Significance of Weld Undercut in Design of Fillet Welded T-Joints

Stress concentration and local yielding due to undercut are determined following study of undercut and its effects relative to undercut size, shape, and location with respect to loading direction

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ABSTRACT. The fitness-for-service of fillet welded T-joints, with or without undercut, was investigated by computer calculations of weld stresses. The finite-element method was used for the analysis of T-joints in plane stress condition under static loads. Some photoelastic stress measurements were made to check the validity of the computer calculations.

The effect of undercut was studied according to its size, shape, and location with respect to the loading directions. Stress concentration and local yielding, due to undercut, were then determined. Some recommendations for the acceptance standard of weld undercut in fillet welded T-joints are presented.

Introduction and Objectives

The engineering technology in many industries has advanced tremendously in the past four decades. Welding has played an important role, but the science of welding engineering has never received the same attention as other disciplines. Confusion and uncertainty usually arise when an engineering decision is needed for the fitness-for-service of a welded structure. A more rational, mathematically proven procedure for determining the behavior of welds under various loading situations should be formulated.

Figure 1 shows the overall scope of fitness-for-service study of welded joints. Nondestructive evaluation identifies the discontinuities of code violation (noncompliances). An engineering analysis that determines the significance of such noncompliances provides a rational basis for engineering decisions on whether they must be repaired.

A noncompliance commonly found in fillet welds is undercut. This paper focuses on the analysis of an undercut flaw at the toe of a fillet welded T-joint under static loading. Results are being used for fatigue study of the same joints and will be offered in future papers.

The objectives of the study described in this paper were twofold:

1. To study the significance of weld undercut in fillet welded T-joints.
2. To provide some guidelines for efficient design of fillet welds.

Background Information

Problem Definition

Consider two fillet welds that join two equal-thickness plates in a T-shape and transmit the applied loads from one member to another. The load applied at an angle θ to the horizontal (flange) plate is uniformly distributed along the top

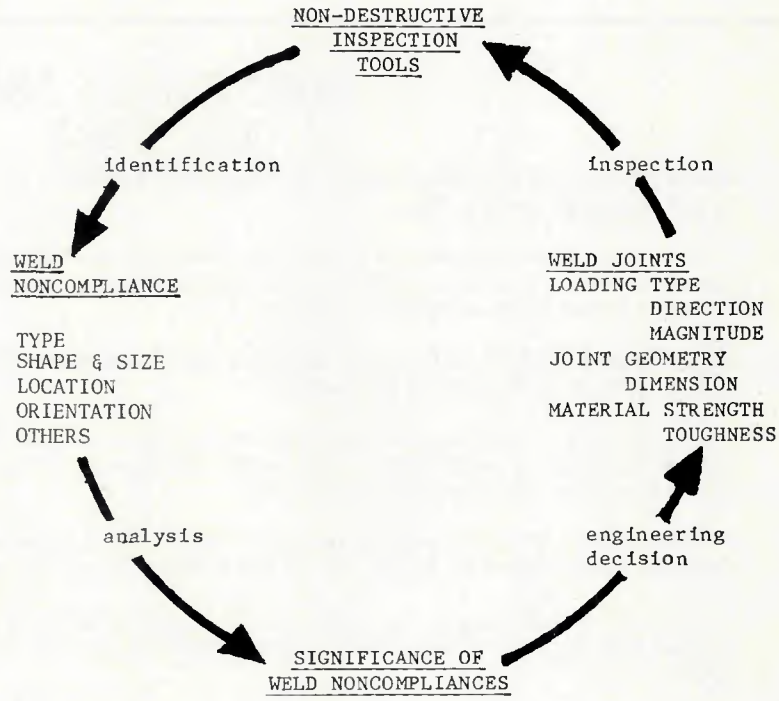

Fig. 1 — Study of fitness-for-service of welded joints

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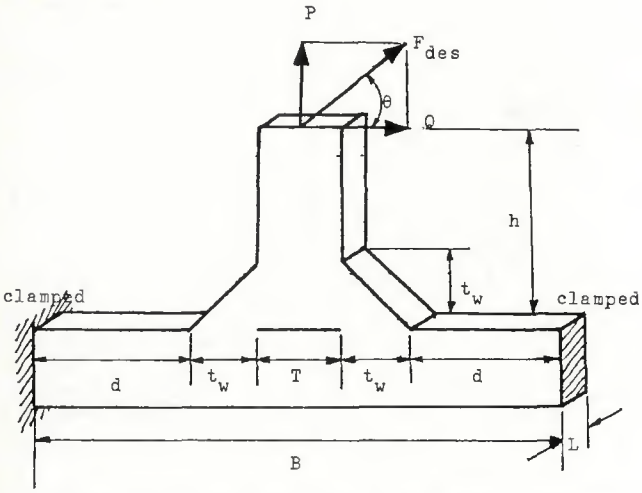


Fig. 2 — Specimen under study. Upper toe: toes at the vertical plate; lower toe: toes at the horizontal plate. Legend: t_W = ¾ in. (19 mm); T = 1 in. (25.4 mm); B = 8 in. (203 mm); h = 4 in. (102 mm); L = ¼ in. (6.4 mm); d = 2.75 in. (70 mm)

