THE STRENGTH OF FILLET WELDS

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Summary

In this paper a strength theory applicable to fillet welds is proposed. Results of tests on a single fillet weld subjected to a single load acting in a plane perpendicular to the axis of the weld are examined. Seven different strength theories are considered and the strength of a single weld as determined by each theory is compared with the test results. In general a maximum shear stress criterion gives the most satisfactory results. This criterion is used to estimate the strength of pairs of fillet welds for several loading conditions and the results compared with experimental values. It is shown, that for the situations examined, conventional design methods are in general over conservative, and design curves are proposed for two loading conditions.

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NOTATION

The following notation has been adopted in this paper.

\( M = \) Moment applied to the leg of a fillet weld. (See Fig. 4)
\( N = \) Force per unit length of weld acting normal to a leg of a fillet weld.
\( P = \) Load applied to a welded bracket or connection.
\( R = \) Resultant of forces \( N \) and \( T \).
\( T = \) Force per unit length of weld acting tangential to a leg of a fillet weld.
\( e = \) Eccentricity of the applied load.
\( f_s = \) Shear strength of weld metal.
\( h = \) Distance between centres of parallel welds.
\( l = \) Length of weld.
\( m_\alpha = \) Moment on plane \( \alpha \).
\( \eta_\alpha = \) Normal force on plane \( \alpha \).
\( s = \) Nominal size of weld.
\( t_\alpha = \) Tangential force on plane \( \alpha \).
\( \alpha = \) The angle of inclination of a plane to the plane of the throat. (See Fig. 5)
\( \sigma = \) Average normal stress (general term) on the throat of a weld.
\( \sigma_\alpha = \) Maximum normal stress on plane \( \alpha \).
\( \sigma_{n\alpha} = \) Average normal stress corresponding to \( \eta_\alpha \).
\( \sigma_{b\alpha} = \) Normal stress corresponding to the moment \( m_\alpha \).
\( \sigma_c = \) The "comparison stress" or critical stress at failure.
\( \tau_{\perp} = \) Average tangential (shear) stress on the throat of a weld and acting in a direction perpendicular to the length of the weld.
\( \tau_{\parallel} = \) Average tangential (shear) stress on the throat of a weld and acting in a direction parallel to the length of the weld.
Introduction

Fillet welds are widely employed in building construction and in machine fabrication in situations where they may be subjected to direct loads applied at any inclination to the length of the weld. In other situations a weld group may be subjected to any of the possible combinations of direct force, bending moment and twisting moment.

The Standards Association of Australia in 1952 published "S. A. A. Int. 352- S. A. A. Interim Code for Manual Arc Welding in Building Construction". In the preface to this publication mention was made of the fact that the code had been based largely on the American Welding Society's standard code for arc and gas welding in building construction (No. D1-O4b) and that reference had also been made to relevant British codes. The Australian code consequently agrees generally with accepted practices in English speaking countries for the design of welded joints.

Clause 225 of the code S. A. A. 352 states that the maximum permissible stress in shear on the section through the throat of a fillet weld shall be taken as 70% of the permissible stress in tension for the parent metal. It further states that "stress in a fillet weld shall be considered as shear on the throat for any direction of the applied load". The latter requirement indicates that end fillet welds are to be considered as having the same strength as side fillet welds, whereas various investigations have shown that end fillets are stronger than side fillets. (Reference 1)

Under the heading of "Combined Stresses in Welds" - Clause 226, the Code states, "in fillet welds subject to tension or compression (axial and/or bending) in combination with shear (direct and/or torsional) the resulting stress shall be taken as the vectorial sum of the component
stresses and shall not exceed the permissible shear in table ix (i.e. 70% of the permissible stress in tension of the parent metal).

It is clear from sample calculations given in an appendix to the code that the methods for the design of rivet groups has been applied to the design of welded connections. It appears that this method has been employed since the inception of welding.

C.H. Jennings (Reference 2) presented methods for calculating nominal stresses in fillet welds in various situations. For the case of the lapped joint employing end fillet welds he suggested that the nominal stress on the throat area is a tension of magnitude

\[ \sigma = \frac{P}{\text{Throat Area}} = \frac{\sqrt{2} \frac{P}{s \ell}}{\text{Throat Area}} \]

For the case of a pair of transverse fillet welds, each of unit length, subjected to bending and shear, (see Figure 1), Jennings assumed that the shear force is \( T = \frac{P}{2} \) in each weld, while the force due to bending moment is \( N = \frac{P \varepsilon}{h} \).

He then calculated the resultant of the forces \( T \) and \( N \) as

\[ R = \sqrt{T^2 + N^2} = \sqrt{\left(\frac{P}{2}\right)^2 + \left(\frac{P \varepsilon}{h}\right)^2} \]

and the corresponding stress on the throat as

\[ \frac{R}{\text{Throat Area}} = \sqrt{2} \frac{R}{s} \]

For parallel fillet welds subjected to bending moment and shear (the shear force being parallel to the length of the weld) he suggested that the shear force could be neglected, reasoning that the shear stresses at the ends of the welds must be zero. (Figure 2)
On this basis the stress on the weld throat area at the extremities would be

\[ \frac{6 \, P e}{2(\sqrt{12}) s \ell^2} \]

\[ = 4.24 \, P e / s \ell^2. \]

It is seen then that Jenning's proposals agree with those suggested by the Code except for the case of combined bending and shear, with the applied shear force acting parallel to the welds. It is obvious of course that Jenning's method would be entirely unsatisfactory for cases where the ratio \( e / \ell \) is small as then the longitudinal shear on the welds must be of paramount importance.

