Strength of Aluminum T-Joint Fillet Welds

New design considerations are proposed for T-joints loaded in both transverse and longitudinal directions

BY C. MARSH

ABSTRACT. A theoretical study of the strength of fillet welds is presented. Results are reported for tests on T-joint fillet welds subjected to tension forces at different inclinations, to moment in the plane of the stem of the T, and to moments across the welded joint. The results are interpreted and design expressions proposed which, although seen to be conservative, are much more liberal than current codes permit.

Introduction

A fillet weld may be loaded in such a manner that pure shear is created on the fillet throat. This is the longitudinal, or X-direction, indicated in Fig. 1, and represents the standard loading condition used to determine the shear strength of the filler alloy.

Should the weld be loaded in the transverse, or Y-direction, the force required to cause failure is some 40% higher than that for the longitudinal direction.

For a force in the Z-direction in Fig. 1, representing a tension force in the plane of the stem of the T in a T-joint, the failing load falls between those for loading in the X- and Y-directions.

This paper reports a test program conducted to establish the ultimate force for the Z-direction of loading and, in particular, how T-joints resist moments.

KEY WORDS

Aluminum T-Joints
T-Joint Fillet Welds
Fillet Throat Shear
Shear Strength
Z-Direction Loading
Shear Stress
Tension Force
Tension Tests
Tension Strength
Bending Tests

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Analysis

Consider a fillet weld loaded in the X-direction, in Fig. 1. The ultimate shear stress, τ_{xu}, is

$$\tau_{xu} = R_{xu}/Lt \qquad (1)$$

in which R_{xu} = the ultimate force, t = the throat thickness = $s/\sqrt{2}$, s = the fillet size, and L = the weld length. If the force is applied in the transverse, Y-direction, the stresses on the weld throat, on the 45-deg plane (Fig. 2), will approximately satisfy the relationships:

$$\sigma = \tau$$
$$R_y = L\,(\sigma + \tau)\,t/\sqrt{2} \qquad (2)$$

If failure occurs when $\tau = \tau_{xu}$, then the ultimate force is given by

$$R = \sqrt{2}\,\tau_{xu}\,Lt \qquad (3)$$

Thus, the ratio of the transverse strength to the longitudinal strength is $\sqrt{2}:1$. This agrees with the theory in Ref. 2 and with the tests of Refs. 1 and 3. However, the assumption of failure across the 45-deg plane in the fillet is questionable.

Consider a plane cutting the fillet at an angle ϕ to the direction of the force—Fig. 2. For equilibrium, the stresses on the plane satisfy

$$\cos\phi = \tau \sin\phi$$
$$R = (\sigma \sin\phi + \tau \cos\phi)\,Lt/\cos(45°-\phi) \qquad (4)$$

Giving:

$$R = 2\sqrt{2}\,Lt/(1 + \cos 2\phi + \sin 2\phi) \qquad (5)$$

For a given value of τ, this is a minimum when ϕ = 22.5 deg, and the force is

$$R = \tau\,Lt\,2\sqrt{2}/(1+\sqrt{2}) = 1.17\,\tau\,Lt \qquad (6)$$

If the fillet weld fails when $\tau = \tau_{xu}$, then

$$R_u = 1.17\,\tau_{xu}\,Lt \qquad (7)$$

The ratio of the transverse strength to the longitudinal strength is thus approximately 1.2:1. This agrees closely with the test results of Refs. 4 and 5 for fillet welded T-joints loaded in tension.

Attempts have been made to explain the difference in the test values for the two directions of transverse force, and have included such notions that friction increases the force for the Y-direction case and that prying action reduces the value for the Z-direction case. Test results, however, are consistent enough to justify the acceptance of the three different values for the three directions of loading.

A test program was conducted to establish the ultimate force on a fillet welded T-joint, as the direction of force varied between 0 and 90 deg to the axis of the weld.

Tension Tests

Plates were welded together to form an assembly, as shown in Fig. 3. This assembly was then cut at various angles to provide tension specimens in which the inclination of the weld to the direction of force took the values of 90, 60, 45 and 30 deg. A special specimen was machined from the same assembly, as shown in Fig. 4, to give 0 deg, *i.e.*, the longitudinal direction of loading.