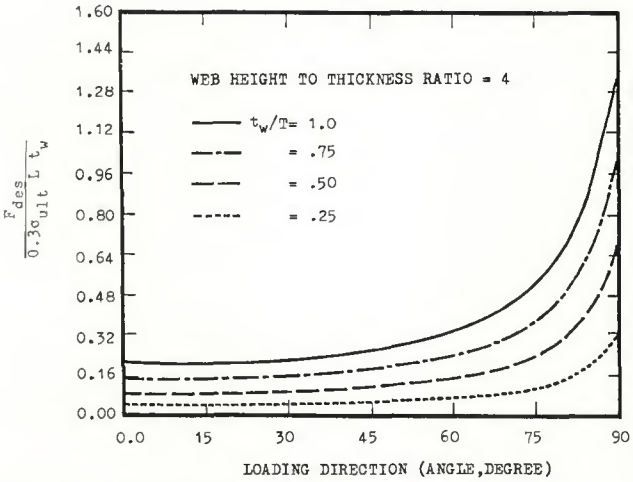


Fig. 3 — Typical welding design curves for T-joints

edge of the vertical (web) plate. The horizontal plate is clamped along its ends parallel to welds.

Any displacement in the direction transverse to the weld is prevented. The joint is free to move in the other two directions. Therefore, the joint can be assumed to be in a plane stress condition.

Figure 2 shows the schematic presentation of the isolated T-section studied. Two undercut locations at either upper or lower toe are also defined in Fig. 2.

AWS Design Code for Fillet Welded T-Joints

The code which governs the design of fillet welded joints is the AWS D1.1 *Structural Welding Code* (Ref. 1). Table 8.4.1 of this code specifies the allowable stresses for weld metal in fillet welded joints under static loading. The calculation of design load is based on the assumption that the throat of welds is the critical section. The criterion for weld size determination is to let the combined stress in the effective weld area (effective weld throat times joint length) be less than the allowable weld stress; this equals 0.3 times the ultimate tensile strength of weld metal as indicated by the electrode classification number. The equation correlating weld size and design load is (Ref 2):

$$\frac{F_{des}}{0.3\,\sigma_{ult}\,L\,T} = \left(\frac{t_w}{T}\right)\left\{\frac{1}{2} + X\,\mathrm{Sin}\,2\theta + 2\,X^2\,\mathrm{Cos}^2\theta\right\}^{-1/2} \qquad (1)$$

where X is a non-dimensional term, which is defined by:*

$$X = \frac{\left(\frac{h}{T}\right)\left(1+\frac{t_w}{T}\right)}{\frac{5}{12}\left(\frac{t_w}{T}\right)^2 + \left(\frac{t_w}{T}\right) + 1} \qquad (2)$$

Since the code does not allow the shear stress in the base metal adjacent to welds to exceed 40% of the base metal yield stress, the design load should also be governed by the following equation (Ref. 2):

$$\frac{F_{des}}{0.3\,\sigma_{ult}\,L\,T} \leq \frac{8}{3}\,\frac{F_y}{\sigma_{ult}}\,\frac{t_w}{T}\,\frac{1}{\beta} \qquad (3)$$

where F_y is the yield strength of base metal and β is sin θ or cos θ, whichever is larger.

The design load is also governed by the size of joint members. The governing criteria can be found in the AISC (American Institute of Steel Construction) specification and other relevant codes.

For a given value of X or weld size, the minimum design load occurs when the load is applied in a direction of:

$$\theta = \frac{1}{2}\,\mathrm{Tan}^{-1}\left(\frac{1}{X}\right) \qquad (4)$$

The angle of minimum design load decreases as h/T increases or t_w/T decreases. The maximum design load always occurs when the load applied is normal to weld (θ = 90 degrees). Typical design curves are shown in Fig. 3.

The maximum permissible undercut for building, according to the AWS code, is 1/16 in. (1.6 mm) regardless of the member thickness. The actual permissible undercut can be as small as 0.01 in. (0.25 mm) depending upon the member thickness and loading directions. In this study, for a 1 in. (25.4 mm) thick member, the permissible undercut values vary from 0.02 in. to 1/16 in. (0.51 to 1.6 mm). The code does not consider the shape effect of undercut on the permissible allowance.

Significance of Weld Undercut

Weld undercut can cause a welded joint to be unfit for service through three mechanisms:

1. Reduction of cross-sectional area. Undercut, in fact, reduces the cross-sectional area of welded joints. The net stress increase in the loaded joints is equivalent to the reduction of permissible design capacity. For ductile materials, the joints fail by shear if the applied load is beyond the joint capacity governed by the weld strength of the specimens under study.*

2. Local yielding. Local yielding at the tip of undercut is usually observed due to high stress concentration. Local yielding may not necessarily mean the deterioration of static joint strength. The constraint caused by the elastic material surrounding the small plastic zone at the tip of undercut keeps the joint integrity. In fact, if sufficient ductility exists in the joint, the plastic zone at the crack tip absorbs the strain energy and prevents the crack tip from propagation. Nevertheless, high stress concentration can cause fatigue crack initiation if the applied load is cyclic.