It has long been recognised that the methods of design which have been borrowed from rivet design are at best an imperfect solution of the problem. The Engineering News Record (15th May, 1930) in reporting on a paper by L.C. Bibber (Reference 3), who had made an attempt to explain the stress distribution in a fillet weld, made the following comment, "In the main, it is possible to connect beams, girders, columns and truss members to one another by welding with considerable confidence. But the theoretical background, the ability to analyse and explain, which has always been the bulwark of other fields of science, has been lacking in the field of welding. The reason why certain joint arrangements have stood up while others have failed has not always been easy or even possible to explain. The attempt by Mr. L.C. Bibber . . . . . . to develop a theory of stress distribution in welds and of stress transfer through them is an important step forward". Bibber's work gave a stimulus to both theoretical and experimental investigations into the strength of fillet welds.
Strength of Single Fillet Welds

In 1934 Jensen (Reference 4) reported an investigation into the strength of single fillet welds subjected to a force acting perpendicular to the longitudinal axis of the weld. The main purpose of the investigation was to determine the effect on the ultimate load of varying the angle of inclination of the applied force, (see Figure 3) and to compare the test results with the estimated ultimate loads determined by three existing methods. The three methods were as follows:

Method 1. In this method the maximum stress is considered to be the oblique force $R$ divided by the throat area. For this theory to be satisfactory the maximum stress so determined should be constant for all angles of inclination of the force.

Method 2. This method proposed by L.W. Schuster (Reference 5) assumes a uniform distribution of the resultant stress across the throat of the weld. The resultant stress can be resolved into components normal $\sigma$, and parallel $\tau_i$, to the plane of the throat, and from these separate stresses the maximum shear stress, and principal stress can be calculated

$$\text{Maximum shear stress} = \sqrt{\sigma^2/4 + \tau_i^2}$$

$$\text{Principal stress} = \sigma/2 \pm \sqrt{\sigma^2/4 + \tau_i^2}$$

It is assumed that the weld will fail when either the maximum shear stress or the principal stress reaches limiting values.
Method 3. In this method Jensen applied the argument used by Bibber for a single force acting parallel to one leg of a fillet weld to the two components of the oblique force so that the resulting stress (a tension) on the throat became \( \frac{2(N+T)}{\text{Nominal size}} \).

Jensen performed a number of control tests on butt welds to determine the strength of weld metal in shear and in tension, the average value being 44,500 lb./sq.in., in shear and 61,200 lb./sq.in., in tension. Tests on side fillet welds gave an average shear strength of 48,100 lb./sq.in. Use is made of these values in a later section of this paper to calculate maximum loads using various strength theories.

Jensen states in his conclusion that none of the methods of analysis are substantiated. Referring to the vector method, which is the method agreeing with the Code, he states that this method "gives results which vary from excellent to about 37% on the safe side. It is therefore, a simple and safe (although sometimes ultra-safe) method suitable for use in design".

Analysis

There are of course very many other criteria which might be employed to estimate the ultimate load that can be sustained by a fillet weld loaded as in Jensen's tests. Some of these possibilities are now considered.

Consider a fillet weld of unit length loaded as in Figure 3.

If the forces acting on the legs of the weld (both normal and tangential) are considered as uniformly distributed, then for equilibrium the forces are as shown in Figure 4.
where \( M = (N - T) \frac{5}{4} \), \( M \) being the same on each leg if it is assumed that the resultant force \( R \) acts through the mid-point of the throat of the weld.

Consider the free body ABC Figure 5, where BC is inclined at an angle \( \alpha \) to the throat of the weld. For equilibrium the
tangential force on BC is
\[
\ell_\alpha = N \cos(45 - \alpha) - T \sin(45 - \alpha)
\]
and the normal force on BC is
\[
\mathcal{N}_\alpha = N \sin(45 - \alpha) + T \cos(45 - \alpha)
\]
and the moment
\[
\mathcal{M}_\alpha = \frac{N s}{2} - \mathcal{N}_\alpha s \frac{\sqrt{2}}{4} \sec \alpha - M
\]

For the weld loaded as in Figure 6 the forces acting on the weld are as shown in Figure 7.

For equilibrium
\[
M = (N + T) \frac{5}{4}
\]
\[
\ell_\alpha = N \cos(45 - \alpha) + T \sin(45 - \alpha)
\]
\[
\mathcal{N}_\alpha = N \sin(45 - \alpha) - T \cos(45 - \alpha)
\]
\[
\mathcal{M}_\alpha = \frac{N s}{2} - \mathcal{N}_\alpha s \frac{\sqrt{2}}{4} \sec \alpha - M
\]

Photo-elastic investigations (Reference 10) to determine stress distributions in fillet welds have indicated that stresses are not uniformly distributed across any section through the weld. Peak values of stress occur particularly in the vicinity of the heel and toes of the fillet. Such investigations, however, are only valid if the weld material is behaving in a hookean manner.
In this paper no attempt is made to determine actual stress distributions for the situation at failure. The stresses referred to are nominal stresses only, being obtained by dividing the force on any specified plane by the area of that plane.