All the plates were 12.5-mm (0.5-in.) thick Alloy AA 5083-H321. The filler alloy was AA 5356, and the weld size was nominally 6 mm (0.25 in.) throughout.

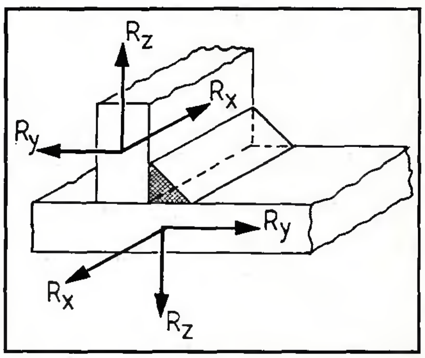

Fig. 1—Forces on a fillet weld

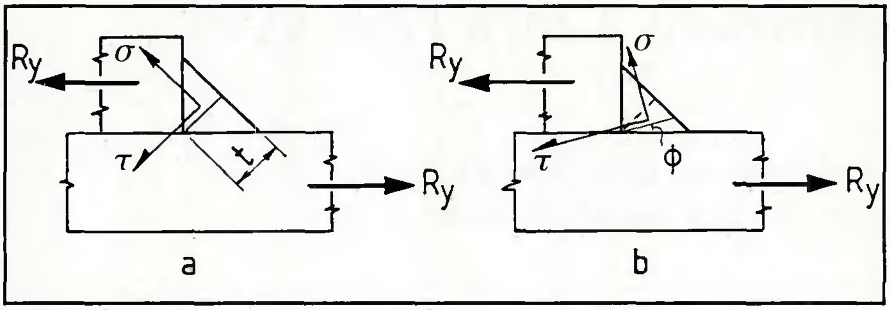

Fig. 2—Stresses in a fillet weld

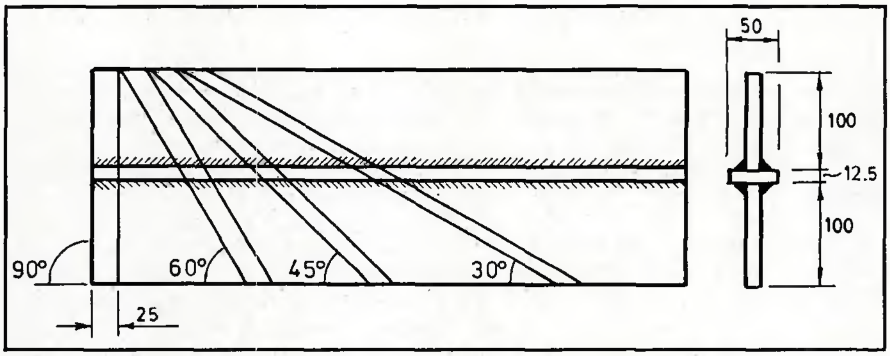

Fig. 3—Cutting of welded assembly

Table 1—Welding Variables for Test Welds

Filler wire size	1.6 mm (1/16 in.)
Current	295-305 A
Voltage	20.5-21 V
Speed	14.8 mm (0.58 in.)/s
Shielding gas	Argon at 33 L/min
Position	True flat
Torch work angle	6 deg from vertical

The welding was carried out using mechanized GMAW. Details of the procedure are listed in Table 1. Each weld was nominally 25 mm (1 in.) long, thus the width of the specimen varied from 25 to 12.5 mm as the angle varied from 90 to 30 deg.

Table 2 gives the mechanical properties of the materials. Some of the values are taken from the specifications for the alloy (Ref. 7), some obtained in this test program, and some from design codes (Refs. 6, 8, 9), as appropriate.

Actual weld sizes were measured before testing, particularly the throat depth. The area of the fracture surface was measured after testing. Each specimen was loaded to failure in an Instron Universal Testing Machine, at a rate of 1 mm/min (0.04 ipm), and the force-elongation relationship recorded. At least three specimens were tested at each angle (Table 3).

The smaller areas of the two welds that failed in each test was used to calculate the effective ultimate stress on the weld throat. The difference between the weld throat area calculated from the measured dimensions of the fillet and the measured area after failure was small enough to be neglected.

Comments on the Test Results

The inclination of the fracture surface within the fillet varied between 5 and 20 deg, with a mean value of 10 deg. The deviation from the theoretical value is attributable to the convexity of the weld bead, which also causes the failing stress to be somewhat higher than predicted. The ratio of the strengths for 90- and 0-deg directions of loading has a mean value of 1.25.