3. Brittle fracture instability. A crack may propagate under very low load if the material is brittle. For an extremely con-

See Fig. 2 for nomenclature.

Any double fillet welds in matching "base metal/weld metal" condition having a leg size equal to ¾ of the enclosed thickness develop the tensile capacity of the material and are considered full strength welds (Ref. 3).

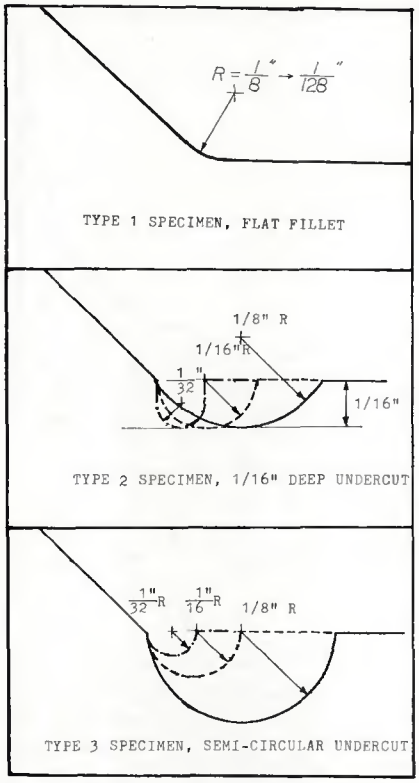


Fig. 4—Geometries of three types of specimens under study

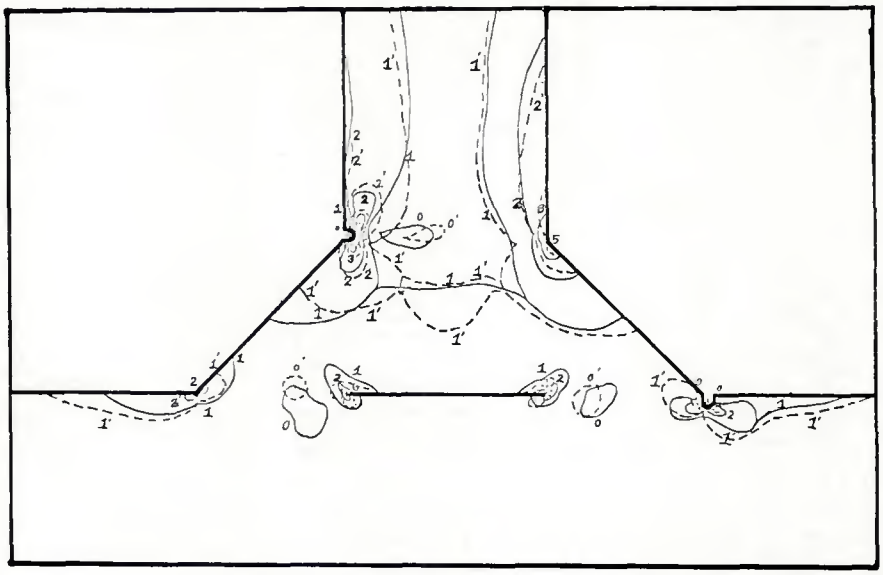


Fig. 5—Comparison of fringe lines of U-groove weld specimen under transverse load

Table 1—Description of Specimen under Study

Under cut type	Specimen designation[a]	Description[a]
1	F F1:⅛ in. radius F2:1/16 in. radius F3:1/32 in. radius F4:1/64 in. radius F5:1/128 in. radius	Flat fillet with toe radius varying from 1/128 to ⅛ in.
2	UG UG1:⅛ in. radius UG2:1/16 in. radius UG3:1/32 in. radius	1/16" deep U-grooves radius varying from 1/32 to ⅛ in.
3	CG CG1:⅛ in. radius CG2:1/16 in. radius CG3 1/32 in. radius	Semi-circular grooves radius varying from 1/32 to ⅛ in.

(a) 1 in. = 25.4 mm.

servative analysis, an undercut may be treated as a sharp crack in order to determine the brittle fracture instability. For ductile materials at temperatures above their Nil Ductility Transition (NDT) temperature, brittle fracture instability is usually not considered.

Finite Element Analysis of Undercut

Types of Specimens Under Study

In this paper, full strength fillet welds are analyzed. The effect of undercut, due to loss of cross-sectional area or stress concentration, is studied by analyzing two types of undercut specimens. They are:

1. U-shape undercut (U-groove), 1/16 in. (1.6 mm) deep.
2. Semi-circular undercut (C-groove).

The tip radii of the grooves varied from ⅛ to 1/32 in. (3.2 to 0.8 mm). The depth of C-groove undercut specimens depended on the radius of the undercut tip. The depth of undercut represented the amount of reduction in the cross-sectional area, and the tip radius of undercut represented the acuity of the discontinuity.

Figure 4 shows the graphical presentation of the types of weld undercut studied in this paper. The flat fillet specimen (without undercut) was also studied. This was to generate reference information on flat fillet welds with various toe radii and, hence, stress concentration sensitivities. The three types of specimens are listed in Table 1.

