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BUCKLING AND ULTIMATE STRENGTHS OF PLATING LOADED IN EDGE COMPRESSION

Progress Report 1 - 6061-T6 Aluminum Plates

by

Donald J. Duffy and Ralph B. Allnutt

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STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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ABSTRACT

The buckling and ultimate strengths of welded and nonwelded 6061-T6 aluminum plates have been determined. Each plate was simply supported and loaded in edge compression. Ultimate strengths of nonwelded plates were 2 to 15 percent less, depending upon the b/t ratio, than those obtained by the present Bureau of Ships design procedure. Ultimate strengths of welded plates were 0 to 30 percent less, depending upon the location of the weld.

INTRODUCTION

When designing stiffened plating to withstand edge compression, the Bureau of Ships currently bases the design on the ultimate strength of the plating material, assuming simple supports at the unloaded edges. The stiffeners are considered adequate if they support the plating until its ultimate strength is realized. Previous work at the David Taylor Model Basin has provided the designer with experimental curves and empirical equations from which the ultimate strengths of mild-steel and HTS plates can be estimated. No data on the ultimate strength of aluminum plates are available; hence the designer must extrapolate from curves and equations presently in use for HTS and mild steel. In addition, the effect of welded joints on the buckling and ultimate strength of aluminum is not known. Therefore, the Model Basin was requested[1] to conduct tests and analyses to determine the buckling and ultimate strengths of nonwelded and welded aluminum plates and plate-stiffener combinations.

This program has been divided into two phases:

Phase 1 - Tests on unstiffened welded and nonwelded plates.

Phase 2 - Tests on stiffened plates.

For both phases two types of aluminum alloys; i.e., 6061 and 5456, will be tested. Data are needed for 6061 material in order to reevaluate the strength of existing structures. Since 6061 is being replaced as a plating material by 5456, experimental data are needed for this material to provide information for new designs.

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[1]References are listed on page 6.

This report presents the results of tests conducted on 6061 alloys as part of Phase 1. A total of 32 welded and nonwelded plates has been tested. Also, there is included in this report a brief description of a special loading fixture used to support a plate.

TESTING FIXTURE

The fixture developed by the Model Basin for testing the plates is shown in Figures 1 and 2. The fixture (Figure 1) consists of an upper platen, a lower platen, two side supports or columns, and clamping bars. The identical upper and lower platens are made of 1-in. by 3-in. medium steel stock 24 in. in length with a 1/2-in. T-slot running lengthwise. The columns are made in two sections. One is attached to the lower platen and one to the upper platen. The section of column attached to the upper platen has a 2-in. diameter by 2-in. deep hole reamed into it. The section of column attached to the lower platen is machined down to telescope into the upper section. For attachment to the platens, the ends of the columns have 1/2-in. T-bolts which make a sliding fit with the T-slots of the upper and lower platens. The plate to be tested slides between the columns attached to the lower platen. The upper section of column together with the upper platen is fitted to the lower sections of columns, and the fixture is clamped together with clamping bars. The fixture completely assembled and ready for test is shown in Figure 2.

DESCRIPTION OF PLATES

All plates tested were made of 6061-T6 aluminum and were 36 in. long and 18 in. wide. The physical and strength properties of the plates are presented in Table 1. For classification purposes the plates were divided into four groups of eight each. Group 1 encompassed a range of b/t ratios from 60 to 145 for the plate in its nonwelded condition. Groups 2, 3, and 4 were tested to determine the effects of welding on the ultimate strength of the plate. All the plates tested in these groups had a b/t ratio of approximately 95. The plates were grouped according to the locations of the welds, i.e., longitudinal, transverse, or a combination of a longitudinal and transverse weld. The plate designations A, B, C, D, or combinations thereof, refer to the type of weld or welds. The location and directions of these welds are shown in Figure 3. The subscript G on the corresponding plate designations listed in Table 1 indicates that the weld was ground smooth and flush with the metal. Each plate was tested in duplicate.

INSTRUMENTATION AND TEST PROCEDURE

To obtain the strain distribution through the cross section of each type of plate tested, the plates were instrumented as shown in Figure 4. The duplicate plate was instrumented with a minimum number of gages to determine buckling loads.

All plates were tested under edge compression in the Model Basin 600,000-lb testing machine. With the plate mounted in the testing fixture, strains were measured for small increments of axial load. For those plates which did not show uniform strain distribution, the load was removed and alignment was checked.

RESULTS

The experimental buckling loads were obtained by plotting the load versus the difference in the extreme fiber strains at the center of an expected buckling lobe. Since the strain difference is a function of the lateral deflection, the buckling load was established as the load at which the inflection point of the strain-difference curve occurs. This method for determining the buckling load is described in Reference 2. Buckling loads for all plates tested are listed in Table 1 and sample curves used to determine buckling loads are shown in Figure 5.

The experimental ultimate load of each plate was determined by noting the load at which the strains in the plate increased without limit. The ultimate load also corresponds to the point where the plate will not support an increase in load. The experimental ultimate loads for all plates are listed in Table 1.