On this basis the shear stress on BC corresponding to \( \tau_\alpha \) is,

\[
\tau_\alpha = \frac{1}{2} \frac{t_\alpha}{s} \cos \alpha
\]

The normal stress corresponding to \( \eta_\alpha \) is

\[
\sigma_{n\alpha} = \frac{1}{2} \eta_\alpha \cos \alpha
\]

The normal stress corresponding to the moment \( m_\alpha \) will have a maximum value at B and C given by

\[
\sigma_{b\alpha} = \pm 12 m_\alpha \frac{\cos^2 \alpha}{s^2}
\]

if the bending stress is assumed to vary linearly from B to C.

If, however, it is assumed that the stress due to \( m_\alpha \) is constant from B to D and from D to C (rectangular stress block) then the value of the stress is

\[
\sigma_{b\alpha} = \pm 8 m_\alpha \frac{\cos^2 \alpha}{s^2}
\]

The maximum normal stress on BC is then

\[
\sigma_\alpha = \sigma_{n\alpha} + \sigma_{b\alpha}
\]

If the moment \( M \) is ignored then the normal stress is

\[
\sigma_\alpha = \sigma_{n\alpha}
\]

Corresponding to stresses \( \sigma_\alpha \) and \( \tau_\alpha \) the maximum shear stress is given by

\[
\text{Maximum shear stress} = \frac{1}{2} \sqrt{\sigma_\alpha^2 + 4 \tau_\alpha^2}
\]

the principal stress is given by,

\[
\text{Principal stress} = \sigma_{\alpha}/2 \pm \frac{1}{2} \sqrt{\sigma_\alpha^2 + 4 \tau_\alpha^2}
\]

and the octohedral shear stress is proportional to:

\[
\sqrt{\sigma_\alpha^2 + 3 \tau_\alpha^2}
\]

Each of these stresses is a function of the angle \( \alpha \) and \( N/T \).
and the maximum values do not necessarily occur for $\alpha = 0$, that is the throat of the weld. Jensen's tests show that failure in general does not occur through the throat of the fillet weld. It is of interest, therefore to investigate the variation of each of these quantities with $\alpha$ and $N/T$.

As a typical example the variation of maximum shear stress in terms of $\alpha$ for the case $N/T = 2$ considering a rectangular stress distribution for $\alpha$ is shown on Figure 8.

Graphs similar to Figure 8 have been prepared to show the variation of the following critical 'nominal' stresses with $\alpha$ and $N/T$.

**Cases Considered.**

1. Maximum Shear Stress ($m_\alpha$ Neglected)
2. Principal Stress ($m_\alpha$ Neglected)
3. Maximum Shear Stress (triangular stress block due to $m_\alpha$ included)
4. Principal Stress (triangular stress block due to $m_\alpha$ included)
5. Maximum Shear Stress (rectangular stress block due to $m_\alpha$ included)
6. Principal Stress (rectangular stress block due to $m_\alpha$ included)
7. The Stress $\sqrt{\sum_\alpha^2 + 3 \gamma_\alpha^2}$ (rectangular stress block due to $m_\alpha$ included).

From these graphs maximum values of each of the above seven 'critical stresses' were determined for values of $N/T$ from 0 to 5. The maximum values of the critical stresses are plotted against $N/T$ in Figures 9, 10, 11 and 12.

To compare these various methods of estimating the ultimate
strength of fillet welds the failure loads of $\frac{3}{8}$ inch fillet welds 2 inches long loaded as in Figure 3 and 6 were estimated. For cases 1, 3 and 5, i.e. maximum shear stress criteria the shear strength of the weld metal was taken as 48,100 lb./sq. in., and for cases 2, 4, and 6, i.e. principal stress criteria, the tensile strength of the weld metal was taken as 61,200 lb./sq. in. to correspond with the strength of deposited weld metal in Jensen's tests. For case 7 the strength of the weld metal was taken as $\sqrt{3} \times 48,100$ lb./sq. in. The information provided by Figures 9 to 12 was used in the calculation of the ultimate loads. The results are shown graphically in Figures 13 (welds loaded as in Figure 3) and 14 (welds loaded as in Figure 6) on which Jensen's experimental results are also plotted.

An examination of these curves (Figure 13) and Jensen's results show for the weld loaded as in Figure 3 that for $N/T$ greater than 2 all of the curves fit the experimental results reasonably with the exception of the two curves corresponding to Principal Stresses with the moment term included. However for values of $N/T$ less than two the curve representing maximum shear stress with a rectangular stress block due to bending moment fit the results exceptionally well, although the maximum shear (moment neglected) fits the experimental results almost as well.

For the welds loaded as in Figure 6, the three curves (Figure 14) for maximum shear stress fit the experiments very well for all values of $N/T$. The curve for principal stress including moment $m$ with a rectangular stress block also fits the experimental values.