In order to determine the stress field in welded joints with good accuracy, finite element idealization procedure (Ref. 4) was studied to create optimum mesh patterns. Photoelectric measurements were conducted to calibrate the mesh refinement. Figure 5 shows a typical comparison of stress (fringe) lines between the calculated and measured values. The calculated general stress field in a T-joint is in reasonably good agreement with the photoelastic results. The photoelastic fringe lines represent the true stress distribution in the T-joint specimen under the given loading condition.

Stress Characteristics of Weld Undercut

Weld undercut affects the integrity of the joint according to its size, shape and location with respect to the loading directions. To characterize the effects of undercut, three variables, each with its own physical significance, were determined in this study. They were stress concentration factor, stress concentration variable, and Von Mises stress distribution:

Stress Concentration Factor (SCF). Stress concentration factor is an indication of local stress sensitivity of undercut to the applied load. It is defined as the ratio of actual stress at undercut to local nominal stress. Nominal stress is the theoretical stress at the undercut location caused by the same load without any change in surface direction. Nominal stress can, therefore, vary at different locations in a fillet specimen.

The stress concentration factor can be written in the following mathematical expression:

$$SCF = \frac{\sigma}{\sigma_{nom}} \quad (5)$$

where σ is the actual stress at the point of interest (*i.e.,* undercut) and σ_{nom} is the nominal stress at the same location. For the joint dimensions specified in Fig. 2, the nominal stresses are given as follows (Ref. 5):

At upper toes:

$$\sigma_{nom} = \frac{1}{LT}\left\{\frac{6\,Q\,(h - t_w)}{T} + P\right\} \quad (6)$$

At lower toes:

$$\sigma_{nom} = \frac{1}{LT} \quad (7)$$

$$\left\{Q + \frac{6Qh}{BT}\left(\frac{3}{2}d - \frac{B}{4}\right) + \frac{3P}{T}\left(d - \frac{B}{4}\right)\right\}$$

where P and Q are two components of the applied load at given angle.

Stress Concentration Variable (SCV). Stress concentration variable is defined as:

$$SCV = \frac{\sigma}{\sigma_{ref}} \quad (8)$$

where σ is the actual stress at the point of interest (*i.e.,* undercut) and σ_{ref} is a reference stress value which is independent of location. Therefore, stress concentration variable reflects the relative stress magnitude at a given point in the overall stress field of fillet joints.

The reference stress is defined as follows:

$$\sigma_{ref} = \frac{\text{Total Applied Load}}{\text{AWS Design Load}} \times (0.3\ \sigma_{ult}) \quad (9)$$

where σ_{ult} is the ultimate tensile strength of weld metal.

Physically, the reference stress is (for a given fillet welded T-joint with a known weld size) the net stress in the effective weld area proportional to the AWS allowable stress depending upon the load ratio. As defined in equation (1), the weld stress reaches the AWS allowable value ($0.3 \times \sigma_{ult}$) when the design load is applied to the joint. Therefore, the actual applied load is expressed as a percent of the design load and the reference stress can therefore be expressed by equation (9).

Von Mises Stress Distribution. Local yielding usually occurs at fillet toes, with or without undercut, when a fillet welded T-joint is loaded to its design load. This phenomenon is due to high stress concentration at fillet toes.

As discussed previously, local yielding may not be detrimental to the overall integrity of the joint. However, the unyielded area between two yielded zones represents the strength reserve of a fillet joint under its design load. Furthermore, the progressive expansion of the yielded zone in a joint as the load increases characterizes the ductile mode of joint failure. Von Mises stress distributions under various load magnitudes present such characterization.

Results and Discussion

Local Stress Sensitivity at Fillet Toes—SCF

Factors Affecting SCF Notch Acuity. Four factors are involved as discussed below:

1. Notch acuity. The sharpness of toe or undercut plays a dominant role in stress concentration factor. Figure 6 shows the relationship between SCF and radius of undercut at lower toe. Stress becomes infinitely large in theory when the toe contains an infinitely sharp corner. The SCF at both upper and lower toes increases with the decrease of