To provide an interaction relationship between longitudinal and transverse loading for forces in the X-Z plane, the one used in Ref. 1 is proposed:

$$(\tau_x/\tau_{xu})^2 + (\tau_z/\tau_{zu})^2 = 1 \qquad (8)$$

For forces acting at an angle Θ to the weld, the force is resolved into its components along and across the weld. The stresses are then

$$\tau_x = (R_\Theta \cos \Theta)/Lt, \qquad \tau_z = (R_\Theta \sin \Theta)/Lt$$

and Equation 8 can be expressed as

$$\tau_{\Theta u} = \tau_{xu}/[1 - (\sin^2\Theta)/3]^{1/2} \qquad (9)$$

when the ratio τ_{zu}/τ_{xu} is 1.2, which is close to the value adopted in Ref. 6. The form of Equation 9 may be compared to that proposed in Refs. 1 and 2 for loads in the X-Y plane:

$$\tau_{\Theta u} = \tau_{xu}/[1 - (\sin^2\Theta)/2]^{1/2}$$

Figure 5 shows how the test results fit with the relationship of Equation 9.

Bending

Knowledge of the tension strength of fillet welds is required in order to calculate the moment resistance of T-joints. Two cases arise:

1) Bending about an axis parallel to the direction of the weld—Fig. 6A.

2) Bending in the plane of the stem of

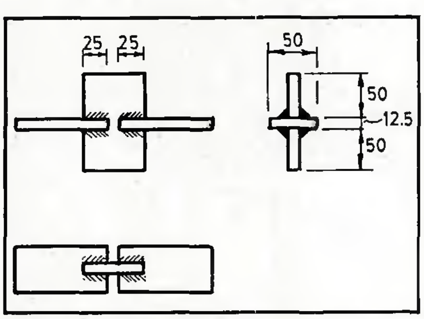

Fig. 4—Specimen for Θ = 0

Table 2—Mechanical Properties

Alloy	Temper	Tension, N/mm²(a) Yield Range	Yield Design	Ultimate Range	Ultimate Design	Compression, N/mm² Ultimate Test
Plate						
5083	H321	215-295	215	305-385	305	
	0	125-200	125	275-350	260	420

		Shear Ultimate, N/mm² X Design	X Test	Y Design	Y Test	Z Design	Z Test
Filler			186		(1)(b)250		233
5356	(9)(b)	120		170		120	
	(8)(b)	120		120		120	
	(6)(b)	140		170		170	

(a) N/mm² = 0.145 ksi.
(b) Indicates a reference.

the T-joint, about an axis normal to the weld direction—Fig. 6B.

For bending about an axis parallel to the weld, the ultimate moment is the product of the ultimate strength of the weld and the effective distance between the welds (Fig. 6A) expressed by

$$M_u = \tau_{zu} Ltc \qquad (10)$$

in which M_u = the ultimate moment, t = throat thickness and c = effective moment arm.

Specimens nominally 25 mm (1 in.) wide were cut from an assembly of the type shown in Fig. 3. Because the bending strength of the combined 6-mm fillet welds exceeded that of the plate, the welds were machined down to give a 3-mm (1/8-in.) throat. Each specimen was supported over a span of 180 mm (7 in.) and subjected to a central load to failure. Using the value of the ultimate strength of the fillet weld obtained from specimens cut from the same welded assembly, and the ultimate moment obtained from the bending test, the value of the effective moment arm, c, was calculated from the relationship:

$$c = M_u/Lt\,\tau_{zu} \qquad (11)$$

As expected, the value obtained was close to

$$c = h + s \qquad (12)$$

in which h = plate thickness and s = fillet size. This indicates that the full strength of the weld is developed and it can be assumed to act at the center of the weld face.

Bending in the Plane of the Stem of the T-Joint—Mechanical Properties

The nonlinear force-deformation behavior of fillet welds is seen in the typical curves shown in Fig. 7. It is evident that a plastic type of analysis is more realistic than linear elastic theory. However, at this point, there is no information on the behavior of the zone in compression. It is to be remembered that in welded aluminum joints there is a heat-affected zone (HAZ), extending a small distance from the weld, in which the mechanical properties are below those for the unaffected base metal. For this zone, the properties of the annealed base metal are assumed to apply for non-heat-treated alloys.