In general the maximum shear stress criterion (for the case where moment is ignored or for a rectangular stress block for the moment) appears to suit both loading situations over the full range of
Discussion

It might appear unexpected that the test results as plotted in Figure 13 are so much greater than the strengths predicted on the basis of principal stresses. It must be remembered however that the principal stress curves have been determined using the tensile strength of the weld metal as determined in a normal tension test in which the yielding is not restrained. In the fillet welds considered here, however, such free deformation is not permitted and the tensile strength given by the standard test is therefore not applicable.

It must be remembered, however, that the calculation of these critical stresses, occurring as they do on planes other than the throat of the weld is a tedious operation and would therefore be unattractive as a design procedure.

Vreedenburgh (Reference 6) has arrived at the conclusion that there is no single criterion of failure which can be applied to fillet welds and suggests that the only practical solution is to employ an empirical curve which fits the experimental results. He has proposed an interaction surface (pearoid) relating the average normal stress and average shear stress on the throat of a fillet weld at failure. The pearoid chosen by him is a surface of revolution, the vertical axis of which represents the normal stress. The right vertical section has the form shown in Figure 15.

The curve is composed of three parts, an ellipse with major and minor semi-diameters equal to 2.39 ft and 0.97 ft (ft is the tensile strength of the weld), with the major axis coinciding with the axis \( \sigma \), a circle with centre at the origin of coordinates and of radius 0.75 \( f_t \) and a straight line which passes through \( \sigma = -1.7 f_t \) and \( \tau = 0 \). The
ellipse extends from \( \sigma = \frac{f_t}{3} \), \( \tau = 0 \) until it meets the circle, and the circle continues to its point of tangency with the straight line.

The International Institute of Welding (Institut International de la Soudure) has proposed the adoption of a simpler interaction curve known as the I.S.O. combination formula,

\[
\sigma'_c = \sqrt{\sigma'_1^2 + 1.8 (\tau'_1^2 + \tau'_n^2)}
\]

in which \( \sigma'_c \) is the "comparison stress" or critical stress at failure.

\( \sigma'_1 \) is the average normal stress on the throat of the fillet weld.

\( \tau'_1 \) is the average tangential (shear) stress on the throat of the weld and acting in a direction perpendicular to the length of the weld.

\( \tau'_n \) is the average tangential (shear) stress on the throat of the weld and acting in a direction parallel to the length of the weld.

It is seen that the surface represented by the I.S.O. formula is a surface formed by rotating an ellipse about the major axis represented by \( \sigma'_1 \). If \( \sigma'_c = \frac{f_t}{3} \) the semi-diameters of the ellipse have the values \( \frac{f_t}{3} \) and 0.75 \( \frac{f_t}{3} \).

The ellipse is shown in Figure 15 in which Vreedenburgh's limiting curve is also shown. It is seen that for cases where \( \sigma'_1 \) is a tension the two curves are almost coincident. Because of its simpler mathematical expression the I.S.O. curve is better suited to design purposes than Vreedenburgh's curve.

In Figures 16 and 17 the estimated ultimate loads according to the I.S.O. Formula for the welds of Jensen's tests have been...
plotted and compared with Jensen's test results. The critical stress $f'_{c}$ has been taken as $f'_{c} = 61,000$ lb./sq. in. The S.A.A. method is also shown on the graph but the critical stress has been taken as the shear strength of the weld metal i.e. $48,000$ lb./sq. in.

For the weld loaded as in Figure 3 the I.S.O. curve gives a conservative estimate of the ultimate load. For small values of $N/\tau$ the ultimate load is under-estimated by approximately 25%. The S.A.A. method is even more conservative than the I.S.O.

For the weld loaded as in Figure 5 the I.S.O. and S.A.A. methods agree closely with one another and are only slightly conservative. In general it can be said that for welds loaded as in Figures 3 and 5 the I.S.O. method will give a conservative estimate of the ultimate strength but less conservative than the S.A.A. Method.

As stated earlier the I.S.O. formula is designed to deal with the single fillet weld loaded in a general manner so that the three nominal stresses on the throat $\sigma_1$, $\tau_1$, and $\tau_{11}$ are present. Experimental investigations in which $\sigma_1$ and $\tau_1$ are present and $\tau_{11} = 0$ on the one hand, and on the other in which $\tau_{11}$ is present (side fillet test) while $\sigma_1 = 0$ and $\tau_1 = 0$ have demonstrated that the I.S.O. formula gives a conservative estimate of ultimate strength. It is not unreasonable therefore to assume it will be conservative for the general situation.

The End Fillet Weld.

The fillet weld loaded as shown in Figure 18 is commonly referred to as an End Fillet Weld. Although the total force $T$ in the separate bars which are joined by the weld will be known in any particular case, the distribution of forces in the individual welds cannot be determined with certainty.
If it were assumed that at failure, the applied load $T$ acted at the centre of the leg of the weld then equilibrium of the weld element could be obtained by forces $N$ and/or moments $M$ as shown in Figure 19. There is an infinite number of combinations of $N$ and $M$ which would satisfy equilibrium, but the following relationship must hold,

$$2M = (T-N)S/2$$

Now it is reasonable to assume $0 \leq \frac{N}{T} \leq 1$ and from Figure 9 it is seen that the maximum shear stress on any section does not alter markedly for variations of $\frac{N}{T}$ from 0 to 1. For example if the rectangular stress block for moment is followed, when $\frac{N}{T} = 0$ the maximum shear stress is $1.22 \frac{T}{S}$, when $\frac{N}{T} = 0.5$ the maximum shear stress is $1.0 \frac{T}{S}$, and when $\frac{N}{T} = 1$ the maximum shear stress is $1.14 \frac{T}{S}$.