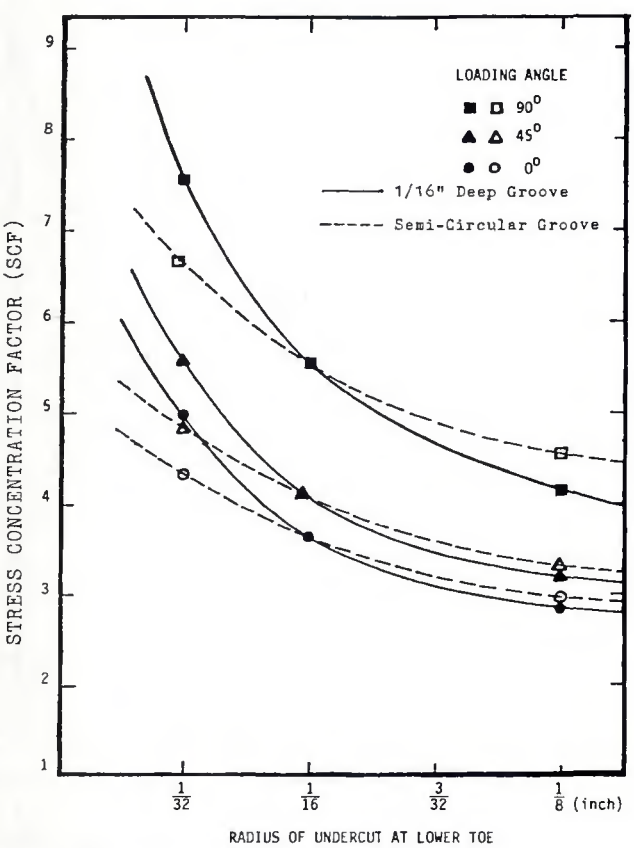


Fig. 6 — SCF vs. undercut tip radius and depth

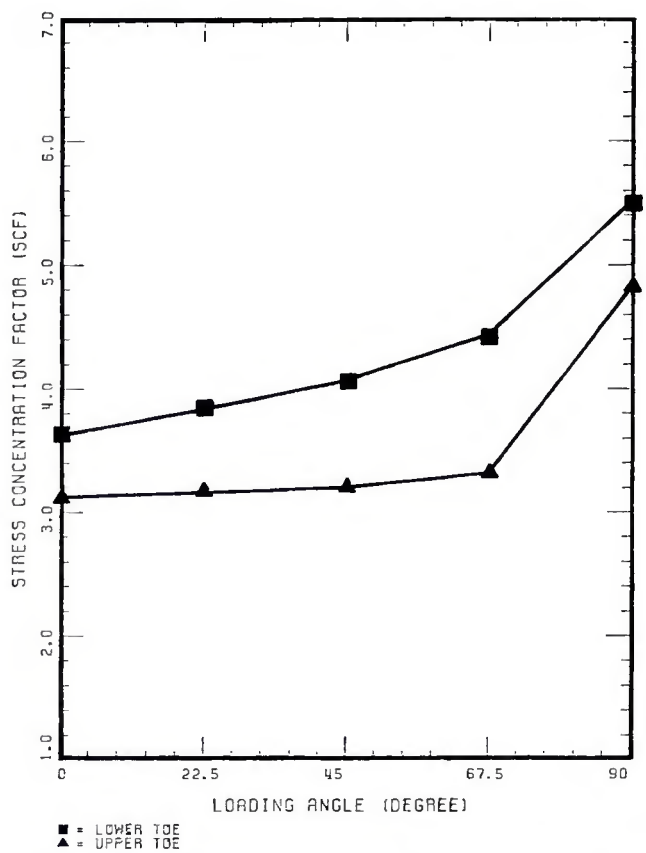


Fig. 7 — SCF vs. loading angle of a specimen with 1/16 in. (1.6 mm) radius semi-circular undercut

undercut tip radius.

2. Reduction of cross-sectional area. Basically, undercut will cause local stress concentration, since the depth of undercut reduces the cross-sectional area of base metal. Figure 6 also shows another implication in local stress sensitivity of two types of undercut at fillet toes. The difference in SCF values between two types of undercut at a given loading angle shows the stress increases due to loss of cross-sectional area. For example, the C-groove undercut having ⅛ in. (3.2 mm) radius has higher stress concentration sensitivity than the 1/16 in. (1.6 mm) deep U-groove with the same tip radius (⅛ in. or 3.2 mm).

The solid lines in Fig. 6, which show the stress concentration sensitivity of constant depth (1/16 in. or 1.6 mm) U-grooves with various tip radii, reflect the effect of groove tip acuity. The SCF value of the U-groove undercut decreases at a rather fast rate as the tip radius increases. The C-groove undercut also shows a decreasing trend in SCF with increasing tip radius but at a slower rate. This leads to a conclusion that the groove tip acuity plays a more significant role in the local stress concentration than the reduction of cross-sectional area.

It is anticipated that the SCF value will reach a minimum and rise again when the lower toe radius of C-groove undercut goes beyond a certain limit. In this situation, reduction of cross-sectional area becomes a more dominant factor. For the T-joint specimens under study, the limiting undercut size is ⅛ in. (3.2 mm) deep. Since the AWS code allowance for weld undercut size is only 1/16 in. (1.6 mm) in depth, the local stress sensitivity of these undercuts of practical interest is primarily due to the tip acuity rather than the loss of cross-sectional area.

3. Loading direction. Figure 7 shows the stress concentration factors of flat fillet specimens at both toes. It demonstrates that the highest stress occurs when the load is applied at a 90 deg angle (vertical pulling). It drops quickly and reaches the smallest value when the load is at a 0 deg angle (transverse shear). This leads to the conclusion that the local stress sensitivity at fillet toes increases as the loading angle changes from transverse shear to vertical pulling at an accelerated rate when approaching the 90-degree loading angle. This phenomenon has been observed for all specimens, with or without undercut, in the study reported here.

4. Location of undercut. The results from the stress concentration analysis also show the relative sensitivity of toe locations. The lower toe, with or without undercut, appears to be more sensitive to stress concentration. A typical example is shown in Fig. 7.