Thus, bending stresses in the joint must be looked at in several places to determine the minimum moment of resistance.

In tension, there are the fillet welds, limited to the ultimate strength for transverse loading; the HAZ, limited to the ultimate strength in tension of the annealed base metal; and the base metal, limited to the tension yield strength of the unaffected alloy.

In compression, there are the fillet

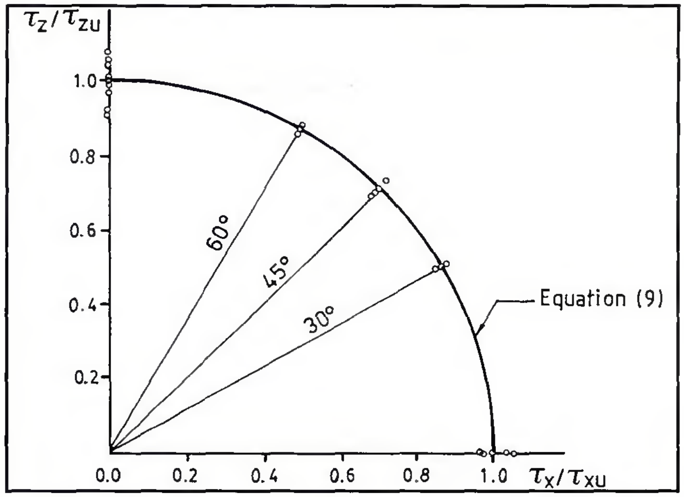

Fig. 5—Test results for oblique forces

Table 3—Test Results for Fillet Welded T-Joints in Tension

Angle	Weld Size, mm[(a)]	Measured Throat, mm	Weld Length, mm	Failure Load Mean kN[(b)]	Failure Load C.V.	Ultimate Stress Mean N/mm^2	Ultimate Stress C.V.
0	7.0	5.3	25.0	23.7	0.04	186	0.04
30	7.0	5.2	25.0	24.3	0.01	194	0.01
45	6.7	5.0	24.9	25.9	0.01	211	0.02
60	6.9	5.2	24.8	27.8	0.03	216	0.01
90	7.0	5.2	25.0	29.4	0.04	233	0.05

(a) 25.4 mm = 1 in.
(b) kN = 1000 N = 224.8 lb-force.

welds and the contact area of the plate; the HAZ, limited to the ultimate strength in compression of the annealed base metal of non-heat-treated alloys; and the base metal, limited to the compressive yield strength of the unaffected alloy.

Of mechanical properties required for this analysis, all are available in the literature with the exception of the limiting strength in compression of the HAZ. For this reason, direct compression tests were made on welded joints cut from the assembly. The stress/strain relationship is shown in Fig. 8, indicating a very ductile behavior. The limiting stress of 420 MPa (61 ksi) obtained in these tests well exceeds maximum ultimate tensile strength permitted for this alloy—Table 2.

Analysis

Assuming a fully plastic condition at failure (Fig. 9), the ultimate moment in the joint is given by

$$M_u = N_c N_t d^2/2(N_c + N_t) \qquad (13)$$

in which N_c is the lesser of $\sigma_{cwu}h$ and $\sigma_{cy}h$, and where

- σ_{cwu} = ultimate compressive strength of welded base metal,
- σ_{cy} = compressive yield strength of unaffected base metal, and
- h = plate thickness;

N_t is the least of $2\tau_{zu}t$, $\sigma_{twu}h$ and $\sigma_{ty}h$, and where

- τ_{zu} = ultimate strength of fillet weld, in Z-direction,
- σ_{twu} = ultimate tensile strength of welded plate, and
- σ_{ty} = tensile yield strength of unaffected base metal.