The bending and axial strain distributions across a nonwelded plate and across two welded plates are shown in Figures 6 through 11. These strain distributions are presented for various increments in loading.

DISCUSSION OF RESULTS

The experimental elastic buckling loads are compared in Table 1 with the theoretical buckling loads obtained by the Bryan theory.[3] For Group 1 the maximum difference between experiment and theory is -22 percent which occurs at a b/t ratio of 73.8. Possible sources of deviation between experiment and theory include:

1. The experimental error in determining the buckling load. The strain-difference method used to determing the buckling loads is considered the most accurate of several discussed in Reference 3. For the increments of loading used, the buckling loads should be determined with an experimental accuracy of $\pm$ 5 percent.

2. Variations in plate thickness and deviation from true flatness. No attempt was made to ensure uniform plate thickness or true flatness since it was desired that the results obtained be representative of those plates used in run-of-the-mill shipboard application.

3. Uneven loading distribution. Each plate was loaded to obtain an even distribution of load across the width of the plate. However, it was noted that the magnitude of membrane strain was sometimes 10 percent lower near the bottom of the plate than at the top.

4. Edge supports of the test fixture. For a true simple support the bending moment or bending strain should be zero. From Figure 7 it is noted that there is a small amount of bending strain at the edges of the plate. However, this strain is only a small percentage of the bending that takes place at the center of the plate, and, therefore, it may be concluded that the fixture does simulate the desired condition of simple support.

The experimental ultimate strengths for nonwelded aluminum plates have been compared in Figure 12 with results calculated from Equation [1]. Equation [1] describes the empirical curve originally obtained for mild steel.[4] Presently this same equation is used by the Bureau of Ships in the design of aluminum plating.[5]

$$F = \frac{2.25}{B} - \frac{1.25}{B^2} \qquad [1]$$

where F is the nondimensional plate strength factor, σ/σ_y,

σ is the average stress at ultimate load in pounds per square inch,

σ_y is the yield strength of the material in pounds per square inch,

B is the nondimensional width factor, $b/t\sqrt{\sigma_y/E}$,

b is the width of the plate in inches,

t is the thickness of plate in inches, and

E is the Young's modulus of the material in pounds per square inch.

The ultimate loads for the nonwelded 6061-T6 plates are less than the values predicted by Equation [1]. From Figure 12 it may be seen that for a width factor of 3.6 there is a 15-percent reduction in ultimate strength, while at a width factor of 6 there is only a 2-percent reduction. It must be remembered that Equation [1] is based upon experimental results for steel plates, and a difference in ultimate strength should be expected. The variation in these curves is probably due to the fact that the stress-strain curves for the two materials are not affine, i.e., the shapes differ. It is apparent that, of the factors listed in the foregoing as affecting the buckling load, the only one that significantly affects the ultimate load is the thickness variation within the plate.

The experimental ultimate loads for all the plates have been compared in Table 1 with results calculated from Von Kármán's equation. The agreement of these experimental data with Von Kármán's equation follows the same trends as comparisons with Equation [1].

The results of tests on the welded plates are shown in Figure 13 as a percentage of the values obtained from Equation [1]. The notable features of these results are:

1. Welds A and C give greater ultimate strength than Welds B and D, respectively, and a plate with a Type A weld has the same ultimate strength as the unwelded plate.

2. Grinding the welds flush on a welded plate does not produce a significant change in ultimate strength.

3. The ultimate strength of a plate with a Type D weld is as much as 30 percent less than that given by the present Bureau of Ships design procedure.

A possible cause for the observed differences in ultimate strength for plates welded at different locations is the variation in strain across the plate. Since welding produces a heat-affected zone which decreases the yield strength of the material, it would be detrimental to place the weld at or near the points of large average strains.

CONCLUSIONS

From these tests it may be concluded that:

1. The ultimate strengths of nonwelded 6061-T6 aluminum plates are from 2 to 15 percent less than the Bureau of Ships specified design strengths. At a width factor of 3.6 there is a 15-percent reduction in ultimate strength whereas at a width factor of 6.0 the reduction in ultimate strength is only 2 percent.

2. For welded plates the ultimate strength is reduced from 0 to 30 percent depending upon the location of the weld. A plate with a longitudinal weld down the center has the same ultimate strength as the nonwelded plate, whereas a plate with a transverse weld located at the crest of a predicted buckling lobe will have an ultimate strength 30 percent less than that obtained from the current Bureau of Ships design procedure.

RECOMMENDATIONS

1. It is recommended that these results be utilized in current design.

2. It is recommended that the need for additional experimental data be examined after tests on 5456 aluminum plates have been completed.

REFERENCES

1. Bureau of Ships letter J1/2(442) Serial 442-52 of 28 May 1959.

2. Coan, J.M., "Large-Deflection Theory for Plates with Small Initial Curvature Loaded in Edge Compression," Journal of Applied Mechanics, pp. 143-151 (Jun 1951).