Comparison of SCF with Photoelastic Results. A photoelasticity study of weld undercut conducted by Fairchild (Ref. 5) has led to similar conclusions regarding finite element analysis. Fairchild measured stress concentration factor for three T-joint specimens having flat fillets, 1/16 in. (1.6 mm) deep U-groove undercut with 1/32 in. (0.8 mm) tip radius, and 1/16 in. (1.6 mm) deep V-groove undercuts, respectively. The V-groove weld specimen had highest stress concentration due to sharp tip. It was followed by the flat fillet specimen without any undercut. The U-groove weld undercut had the smallest stress concentration. This observation has been verified by the finite element analysis in this study.

Figure 8 shows the calculated stress concentration factor values at lower toe of three T-specimens under various loading angles. The three T-specimens were:

1. UG2 specimen, fillet with undercut having 1/16 inch (1.6 mm) tip radius and depth.

2. F4 specimen, flat fillet without undercut having 1/64 inch (0.4 mm) toe radius.

3. F1 specimen, flat fillet without undercut having ⅛ inch (3.2 mm) toe

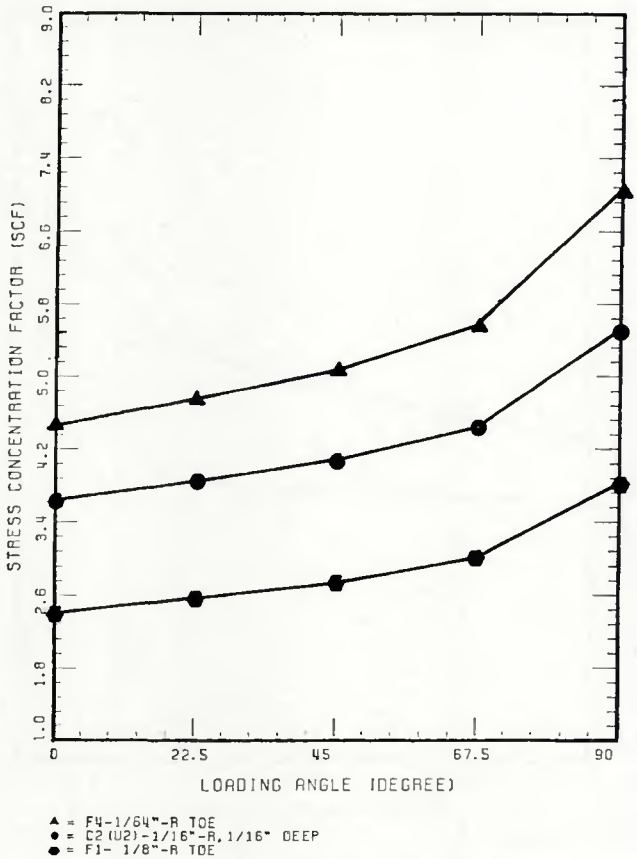


Fig. 8—Relative severity in stress concentration of groove weld undercuts and flat fillet weld specimens

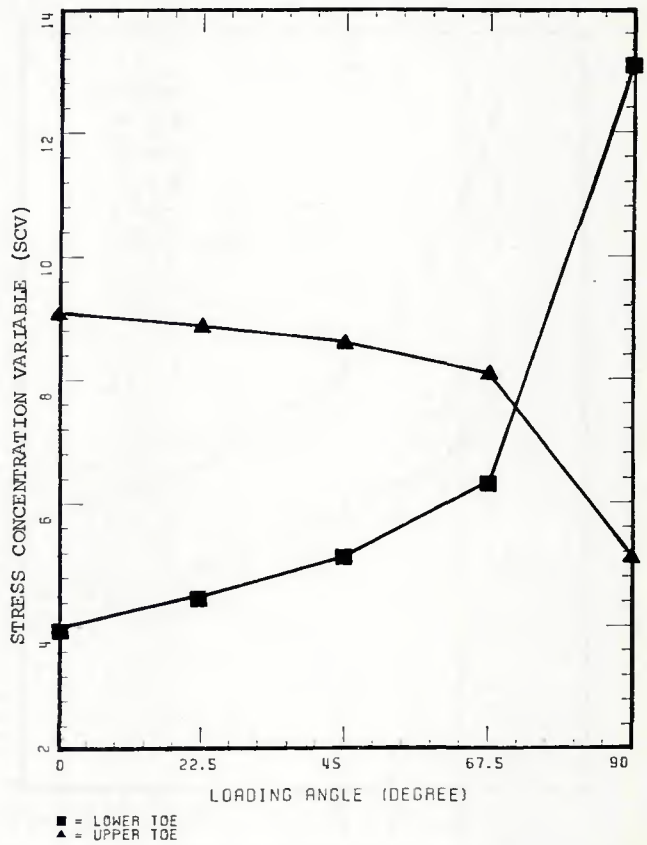


Fig. 9—SCV vs. loading angle of a specimen with 1/16 in. (1.6 mm) radius semi-circular undercut

radius.

