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INFLUENCE OF WELD GEOMETRY ON CYLINDRICAL WELDED JOINT LIFE

UTICAJ GEOMETRIJE ŠAVA NA VEK CILINDRIČNIH ZAVARENIH SPOJEVA

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Ključne reči
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- ugaoni spoj
- faktor intenziteta napona
- radni vek
- otpornost na lom

Abstract

Weld geometry influence on the fracture mechanics parameters of a cylindrical welded joint subjected to combined load is considered in this paper. Three shapes of fillet welds are analysed: triangular, rounded convex, and concave. Stress intensity factors (SIF) are calculated analytically, based on the Linear Elastic Fracture Mechanics (LEFM) concept. Existence of the weld and load are taken into account through corresponding correction factors. In the case of the triangular fillet weld, the normalized Mode I stress intensity factor decreases with crack length, while the normalized Mode III stress intensity factor increases. The same is valid in the case of a convex fillet weld. In the case of the concave fillet weld, both stress intensity factors increase with crack length. Based on the obtained results, it is concluded that with respect to the fracture resistance, the convex fillet weld exhibits the best properties.

Izvod

U ovom radu se razmatra određivanje uticaja geometrije šava na parametre mehanike loma cilindričnih zavarenih spojeva izloženih kombinovanom opterećenju. Analizirana su tri oblika ugaonih šavova: trouglasti, zaobljeni konveksni i konkavni. Faktori intenziteta napona (FIN) su izračunati analitički, na osnovu koncepta Linearne Elastične Mehanike Loma (LEML). Postojanje šava i opterećenje su uzeti u obzir preko odgovarajućih korekcionih faktora. U slučaju trouglastog ugaonog šava, normalizovan faktor intenziteta napona za Mod I opada sa povećanjem dužine prsline, dok normalizovani faktor intenziteta napona za Mod III raste. Isto važi i za konveksni ugaoni šav. U slučaju konkavnog ugaonog šava oba faktora intenziteta napona rastu sa povećanjem dužine prsline. Na osnovu dobijenih rezultata je zaključeno da, s obzirom na otpornost na lom, najbolje osobine ima konveksni ugaoni šav.

INTRODUCTION

In assembling various structures, welding is one of the most used techniques for joining structural elements. The resistance of welded joints is very important for structural integrity. There are several factors that influence welding joints' resistance: the quality of the weld, cleanliness of the parts' surfaces prior to welding, temperature control of the environment before and after the welding, as well as geometrical discontinuities. Those discontinuities are the weld root, weld radius and absence of overlap between the parts that are being welded. All those factors directly influence the resistance of the weld and in its immediate vicinity. The fatigue crack could also develop in that area. Geometrical discontinuities intensify the local stress field and in that way they cause a decrease in the load carrying capacity of welded joints, and subsequently of the whole structure. That in turn causes a significant decrease of the welded structure's safety and reliability.

The fatigue fracture is probably the most frequent type of facture of welded structures. The weld geometry is one of the primary factors that control fatigue life. Fatigue cracks can appear in the welded joint, starting from some of the imperfections which are actually the inherent part of the weld. Fracture mechanics can be applied to describe the fatigue crack growth in the welded joint. Improvement of the fatigue life, related to the weld geometry control, can be achieved by decreasing the stress concentration within the weld, since the geometrical parameters of the weld directly influence the stress intensity factor of the crack existing in the weld. Determination of the fatigue life of the welded structure and analysis of fatigue crack propagation based on the fracture mechanics concept requires exact calculation of stress intensity factors.

When parts are joined by fillet welds, a certain surface appears where there is a geometrical discontinuity. When two structural parts, which are to be welded, are leaned against each other, the filler metal (electrode) creates a fillet weld. The face surface of the thinner part is not connected to the surface of the thicker part, Fig. 1. It behaves like a crack whose size is equal to thickness of the thinner material.

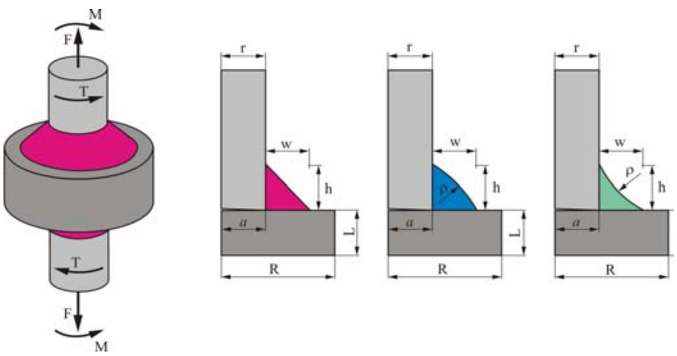

Figure 1. Fillet welds in cylindrical parts; loading and geometry.