3. Bleich, F., "Buckling Strength of Metal Structures," McGraw-Hill Book Company, N.Y. (1952).

4. Frankland, J.M., "The Strength of Ship Plating under Edge Compression," David Taylor Model Basin Report 469 (May 1940).

5. Bureau of Ships Design Data Sheet DDS 1100-3, "Strength of Structural Members" (7 Mar 1956).

TABLE 1

Physical and Strength Properties of Plates Tested

Group	Plate Designation	Nominal Thickness in.	Measured Thickness in.	b/t	σ_y Yield Strength ksi	$B = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}}$ *	Observed Ultimate Strength kips	Observed Buckling Strength kips	Bryan Theoretical Buckling Strength kips	Von Kármán Theoretical Ultimate Strength kips	Observed Average Ultimate Stress ksi
	78	5/16	0.311	57.9	39.7	3.63	96.8	56.0	60.9	116.2	17.3
	79	5/16	0.309	57.3	39.3	3.63	100.0	66.0	59.8	114.9	18.1
	80	1/4	0.246	73.2	40.2	4.61	69.2	33.3	30.0	73.2	15.6
1	81	1/4	0.244	73.8	38.8	4.57	69.5	36.0	29.6	70.7	15.8
	82	3/16	0.188	95.7	39.8	5.94	44.3	15.5	13.1	42.1	13.0
	83	3/16	0.192	93.7	42.3	6.06	41.5	14.6	14.2	45.1	12.1
	84	1/8	0.123	146.3	37.5	8.91	19.5	4.0	3.8	17.7	8.8
	85	1/8	0.123	146.3	41.6	9.38	19.8	4.25	3.8	18.6	8.9
	A-1	3/16	0.1848	97.4	39.4	6.09	45.2		12.9	41.3	13.6
	A-2		0.1860	96.8	40.2	6.05	45.1		13.0	41.9	13.5
	A_G-1**		0.1934	93.1	41.3	5.95	49.5	20.0	14.7	45.9	14.2
2	A_G-2		0.1849	97.3	40.4	6.15	46.5	23.9	13.5	43.7	13.9
	B-1		0.1890	95.2	39.8	5.98	41.1	12.4	13.7	43.0	12.1
	B-2		0.1876	95.9	39.8	6.02	42.6	14.6	13.4	42.4	12.6
	B_G-1		0.1846	97.5	41.8	6.27	43.0	12.4	12.8	42.1	12.9
	B_G-2		0.1851	97.2	41.9	6.27	41.4	13.2	12.8	42.3	12.4
	C-1	3/16	0.1880	95.7	39.9	6.01	40.0	20.0	13.5	44.5	11.8
	C-2		0.1886	95.4	39.7	5.97	37.5	17.6	13.6	42.9	11.1
	C_G-1		0.1874	96.1	41.6	6.16	39.9	15.9	13.3	42.9	11.8
3	C_G-2		0.1873	96.1	43.8	6.32	37.1	14.2	13.3	44.3	11.0
	D-1		0.1855	97.0	39.3	6.04	34.8	14.8	12.9	40.9	10.4
	D-2		0.1848	97.4	40.0	6.13	35.1	18.4	12.8	41.2	10.5
	D_G-1		0.1877	95.9	42.1	6.19	36.7	18.5	13.4	43.6	10.9
	D_G-2		0.1873	96.1	43.0	6.27	33.6	17.8	13.3	43.9	9.9
	AC-1	3/16	0.1866	96.5	40.7	6.12	39.0	16.0	13.1	41.4	11.6
	AC-2		0.1856	97.0	40.6	6.15	39.9	17.3	12.9	41.2	11.9
	AD-1		0.1854	97.1	40.9	6.17	37.4	21.5	12.9	42.7	11.2
4	AD-2		0.1858	96.9	41.9	6.25	41.1	16.0	13.0	42.6	12.3
	BC-1		0.1878	95.8	40.6	6.07	35.3	15.6	13.4	42.9	10.4
	BC-2		0.1877	95.9	40.6	6.08	38.4	16.2	13.4	42.8	11.4
	BD-1		0.1869	96.3	41.0	6.13	32.8	14.7	13.2	42.7	9.8
	BD-2		0.1871	96.2	41.0	6.13	34.6	14.0	13.2	42.8	10.3

*$E = 10.06 \times 10^6$ psi as determined from test.