It is clearly shown that an undercut with large tip radius may, in fact, reduce the stress concentration when compared to the flat fillet with very small toe radius due to the relaxation of toe acuity, even though some loss of cross-sectional area still exists.

Stress Magnitude at Fillet Toes—SCV

As defined earlier, the stress concentration variable (SCV) reflects the stress magnitude of a point. The relative stress level at this point can be compared with the overall stress field of the fillet specimen. To evaluate the significance of undercut, the SCV value at undercut location is more important than SCF value if the welded joint is statically loaded and the material is assumed ductile.

The effects of the acuity and reduction of cross-sectional area on SCV are the same as those on SCF. Figure 9 shows the typical relationship between SCV and various loading angles at upper and lower toes in a specimen with a 1/16 in. (1.6 mm) C-groove undercut. Highest stress occurs at the lower toe when the load is at a 90 deg angle and lowest stress occurs at a 0 deg loading angle. However, the change of stress magnitude at the upper toe with various load angles is just in the opposite sense. This suggests that the severity of undercut depends on its location with respect to the loading directions.

Von Mises Stress Distribution in Fillet Joints

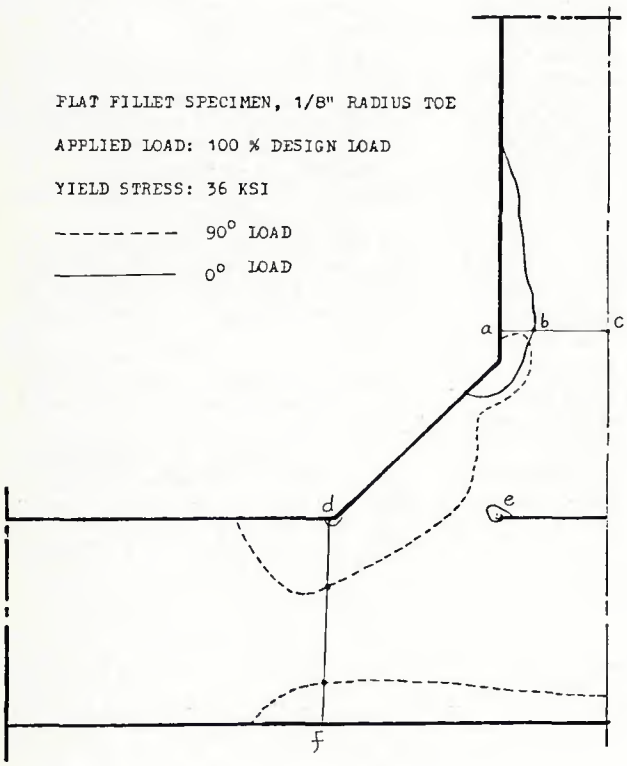
Figure 10 shows the yielded area in a flat fillet weld specimen (no undercut and 1/8 in. (3.2 mm) to radius) under 100% design load at 0 and 90 deg loading directions. The majority of the yielding area appears in the vertical web plate around the upper toes when the load is at 0 deg loading angle. It is expected that the plastic hinge would be formed in the web plate right above two upper toes if the collapse load was applied. Taking the ratio of the plastic zone size (ab) to the web plate dimension (ac), the reserve of joint strength at 100% design load could be at least twice as much as the design load and the fracture in ductile mode would occur in the web plate.

When the load is applied by vertical pulling of the web plate (90 deg loading angle), a rather large yielded area appears in the joint under 100% design load. The standard design procedure, as discussed early in this paper, considers only the normal stress in welds and shear stress in base metal without any justification of bending of the flange plate. A much higher load is permitted at the 90 deg loading angle (see Fig. 3). The plastic zones surrounding the lower toes and covering a large portion of the fillet area and the flange plate, therefore, appear under 100% design load.

The collapse load could be less than 150% design load, and the fracture in ductile mode could occur either in the fillet area connecting the lower toe and the root of fillet (de) or in the flange plate along (df) plane. It must be pointed out that, theoretically, the bending effect could be reduced by improving the flange rigidity, (*i.e.,* increase the flange thickness or move the clamps closer to the fillet). The yielded area could be reduced, and the joint strength could be improved. For a particular case without any flange bending (*i.e.,* infinitely thick flange plate), the fracture plane has been proved to be at a 67.5 deg angle from (de) in the fillet (Ref. 6).

When undercut exists at fillet toes and the specimen is subjected to the design load, some local disturbances in the shape of the yielded area have been observed for all types of undercut specimens under study. Due to undercut, the size of yielded area in the T-joint specimens expands to a limited degree, but the general shape of the yielded areas remains pretty much unchanged.

Figure 11 shows the yielded area in the fillet specimen under 100% design load at a 90 deg loading angle. The broken lines represent the case of 1/16 in. (1.6 mm) deep undercut having 1/8 in. (3.2 mm) tip radius at the fillet toes, and the solid lines represent the same type of undercut but with 1/32 in. (0.8 mm) tip radius. Similar conclusions for other loading directions have been observed.