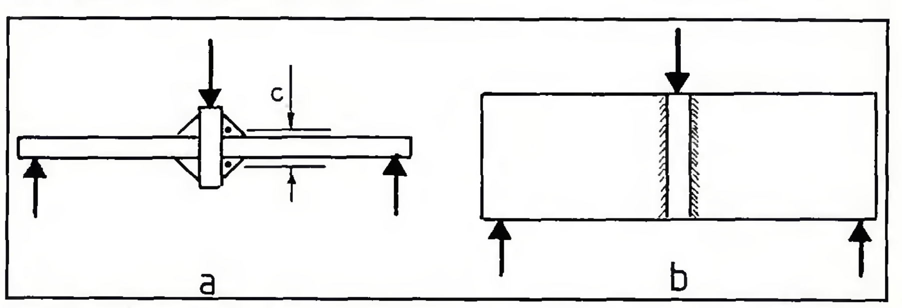

Fig. 6—Welds in bending

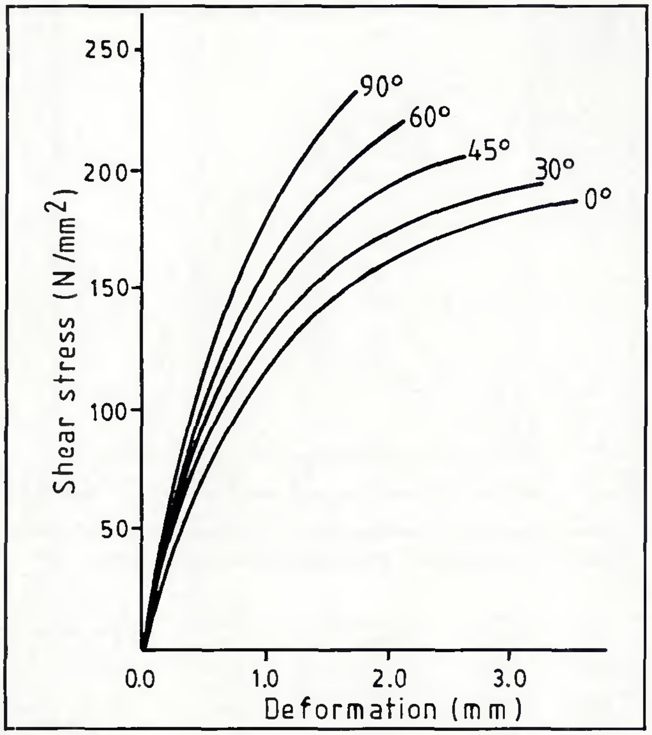

Fig. 7—Stress/deformation of fillet welds

For a given ratio of N_c to N_t, Equation 13 can be expressed as

$$M_u = N_t\, d^2/K \quad (14)$$

in which K would be 6 if N_t were a "modulus of rupture", as used in timber, but can approach 2 if N_t is the true strength of the welds, and the strength of the compressive zone is relatively high. Bending tests were carried out to determine the value of K, and the effective resistance of the compression zone based on the assumption of the validity of Equation 13.

Bending Tests

Specimens were again cut from a welded assembly of the type in Fig. 3, in widths of 25, 50 and 75 mm (1, 2 and 3 in.). Control specimens were also cut to give the ultimate strength of the welds. The specimens rested on articulated supports to avoid horizontal restraint, spanning 170 mm (6.7 in.). A central load was applied at a rate of 5 mm/min (0.2. ipm).

After testing, one specimen was cut to determine the point of contact between the plates, which was considered to be the location of the neutral axis—Fig. 10. Table 4 gives the results of the tests and their interpretation.

The value of K is obtained from Equation 14 rearranged thus

$$K = N_t\, d^2/M_u \quad (15)$$

Using the ultimate moment and the ultimate strength of the welds, Equations 13 and 15 can be used to give the effective ultimate compressive strength:

$$N_c = N_t/(K/2 - 1) \quad (16)$$

The neutral axis for this state of stress is at a distance from the extreme tension fiber given by (Fig. 9):

$$kd = 2d/K \quad (17)$$

Comments on Test Results

Figure 10 shows the cross-section through the joint after testing. The contact point is seen to be at a distance of approximately ⅔rd from the lower edge, agreeing closely with the value required to satisfy the fully plastic failure mode.

The interaction formula, Equation 8, is used to determine the reduced tension strength due to the presence of the shear force. This reduced ultimate tension strength was used in the equations to calculate the stress in the compression zone, and the value of K. The calculated mean limiting stress in the compression zone varies from 350 to 400 MPa (50 to 58 ksi), which is comparable with the value obtained in the compression tests. The almost uniform value of the factor K = 3 correlates well with the measured resistance of the compression zone and the location of the neutral axis.