**Subscript G indicates welds ground smooth and flush with metal.

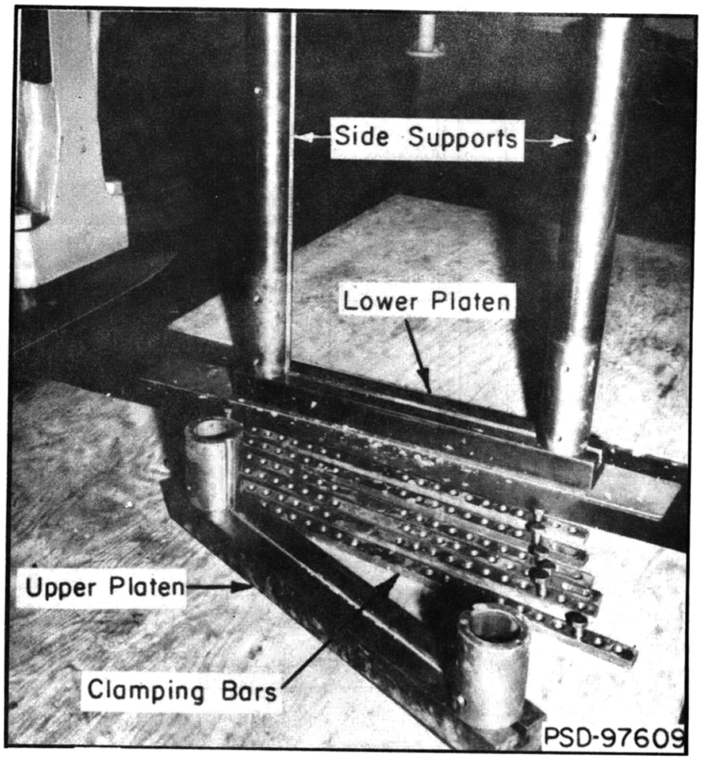


Figure 1 - Details of Test Fixture

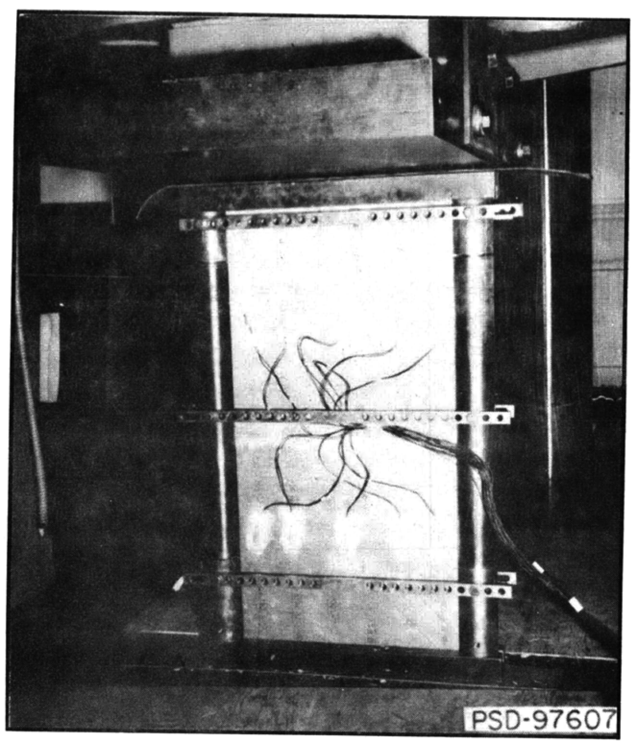


Figure 2 - Typical Test Assembly

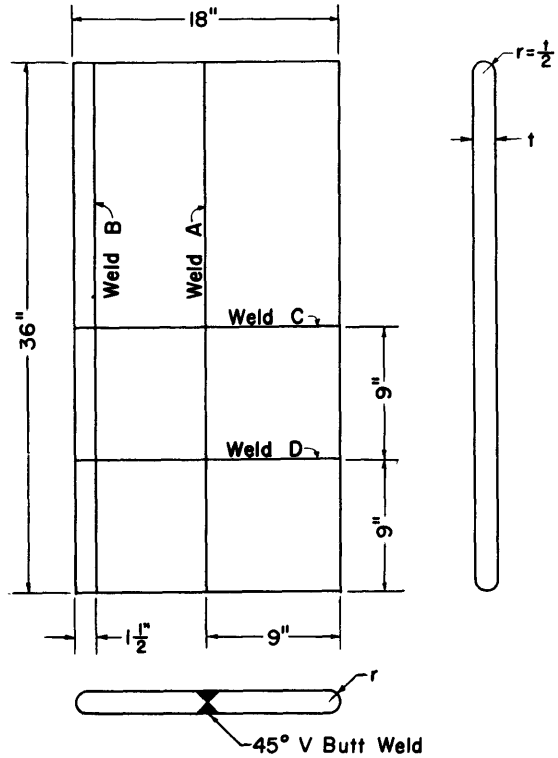


Figure 3 - Typical Test Plate and Welding Locations
All welds of 43-S aluminum electrodes.

