross shear stress for shear webs with edges supported on both sides.

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