Various investigators have reported that the ratio of the strengths of end fillet welds to side fillet welds is in the range 1.3 to 1.4 (References 1 and 7). In this context strength is the maximum load divided by the throat area of the weld.

Consider a side fillet weld of unit length and nominal size $S$ (i.e. throat area = \(\frac{S}{\sqrt{2}}\)). The strength of the weld would be

$$T_{s\text{ide}} = \frac{S}{\sqrt{2}} \times \text{(shear strength of the metal)}$$

while the strength of a similar end fillet weld must lie between

$$T_{e\text{nd}} = \frac{S}{\sqrt{1.22}} \times \text{(shear strength of the metal)}$$

and

$$T_{e\text{nd}} = \frac{S}{\sqrt{1.0}} \times \text{(shear strength of the metal)}$$

Hence the ratio of strengths of end to side fillet welds must lie between

$$\sqrt{2}/1.22 \text{ and } \sqrt{2}$$

i.e. 1.16 and 1.41

If it were assumed that $\frac{N}{T} = 1$ corresponds to the end fillet condition then the ratio of strengths would be

$$\sqrt{2}/1.24 = 1.24$$
Combinations of Fillet Welds.

The preceding discussion has been confined to the single fillet weld. Such welds, however, rarely if ever occur in practice, and it is necessary to consider the strength of combinations of fillet welds. Accordingly, two relatively simple combinations of fillet welds have been investigated:

(i) A pair of parallel welds loaded as in Figure 20.

and

(ii) A pair of parallel fillet welds loaded as in Figure 21.

Case (i). A series of 38 tests has been conducted to determine the maximum load which could be carried by a pair of parallel fillet welds loaded by combined bending moment and shear force, the bending moment being applied about an axis parallel to the length of the welds. The test specimens consisted of brackets of H-section built up out of \(\frac{3}{8}\) inch thick plate. In 28 cases the total depth of the section was six inches and in the remaining ten the total depth was four inches. The brackets were welded to a heavy stanchion section by one run of weld on each flange, and the brackets were loaded on the top flange in a Baldwin Testing Machine.

To ensure that there was no bearing between the web of the test bracket and the flange of the supporting stanchion during test, the web of the bracket was ground back to give a clearance of approximately \(\frac{1}{16}\) inch.

In all the tests of this series and of the series described here as Case (ii), the same type of weld rod was used. As control tests on the weld metal four different types of test were carried out, namely, tests of side fillet welds, end fillet welds, notched-tension specimens and specimens loaded in torsion.
In the case of the notched-tension specimens a standard mild steel round test bar was parted and then \( V \)-butt welded to the full diameter of the bar. A square shouldered notch was then machined in the weld metal to ensure failure in the weld in the tension test. The torsion specimens were prepared by \( V \)-butt welding mild steel tubing and then reducing the thickness at the position of the weld by machining to ensure failure in the weld in a torsion test on the tube.

Complete details of these control tests have been given in a previous paper (Reference 9).

Table 1 gives the dimensions of the welds, the maximum load, the eccentricity of the load and the plane of failure.

In each test failure was initiated by rupture of the top weld. It should be possible therefore, to make use of the earlier investigation into the strength of the single fillet weld loaded as in Figure 3 to predict the strength of the welds in the present situation. It is only necessary to apply the principles of static equilibrium to determine that

\[
N = \frac{P \varepsilon}{h}
\]

See Figure 20.

For a given ratio of \( N/T \) the earlier work could be used to estimate the maximum value of \( T \) for a given weld. The difficult question to be answered in this problem is: how is the total shear \( P \) distributed between the top and bottom welds? In other words the load on the top weld \( T \) cannot be determined from statics alone. If the bracket itself were perfectly rigid then the total shear force would be equally distributed between the top and bottom welds, so long as they were of equal size. For any real bracket the distribution of the total shear force will depend upon the relative stiffnesses of the bracket and the welds. For more flexible brackets a greater proportion of the
vertical load would be carried by the top weld for small eccentricities of the applied load.

From the experimental results shown in Table 1, the maximum load for a bracket with top and bottom welds of one inch nominal size and one inch length have been derived and the values for these "unit" welds have been plotted in Figure 22. On the same graph two curves have been drawn to show the estimated maximum load for the bracket obtained by using the curve of maximum shear stress (rectangular stress block) in Figure 9 and a value of 50,000 lb./sq. in., for the shear strength of the weld. This value has been obtained from the control tests mentioned above.

Three curves marked 1, 2 and 3 have been drawn in Figure 22. Curve 1 was based on the assumption that the total shear force was equally shared by the two welds, while curve 2 was based on the assumption that the proportion of the total shear force carried by the top weld varied from one to one-half as the ratio of the eccentricity of the load to the depth of the bracket varied from zero to one. Curve 3 was based on the assumption that the proportion of the total shear force carried by the top weld varied from three quarters to one-half as the ratio of the eccentricity of the load to the depth of the bracket varied from zero to one.