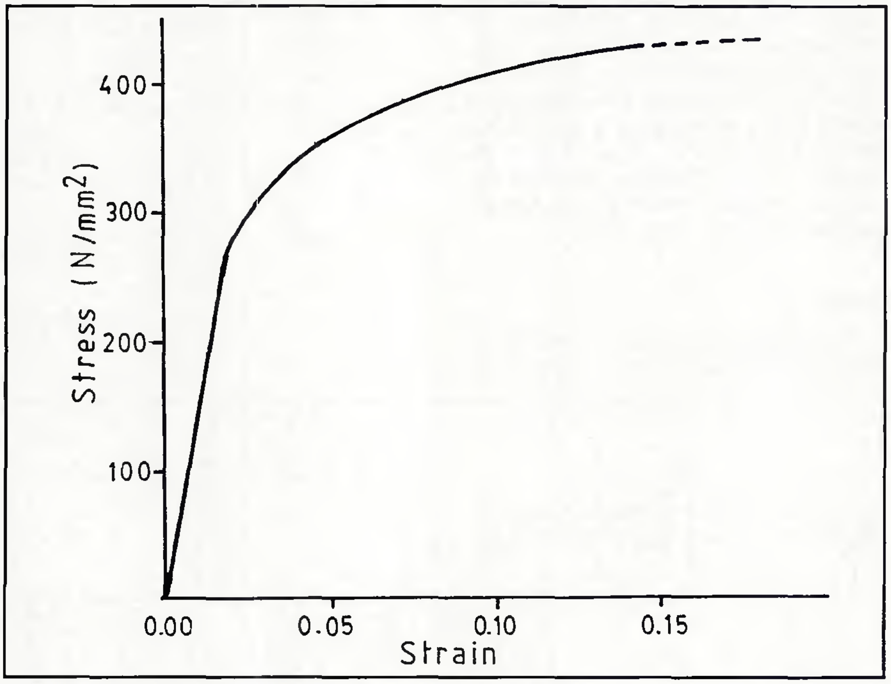

Fig. 8—Stress/strain relationship for weld zone in compression

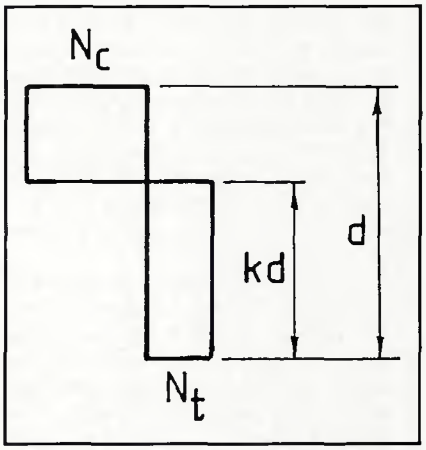

Fig. 9—Limiting stress distribution in bending

Table 4—Test Results for T-Joints in Bending

Length of Weld, mm	Ultimate Forces			Ultimate Tensile Resistance, kN/mm	K	Compressive Stress, N/mm^2	k
	Shear, kN	Moment					
		Mean kN·m	C.V.				
25	6.7	0.51	0.02	2.32	2.9	409	0.69
50	25.6	1.95	0.02	2.26	2.9	403	0.69
75	50.9	3.88	0.01	2.19	3.1	350	0.64

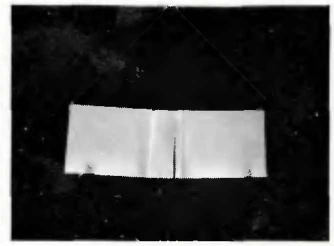

Fig. 10—Contact of plates at maximum moment

Proposed Design Procedure

Transverse Strengths

Values for the transverse strengths can be confidently given as: Y-direction, 1.4 τ_{xu}, and Z-direction, 1.2 τ_{xu}. Using the value τ_{xu} from the codes (Refs. 6, 8 and 9), the resulting design ultimate stresses are given in Table 2, where they are compared with the test values. The margin of safety is considered to be large enough to cover the variability of manual welds.