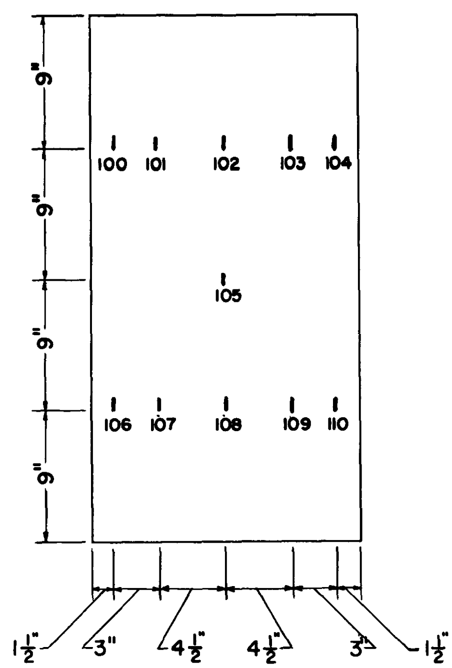


Figure 4 -Typical Strain Gage Locations

Gages were located on both sides of a plate. The duplicate plate was instrumented with Gages 102, 105, and 108

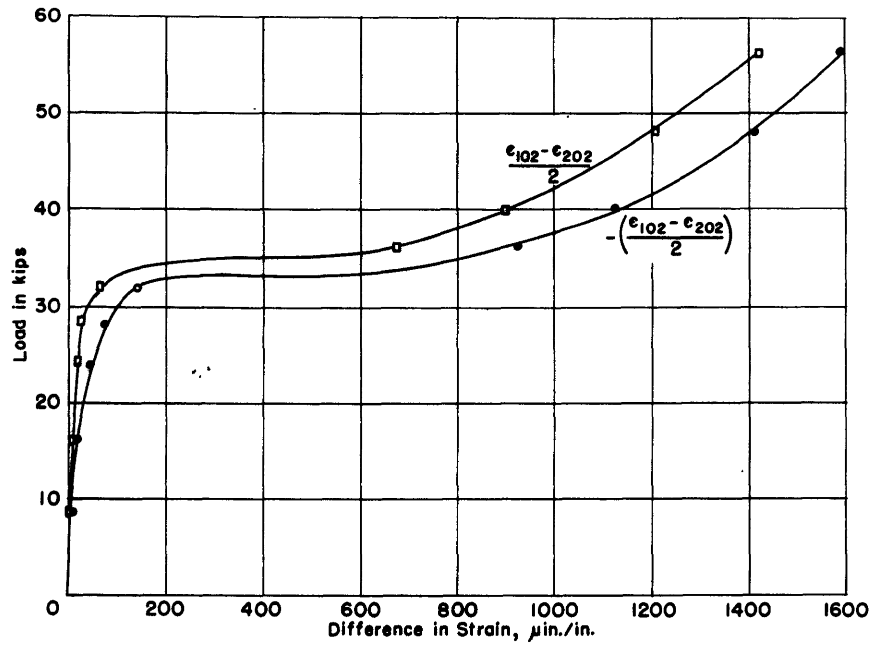


Figure 5 - Sample Curve Used to Obtain Buckling Load

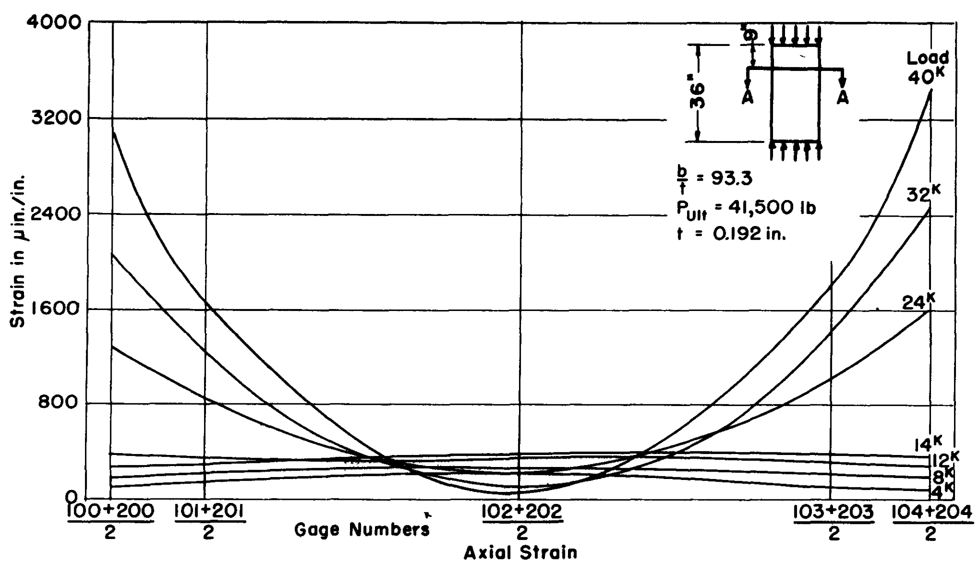


Figure 6 - Axial Strain Distribution across Plate 83