As an illustration of the method of obtaining points on these curves from earlier work the following example is given.

As shown above, the normal force \( N \) is given by

\[
N = \frac{P (\varepsilon/h)}{h}
\]

or

\[
\frac{N}{P} = \varepsilon/h
\]

Assume for example that the shear on the top weld is,

\[
T_1 = \alpha P
\]

where \( \alpha = \left( \frac{3}{4} - \frac{\varepsilon}{4h} \right) \) for \( 0 < \varepsilon/h < 1 \) (i.e. Curve 3)
Then for any particular value of $\varepsilon/h$ one can calculate $N/P$ and $\alpha$ and hence $T_1$. For example if $\varepsilon/h = 0.4$, $\alpha = 0.75 - 0.1 = 0.65$ and $N/T_1 = \frac{N}{P} \left/ \frac{P}{T_1} \right. = \frac{\varepsilon}{h\alpha} = \frac{0.4}{0.65} = 0.615$.

Referring to Figure 9 it is seen that for $N/T_1 = 0.615$ the maximum shear stress on the weld is given by $1.0 T_1/5$. If this stress is now equated to 56,000 lb./sq.in. and $S$ is one inch then $T_1 = 56,000$ lb.

The corresponding value of the total load $P$ is $P = \frac{T_1}{\alpha} = \frac{56,000}{0.65} = 86,000$ lb.

Other points on the curve are obtained in a similar manner.

On the same diagram the curve marked I.S.O. was drawn to show values of maximum load for various values of $\varepsilon/h$ as calculated with the I.S.O. Formula. In this case it was assumed that half of the total shear force was carried by the top weld. For the I.S.O. curve a value of 75,000 lb./sq. in. was taken as the tensile strength of the weld metal; that is $4/3$ of 56,000 lb./sq.in., the basic shear strength as determined by the control tests mentioned above. The curve representing the S.A.A. approach was also drawn using a basic shear stress of 56,000 lb./sq.in. and assuming $T_1 = P/2$.

Case(ii) A series of twenty tests has also been conducted on a pair of parallel fillet welds loaded as shown in Figure 21. Complete details of this series and the control tests have been given in Reference 9.

The welds were loaded by a shear force parallel to the length of the welds and a bending moment about an axis perpendicular to the length of the welds. (Figure 21) The test data is shown in Table 2. The ultimate loads carried by the welds in this series of tests have been expressed as a nominal stress $\frac{P}{Ls}$ for convenience and these values have been plotted in Figure 23.
As a theory of failure based on maximum shear stress appears to be satisfactory for the single fillet weld it was decided to adopt such a theory in order to arrive at a method of estimating the strength of fillet welds loaded as described here.

Figure 21(b) shows the welds in plan view. Normal forces $N$ are required to resist the total bending moment $P e$, while a shear force $P/2$ parallel to the length of the weld is applied to each weld. As far as the forces $N$ are concerned the weld is acting in the same manner as an end fillet weld. As explained earlier, the weld in this situation must be acted upon by an additional force system to balance the couples $N5/2$ acting on each weld.

Following the discussion of the end fillet weld one might reasonably assume that the additional force is equal to $N$ acting normal to the faying surface between the weld and the web of the bracket.

Some assumptions must also be made regarding the manner in which the force $N$ varies along the length of the weld, and it has been assumed here that this force is distributed uniformly, see Figure 24.

If $N$ is expressed as the force per unit length acting on each weld then the forces acting on one inch length of weld are as shown in Figure 24 (b),

$$2N l^2/4 = P e$$

or

$$N = 2Pe/l^2$$

The stresses on the plane A-A, Figure 24(c) are then

$$\sigma_{\perp} = 2\sqrt{2} \cos \alpha \left[ \cos(45-\alpha) - \sin(45-\alpha) \right] \frac{P}{ls} \frac{\theta}{\ell}$$

$$\sigma_{||} = \sqrt{2} \frac{P}{ls} \cos \alpha$$

$$\sigma_{\perp} = 2\sqrt{2} \cos \alpha \left[ \cos(45-\alpha) + \sin(45-\alpha) \right] \frac{P}{ls} \frac{\theta}{\ell}$$
The maximum shear stress is then given by
\[
\frac{1}{2} \sqrt{\sigma_{\alpha}^2 + 4(\tau_{1\alpha}^2 + \tau_{2\alpha}^2)}
\]
Substituting for \(\sigma_{\alpha}, \tau_{1\alpha}\), and \(\tau_{2\alpha}\), the expression for the maximum shear stress becomes
\[
\text{Max. shear stress} = \frac{P \cos \alpha}{2l_5} \left[ 2 \left\{ 40 - 24 \cos 2\alpha \right\} \left( \frac{\ell}{l} \right)^2 \right]^{1/2}
\]
This expression varies with \((\ell/l)\) and with the angle \(\alpha\). For any given value of \((\ell/l)\) it is then necessary to find the angle \(\alpha\) which makes the expression a maximum. As an example, if \((\ell/l) = 0.6\) the variation of maximum shear stress with \(\alpha\) is shown in the following table.