A certain number of researchers has dealt with problems of welded joint resistance from the fracture mechanics point of view. Atzori et al. have investigated the possibility of unifying various criteria used for analysing the fatigue strength of welded joints, based on the influence of the geometry on the local stress field and prediction of residual working life by applying linear elastic fracture mechanics, /1/. Motarjemi et al. have analysed the influence of the geometry of the main- and attachment plates in T- and cruciform welded joints exposed to tension, /2/. Lee et al. have considered the influence of the geometry on the fatigue life of non-load-carrying cruciform fillet welds, /3/. Baik et al. have conducted an analysis of fatigue crack propagation in welded structures exposed to bending, /4/. Chattopadhyay et al. proposed a method that enables the determination of stress concentration and stress distribution in the area of the weld root by using the special shell technique of the finite element method, /5/. Shen and Choo have determined the stress intensity factor of welded tubes exposed to tension, /6/. More details can be found in /7/.

Influence of fillet weld shape and geometry on fracture resistance of cylindrical structural elements is considered in this paper. This is done by determination of stress intensity factors with the application of the Linear Elastic Fracture Mechanics concept (LEFM). The considered problem is presented in Fig. 1. The axle of radius r is welded to a disk of radius R and length L. The welded cylindrical part is loaded by axial tensile force F, bending moment M and torque T. In Fig. 1, one can notice the unwelded area between the two parts of diameter $2a$. This is a geometric discontinuity, considered as a crack. The weld dimensions are height h and width w.

DETERMINATION OF SIF

The stress and displacement fields at the crack tip are characterized by stress intensity factors, $K_{\rm I}$, $K_{\rm II}$ and $K_{\rm III}$:

$$K_{\rm I} = \lim_{r\to 0}\sqrt{2\pi r}\sigma_{\theta\theta},\ K_{\rm II} = \lim_{r\to 0}\sqrt{2\pi r}\sigma_{r\theta},\ K_{\rm III} = \lim_{r\to 0}\sqrt{2\pi r}\sigma_{\theta z} \quad (1)$$

for $\theta = 0$, where r and θ are the polar coordinates with the coordinate frame origin at the crack tip.

The stress intensity factor depends on the shape of the part and on loading conditions. For calculating stress intensity factors, one needs to determine the complete stress field at the crack tip and to calculate the limit values from Eq.(1). Since this takes too much time for practical applications, other approaches are usually used.

For welded joints, stress intensity factors are obtained:

$$K_i = Y_i C_i \sigma_0 \sqrt{\pi a}, \quad (2)$$

where σ_0 is the referential load (axial tension, bending or torsion); Y_i is the dimensionless parameter which depends on sample geometry and applied load; while C_i represents the correction factor which takes into account the stress concentration due to the existence of the weld.

Axial tension and bending in general, require different correction factors, so Eq.(2) can be written in the form:

$$K_i = (Y_t C_t \sigma_t + Y_b C_b \sigma_b)\sqrt{\pi a}, \quad (3)$$

where: σ_t is the normal stress; Y_t and C_t are correction factors in tension; and σ_b is the bending stress; while Y_b and C_b are correction factors in bending.

As for the problem presented in Fig. 1, axial tension and bending dominantly influence the Mode I stress intensity factor $K_{\rm I}$, while their influence of Mode II stress intensity factor is negligible and is not considered in this paper. Torsion influences the Mode III stress intensity factor $K_{\rm III}$.

Mode I stress intensity factor, for the problem shown in Fig. 1, based on Eq.(3) can be written as:

$$K_I = \left[Y_F C_F F + Y_M C_M \frac{4Ma}{(r^2+a^2)} \right] \frac{\sqrt{(r-a)/r}}{\pi(r^2-a^2)} \sqrt{\pi a}, \quad (4)$$

where correction factors for tension and bending are:

$$Y_F = \frac{2}{\pi}\left[1 + \frac{1}{2}(a/r) - \frac{5}{8}(a/r)^2 + 0.268(a/r)^3 \right], \quad (5)$$

$$C_F = \left[1 + 2.2\left(\frac{1}{2.8(1+4(h/r)+0.3(L/r)+0.6(w/r))-2}(1-h/\rho) \right)^{0.65} \right] \cdot \left[1 + 0.64\frac{(a/r)^2}{2w/r} - 0.12\frac{(a/r)^4}{(2w/r)^2} \right], \quad (6)$$