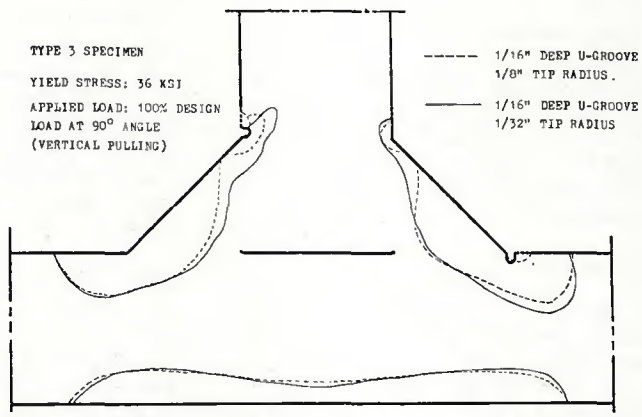


Fig. 11—A comparison of plastic zone size and shape in a fillet welded T-joint with undercut at 90 deg loading angle

Fig. 10 (left)—The calculated yielding area in a fillet welded T-joint (without undercut) at 0 and 90 deg loading angles

Since any practical joint could be at a triaxial state of stress, the actual plastic zone could be smaller than what we have calculated in this two-dimensional analysis. As defined previously, this paper has studied T-joints with full strength fillet welds only. Under such circumstances any undercut (within ⅛ in. (3.2 mm) depth limitation in 1 in. (25.4 mm) thick base metal) would not effectively alter the integrity of the joint under static load if the conventional design procedure is followed.

Concluding Remarks

Study Limitations

In any summary of this study, several constraints on the applicability of the information presented in this paper must be restated:

1. The results from this study should refer to the fillet model defined in the paper and the joint dimensions shown in Fig. 2. The maximum depth of undercut is ⅛ in. (3.2 mm), and the base metal thickness is 1 in. (25.4 mm). The fillet size reflects the full strength weld (¾ of the member thickness). The applied load is static and always lies in the plane of the cross-section (*i.e.,* longitudinal shear force is not considered).

2. The analysis of local yielding by finite element method in this study was limited to the linear elastic range; the yield strength of base metal and weld metal is assumed equal to 36 ksi (248 MPa). Also, the calculated plastic zone size is conservative, because the lateral constraints due to the joint length are not considered in the analysis. Stress redistribution and strain hardening due to plasticity are not incorporated in the analysis. This may result in actual welds showing greater ultimate strength than calculated herein.

3. The joint material is assumed to be ductile in service environmental conditions, and brittle fracture instability is not considered.

Conclusions

Undercut flaws on fillet welded T-joints can be related to three significant variables: size, shape, and location:

1. Undercut size. The size effect is reflected by the loss of cross-sectional area which is insignificant when compared to the shape effect.

2. Undercut shape. High stress concentration is expected when the toe radius of a flat fillet or the tip radius of an undercut is small. An undercut with relatively large tip radius does not necessarily mean higher stress concentration than encountered with a flat fillet having sharp toes. Rounded undercut, in fact, reduces the acuity of fillet toe and relaxes the stress concentration.

3. Undercut location. The upper toes are subjected to higher stress when the load is applied at lower angles (from 0 to 70 deg). The high stress location shifts toward the lower toes when the load angle becomes larger than 70 deg. At a 90 deg loading angle, the highest stress appears at the lower toes. This implies that any undercut existing at noncritical fillet toes will not affect the joint integrity in any form.

Design Precautions for Fillet Welds

The precautions to be observed when considering fillet weld design are as follows:

1. When a fillet welded T-joint is loaded at higher angles (*e.g.,* vertical pulling), the calculated design load is very high—Fig. 3. Meanwhile, under such loading conditions, the lower toe is most sensitive to stress concentration. The local stress magnitude could also be far beyond the permissible value under low load due to high SCP response. Special precautions must be kept in mind, if the member is subjected to any dynamic or repeated loads.

2. The significance of undercut should be properly evaluated as to location with respect to the loading directions. Design precautions should be considered only if undercut appears in the critical area of high SCV response. Any undercut, within the size limitation specified in this paper, outside the critical area may be accepted. (At high loading angles, the lower toe area is considered to be critical; at lower loading angles, the upper toe area is considered to be critical.)

3. Regarding the strength reduction due to undercut, the results described in this paper suggest that the effect of undercut is insignificant when compared to loading directions. Of course, when an undercut exists in a critical condition of loading and location combined, design precautions must be considered.

4. The ratio of plastic zone size to the proper joint dimensions is a measure of reserve strength of a fillet joint. The reserve factors (analogous to safety factors) for flat fillet joints designed by equations (1) through (3) are discussed in a relative rather than absolute sense in this paper.

A fillet joint under design load within a wide range of loading angles shows large reserve factors. The reserve factors are reduced to a relatively small value when loading at a 90 deg angle. This clearly indicates that design equation (1) does not provide a consistent means for fillet weld design at various loading angles.

The results from this study seem to suggest that the code is liberal when fillet joints are loaded at a 90 deg and is conservative at other loading directions. A question may arise whether the fillet joint under design load at a 90 deg angle might still be fit for service, or whether there is still ample reserve to provide coverage against other uncertainties. Special design precautions under such circumstances should be considered. Fracture tests would be necessary for a satisfactory answer.

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