<table>
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<th>(\alpha)</th>
<th>Stress ((P/l_5))</th>
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<tr>
<td>10</td>
<td>1.410</td>
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<tr>
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<td>1.460</td>
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</tr>
<tr>
<td>40</td>
<td>1.480</td>
</tr>
<tr>
<td>45</td>
<td>1.430</td>
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</table>

Hence for \(\ell/l = 0.6\), \(1.506 P/l_5 = 56,000 \text{ (max., shear)}\) and \(P/l_5 = 37,200 \text{ lb./sq. in.}\).

This process has been repeated for various values of \(\ell/l\) and the resulting values of \(P/l_5\) plotted in Figure 23.
For the case just considered, i.e. $\frac{\varepsilon}{\ell} = 0.6$, the analysis indicates that the angle $\alpha$ for which the maximum shear has the greatest value is approximately $30^\circ$. This agreed substantially with the observations made during tests. For small values of $\frac{\varepsilon}{\ell}$ the plane of failure was close to the plane of the throat but diverged from it as $\frac{\varepsilon}{\ell}$ was increased, (see Table II).

An inspection of Figure 23 shows that the experimental values lie very close to the curve which has been derived on the basis of the maximum shear stress criterion.

The tests on welds in this situation covered a range of values of $\frac{\varepsilon}{\ell}$ from 0 to 1.3. For the case of very large values of $\frac{\varepsilon}{\ell}$, or the case of pure moment, the method of analysis based on the maximum shear criterion would give the ultimate moment,

$$ M_u = \frac{P\ell}{2} $$

Schreiner's test results (Reference 8) for pure bending on a pair of parallel fillet welds have been re-examined in the light of the above. For ten cases examined the ratio of ultimate moment as calculated by the above expression to the ultimate moment obtained by test had an average value of 0.93. The indication is that the above expression is satisfactory for predicting the maximum moment.

Consider the force system shown in Figure 24. The nominal stresses on the throat of the weld are

$$ \sigma_1 = \frac{2N}{\ell} = \frac{4PE}{\ell^2s} $$

$$ \tau_1 = 0 $$

$$ \tau_\parallel = \frac{\sqrt{2}P}{2\ell s} $$
If the I.S.O. Formula is now employed then
\[ \sigma_c = \frac{P}{I} \sqrt{16 \left( \frac{h}{t} \right)^2 + 0.9} \]
The corresponding curve has been drawn in Figure 23, using 72,000 lb./sq. in., as the magnitude of \( \sigma_c \), as explained previously. This method, it is seen, gives conservative values for ultimate loads.

A curve has also been plotted to show the application of the S.A.A. Code rule to this weld situation. For \( \frac{h}{t} = 0 \) the S.A.A. method of course coincides with the curve based on the maximum shear criterion, but the two curves diverge for \( \frac{h}{t} > 0 \) the S.A.A. method giving a very conservative estimate of the maximum load.

As explained above a value of 56,000 lb./sq.in (obtained in control tests) has been used for the shear strength of the weld metal. If the working stress in shear in the weld is taken as 0.7 of the working stress in tension of the parent metal, i.e. 0.7 of 20,000 lb./sq.in. or 14,000 lb./sq.in., this corresponds to a load factor of four. For values of \( \frac{h}{t} \) greater than zero the S.A.A. method underestimates the carrying capacity. For example (reading from Figure 23) when \( \frac{h}{t} = 0.4 \) the capacity indicated by the S.A.A. method is only 0.6 of the true capacity, and the real load factor in this case (joint designed by the S.A.A. method and recommended working stress) would be 4/0.6 or 0.6. The value of the load factor would vary with \( \frac{h}{t} \). Schreiner (Reference 8) carried out a series of tests on welds loaded in bending and shear (the range of values of \( \frac{h}{t} \) differed from that covered in this series) and came to this conclusion - "the present design methods are very conservative and give a factor of safety of at least seven when based on the ultimate strength of the weld".
Conclusions

1. In order to understand the behaviour of combinations of welds it is first of all necessary to have an insight into the behaviour of an individual weld. Attention has here been directed to the case where a single run of weld is subjected to a load acting in a plane perpendicular to the long axis of the weld and inclined to the leg of the weld. A re-examination of the results of Jensen's tests has led to the conclusion that a maximum shear stress criterion is the most satisfactory for predicting the maximum strength. This has involved determining the plane in the weld for which this shear stress is a maximum. The analysis has shown that this plane does not necessarily coincide with the throat of the weld. Jensen has demonstrated similarly that failure does not always occur in the throat of the weld.

Using this criterion it has been shown theoretically that end fillet welds should be 25% to 30% stronger than side fillet welds, a fact which has been demonstrated by many tests.

The International Institute of Welding has proposed the use of the empirical I.S.O. Formula which relates the nominal shearing and normal stresses on the throat of the weld to the tensile strength of the weld material. The use of this formula gives a conservative estimate of the strength of the single weld.

2. The knowledge gained regarding the strength of a single weld can only be applied to combinations of welds when the manner in which the total load is shared between the individual welds is known. For the case of a pair of parallel welds loaded by an eccentric force producing moment about the long axis of the weld it has been shown that the relative stiffness of the welds and bracket govern the distribution of shear
force between the welds.