Bending about an Axis Parallel to the Welds

Double fillet welds are required by the codes when the joint is subjected to bending about an axis parallel to the welds. The ultimate moment resistance per unit length of the joint will be taken to be

$$m_u = 1.2\ \tau_{xu}\ t(h + s) \qquad (18)$$

Bending about an Axis Normal to the Welds

Although the tests indicated that the ultimate moment can be given by the expression

$$M_u = 2\ (1.2\ \tau_{xu}\ t)\ d^2/3 \qquad (19)$$

for design purposes it is proposed that the ultimate tensile stress for the annealed material, σ_{tu}, be the value used for σ_{cu}. N_c is then the lesser of σ_{tu} h and σ_{cy}h. N_t is the least of (2 × 1.2 τ_{xu}), σ_{tu}h and σ_yh.

For a balanced design, the limiting force on the welds would equal that on the welded plate, giving

$$M_u = N_t\ d^2/4 \qquad (20)$$

This would then be compared with the fully plastic moment for the unaffected base metal plate. In Fig. 11, the ultimate moment obtained using this design procedure is compared with the results obtained in the test program. Compression buckling of the plate will be treated separately from the local ultimate resistance of the joint.

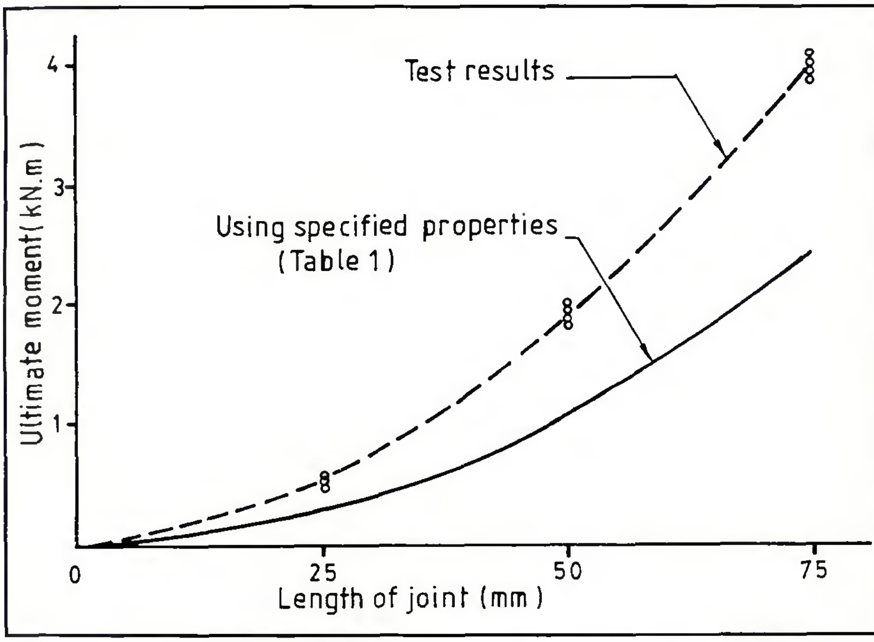

Fig. 11—Comparison of test results and design procedure for bending in the X-Z plane

Conclusion

The ultimate strength of a pair of 5356 aluminum alloy fillet welds in a T-joint has been shown to be some 20% higher in the transverse direction than that of welds loaded longitudinally, and it is suggested that advantage be taken of this in structural design. For each of the principal orthogonal directions of force, there will be a different strength. This has been adopted in the forthcoming CSA Standard, *Welded Aluminum Construction* (Ref. 11).

The moment resisted by a T-joint can be conservatively calculated assuming a fully plastic stress distribution, with the stress in the compression zone limited to the ultimate tensile strength of the welded metal. This simple design procedure is acceptable because of the strong ductility of the compression zone and the adequate nonlinearity of the force/distortion relationship of the fillet welds. The predictions agree closely with those given by the method of Ref. 10 for steel welds.

Throughout the tests, the coefficient of variation was less than 0.05, and the usual rule of mean value less two standard deviations yields values well in excess of the design values proposed above. Even so, the proposed design procedure gives considerably higher resisting moments than those currently permitted in design codes.

Appendix

Symbols

c = moment arm
d = length of weld in bending tests
h = plate thickness
k, K = factors
L = length of weld in tension tests
m = moment per weld unit length
M = moment
N = force per unit length
R = force
s = weld size
t = weld throat
τ = shear stress in fillet weld
σ = normal stress
ϕ, Θ = angles

Subscripts

c, t = compression, tension
x, y, z, Θ = directions of force
u, y = ultimate, yield
w = welded

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