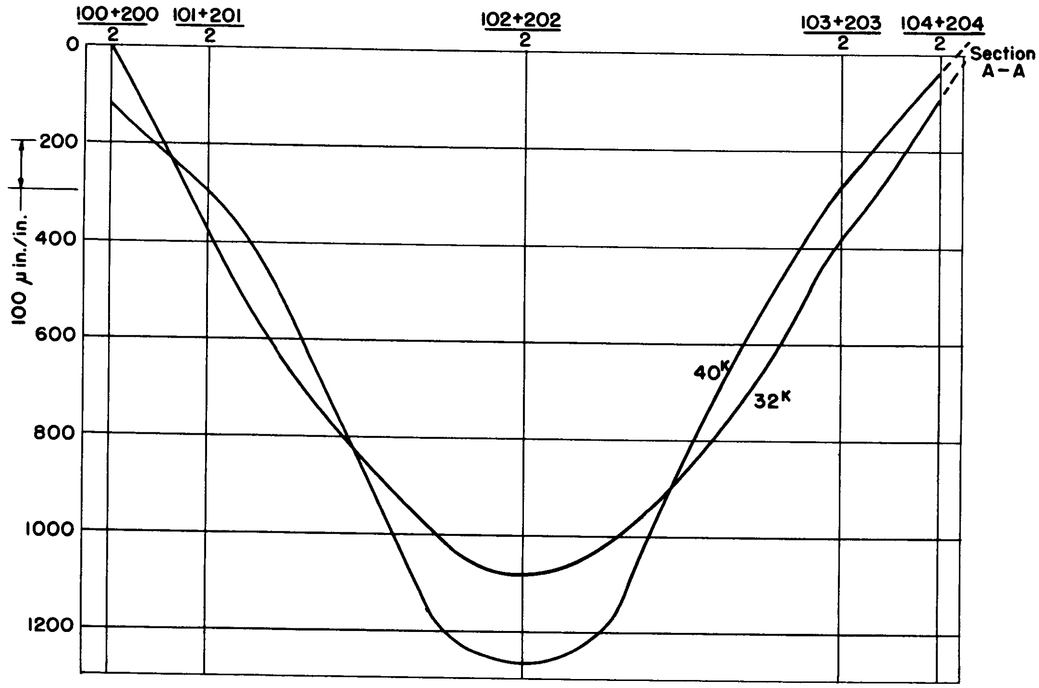


Figure 7 - Bending Strain Distribution across Plate 83

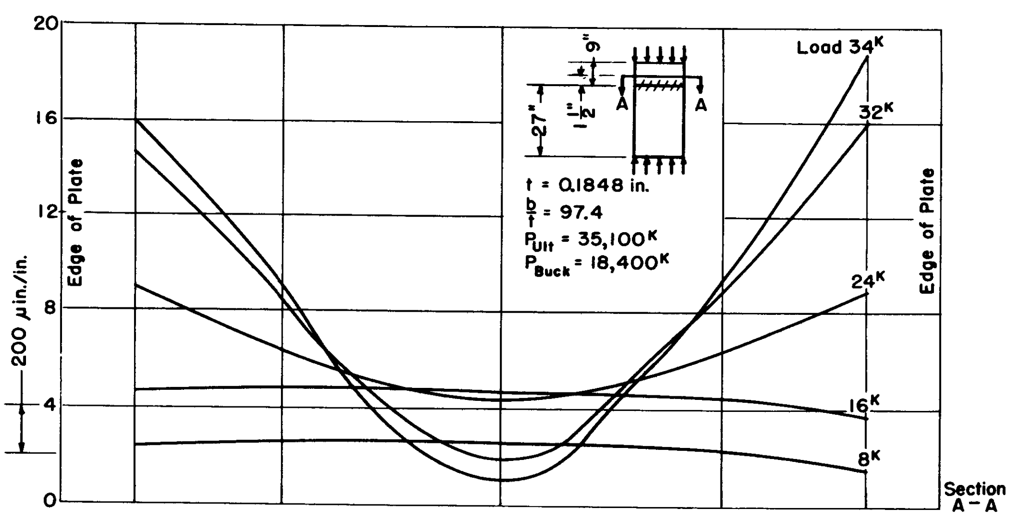


Figure 8 - Axial Strain Distribution across Plate D2

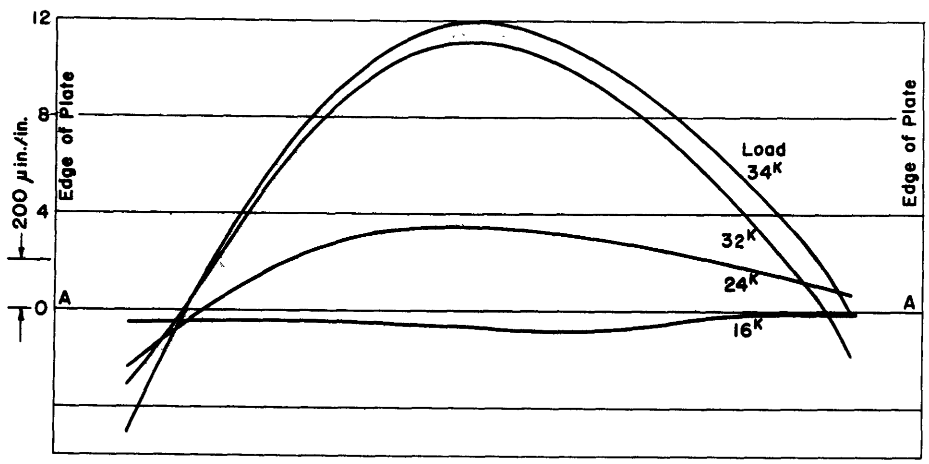


Figure 9 - Bending Strain Distribution across Plate D2

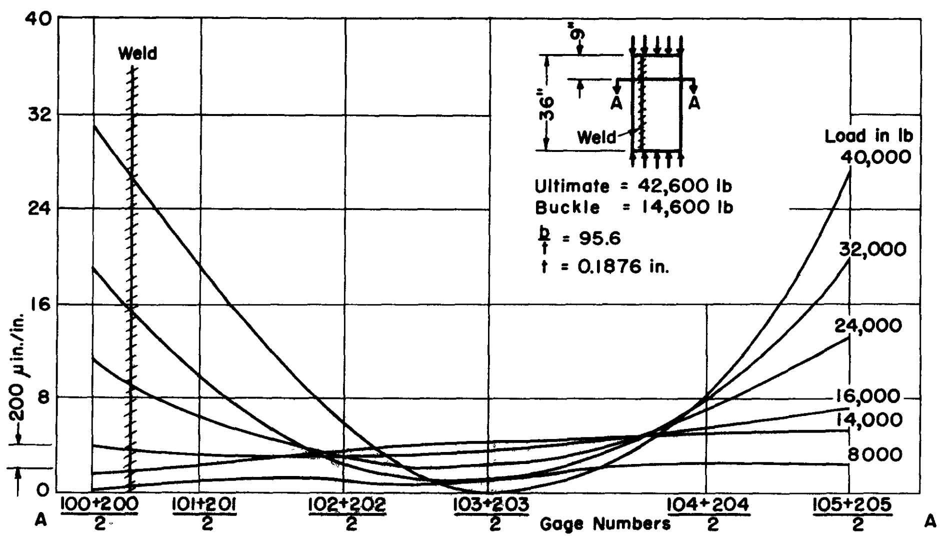