It is suggested that the assumption that the shear force carried on the upper weld is,

\[ T_1 = \alpha P, \]

where

\[ \alpha = \left( \frac{3}{4} - \frac{\epsilon}{4h} \right) \quad \text{for} \quad \frac{\epsilon}{h} < 1 \]

and

\[ \alpha = \frac{1}{2} \quad \text{for} \quad \frac{\epsilon}{h} > 1 \]

is a satisfactory basis for calculating the maximum load for this weld combination. Values of ultimate load, corresponding to Curve 3, have been taken from Figure 22 and have been used to draw an interaction diagram (Figure 25). In this diagram values of \( P / f_s \) are plotted against values of \( P / f_s h \). Such a diagram may be used as a design graph, from which the ultimate load may be read for any value of \( \epsilon / h \). The working load may be obtained by dividing by a suitable load factor.

3. For a pair of parallel fillet welds loaded by a shear force parallel to the length of the welds and a bending moment about an axis perpendicular to the length of the welds it has been assumed that the total shear force is uniformly distributed along the length of the weld and that the forces required to resist the bending moment may be represented by a rectangular force block (fully plastic behaviour). On the basis of these assumptions the maximum loads predicted by the maximum shear stress criterion agree with the results of tests described in this paper.

The maximum shear stress method gives very good estimates of ultimate load for this loading condition, but the S.A.A. code method is very conservative for values of \( \epsilon / h \) greater than zero. The use of the S.A.A. method would consequently lead to uneconomic designs. The I.S.O. method is also conservative. It is suggested therefore that
the maximum shear stress method should be employed in designing welds for this loading condition.

To apply the maximum shear criterion, however, it is necessary to determine the plane in the weld having the greatest value of principal shear stress. The calculations which must be made to determine this plane are probably too involved and time-consuming to allow them to be used in the design office. To overcome this difficulty values of ultimate load have been taken from the maximum shear curve of Figure 23 and used in the construction of an interaction diagram in which \( \frac{P}{l} \frac{f_s}{S} \) is plotted against \( \frac{P \cdot e}{l^2 f_s} \) (Figure 26), where \( f_s \) is the shear strength of the weld metal. This diagram can be used as a direct design aid. The ultimate load can be read off for any value of \( \frac{e}{l} \) and the corresponding working load obtained by dividing by an appropriate load factor.
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<th>Eccentricity of Load</th>
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N.R. = Not recorded.
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<th>Throat (O.707X Nom_Size) (in.)</th>
<th>Width of Plane of Failure (in.)</th>
<th>Eccentricity (in.)</th>
<th>Failure Load (lb.)</th>
<th>Failure Plane °</th>
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* N.R. = Not recorded.
References


FIGURE 1. Loading diagram. Transverse Fillet welds subjected to bending and shear.

FIGURE 2. Loading diagram. "Parallel" fillet welds subjected to bending and shear.


FIGURE 4. Free body diagram of forces acting on a fillet weld loaded as in Figure 3.

FIGURE 5. Forces on a plane inclined to the throat of a fillet weld loaded as in Figure 3.


FIGURE 7. Forces on a plane inclined to the throat of a fillet weld loaded as in Figure 6.

FIGURE 8. Variation of maximum shear stress with the angle $\alpha$.

FIGURE 9, 10, 11, 12, 13, 14. Variation of "Critical Stress" with the ratio of Normal to Tangential Force.

FIGURE 15. Comparison of calculated failure loads with experimental results.

FIGURE 16. Interaction diagrams showing the limiting curves of Vreedenburgh and the I.S.O. criteria.

FIGURE 17. Comparison of the ultimate strengths predicted by the I.S.O. Formula and the S.A.A. Code with experimental results.

FIGURE 18. End fillet test.

FIGURE 19. Forces and moments on a fillet weld.

FIGURE 20. Loading diagram. Transverse fillet welds subjected to bending and shear.
FIGURE 21. Loading diagram. Parallel fillet welds subjected to bending and shear.

FIGURE 22. Comparison of predicted ultimate strengths of fillet welds with experimental results.

FIGURE 23. Comparison of predicted ultimate strengths of fillet welds loaded as Figure 21, with experimental results.

FIGURE 24. Assumed distribution of forces on a fillet weld loaded as Figure 21.

FIGURE 25. Interaction diagram for welds loaded as in Figure 20.

FIGURE 2b. Interaction diagram for welds loaded as in Figure 21.

In the following diagrams \( \triangle \) means that the effect of moment has been included with a linear distribution of stress assumed and \( \square \) means that the effect of moment has been included with a uniform distribution of stress assumed.
Max stress in terms of \( T/5 \)

FIG. 12.
FIG. 13
FIG 14.

Ultimate Load in kips

N/T
σ and τ are given as a proportion of the average ultimate tensile strength on the throat area of a weld loaded as follows with N=T.

FIG. 15
FIG 16.
Figure 17: Graph showing the relationship between ultimate load in kips and the ratio of axial load to T-stress (N/T). The graph includes two lines representing ISO and SAA test results, with data points indicated at various load levels and N/T ratios.
FIG. 18.

FIG. 19.
Load applied through fixed head of Baldwin testing machine.

Test welds

FIG. 21.
FIG. 24.
$f_s = \text{Shear strength of weld metal.}$
Shear strength of weld metal.

FIG. 26.