Figure 10 - Axial Strain Distribution across Plate B2

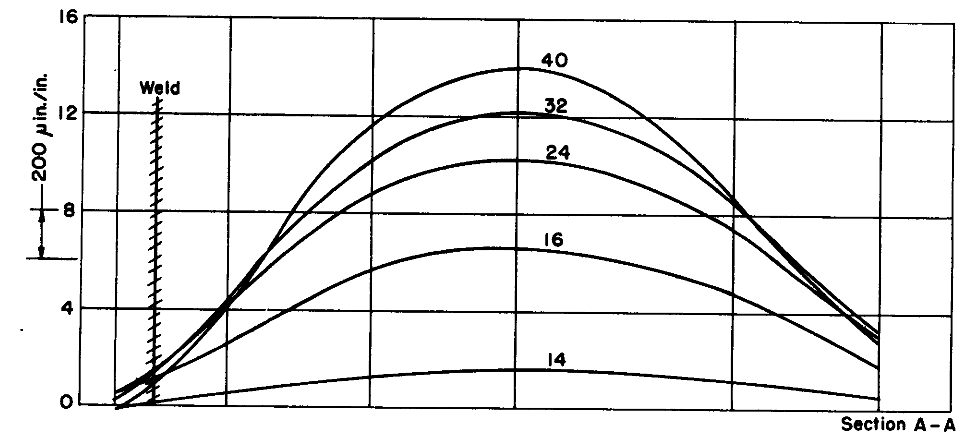


Figure 11 - Bending Strain Distribution across Plate B2

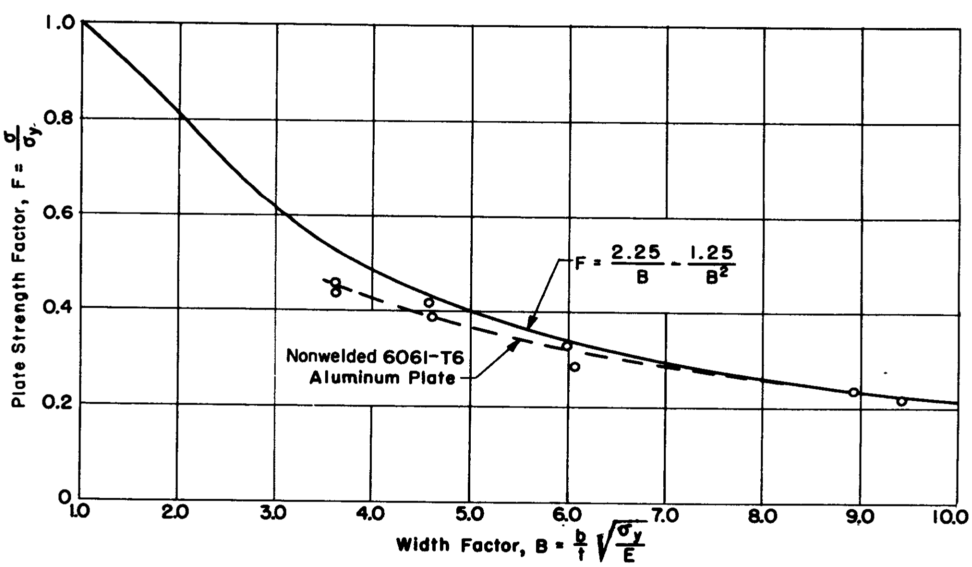
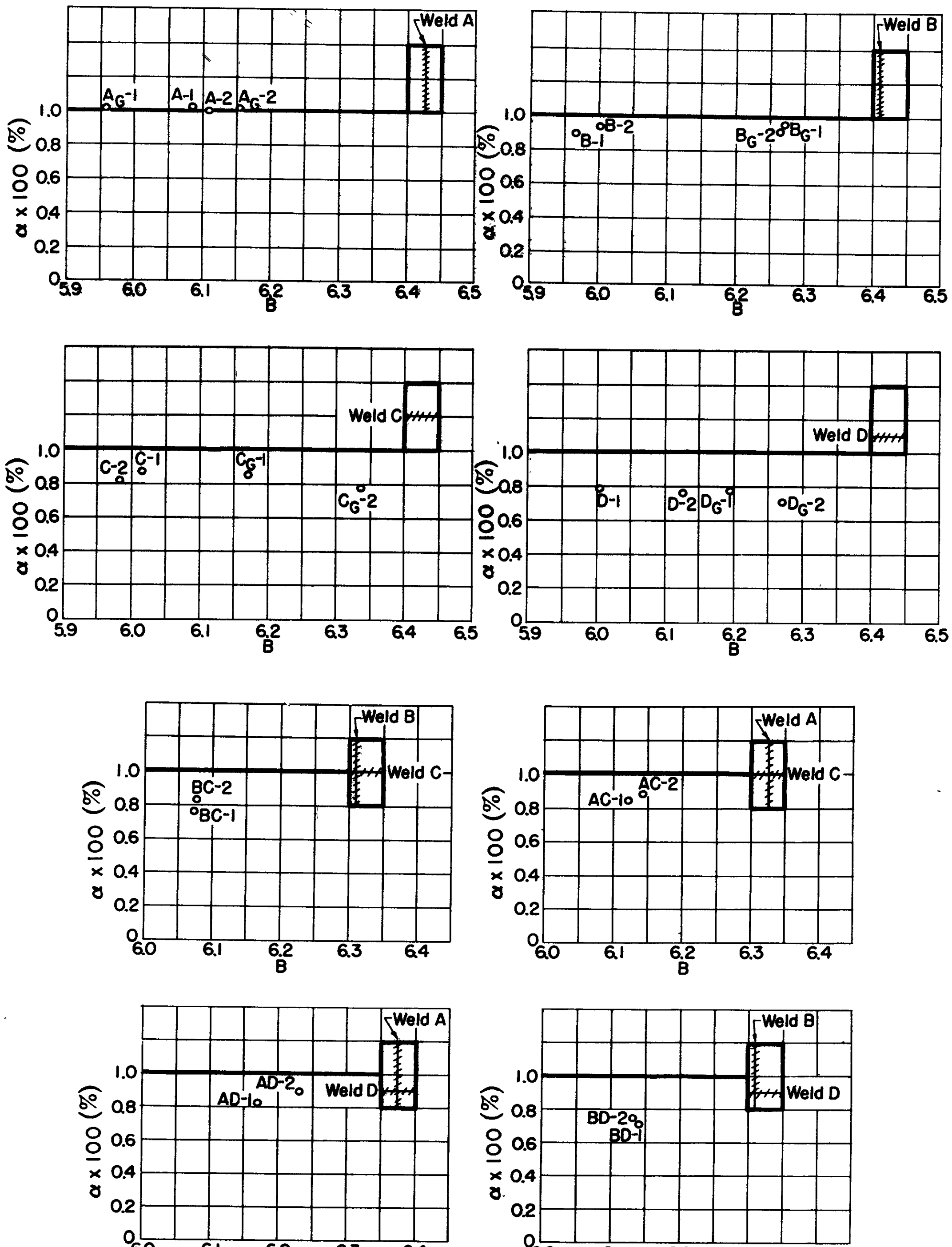


Figure 12 - Comparisons of Ultimate Strengths of Nonwelded 6061-T6 Aluminum Plates with Values Calculated by Present Design Procedure



B (Width Factor) = $\frac{b}{t}\sqrt{\frac{\sigma_y}{E}}$

$$\alpha = \frac{F_{Observed}}{F_{Calculated}} = \frac{\frac{\sigma}{\sigma_y}}{\frac{2.25}{B} - \frac{1.25}{B^2}}$$

Figure 13 - Comparisons of Ultimate Strengths of Various Welded 6061-T6 Aluminum Plates as a Percentage of Values Calculated by Present Design Procedure

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