$$Y_M = \frac{4}{3\pi}\left[1 + \frac{1}{2}(a/r) + \frac{3}{8}(a/r)^2 + \frac{5}{16}(a/r)^3 - \frac{93}{128}(a/r)^4 + 0.483(a/r)^5 \right], \quad (7)$$

$$C_M = \left[1 + \sqrt{\tanh\left(\frac{2L}{r+2h}\right)\cdot \tanh\left(\frac{(2h/r)^{0.25}}{1-\rho/r}\right)\cdot\left(\frac{0.13+0.65(1-\rho/r)^4}{1+\sqrt[3]{\rho/r}}\right)} \right] \cdot \left[1 + 0.64\frac{(a/r)^2}{2w/r} - 0.12\frac{(a/r)^4}{(2w/r)^2} \right]. \quad (8)$$

Mode III stress intensity factor, for the problem shown in Fig. 1, based on Eq.(2), can be written as:

$$K_{\rm III} = Y_T C_T \frac{2Ta\sqrt{(r-a)/r}}{\pi(r^4-a^4)}\sqrt{\pi a}, \quad (9)$$

where the corresponding correction factors are:

$$Y_T = \frac{4}{3\pi}\left[1+\frac{1}{2}(a/r)+\frac{3}{8}(a/r)^2+\frac{5}{16}(a/r)^3-\frac{93}{128}(a/r)^4+0.038(a/r)^5\right], \quad (10)$$

$$C_T = \left[1+\sqrt{\tanh\left(\frac{2L}{r+2h}\right)\cdot\tanh\left(\frac{(2h/r)^{0.25}}{1-\rho/r}\right)}\right]\cdot\left[1+0.64\frac{(a/r)^2}{2w/r}\right] \quad (11)$$

WELDED JOINT LIFE

Unstable crack growth would appear when the stress intensity factor K_I is larger than the experimentally determined material characteristics, the fracture toughness K_{Ic}. The crack growth equation provides the relationship between the crack length extension Δa and increase of the number of load cycles, ΔN. Paris and Erdogan have established that the change of the stress intensity factor can describe the subcritical crack growth in fatigue loading conditions in the same way as the stress intensity factor describes the critical or fast fracture, /8/. They determined that the crack propagation speed is a linear function of the stress intensity factor in the logarithmic diagram, i.e.:

$$\frac{da}{dN} = C(\Delta K)^m, \quad (12)$$

where: a is the crack length that changes from the initial value to critical, leading to fracture; N is the number of load cycles; C and m are material constants; and $\Delta K = K_{max} - K_{min}$ is the change of stress intensity factor (i.e., the difference between the stress intensity factor at maximal and minimal load).

The residual working life is obtained by integration of Eq.(12):

$$N = \int_{a_i}^{a_{cr}} \frac{da}{C(\Delta K)^m}, \quad (13)$$

where: a_i is the initial crack length; and a_{cr} is the critical crack length.

It is usually considered that the fatigue crack growth period is practically the whole working life of the welded joint, since it is believed that the period of the initial crack growth is relatively short for welded joints. The duration of the fatigue crack growth depends on the load and on weld geometry. It affects the working life of the welded joint in such a manner that it increases when the applied cycling load decreases; by increasing it causes an increase of the total life of the welded joint.

RESULTS AND DISCUSSION

Figure 2 shows the normalized Mode I stress intensity factor variation in terms of the normalized crack length, for three different fillet weld geometries, determined by analytical expression, Eq.(4), and by application of the symbolic programming routine *Mathematica*®. The normalization factor for the Mode I stress intensity factor is 1 MPa$\cdot\sqrt{\pi 0.01}$ m. The dimensions and loads are $h/r = w/r = 1$, $F = 1$ kN, $M = 1$ kNm. Material properties are $E = 210$ GPa and $\nu = 0.3$.

From Fig. 2 one can see that the normalized Mode I stress intensity factor is almost constant, with a small decrease as the crack length increases for the triangular and convex fillet welds, while for the concave fillet weld, it increases with crack length.

Figure 3 shows the normalized Mode III stress intensity factor variation in terms of normalized crack length for three different fillet weld geometries, determined by analytical expression, Eq.(9), and by application of the symbolic programming routine *Mathematica*®. Normalization factor for Mode III SIF, the dimensions, loads and material properties are the same as above.

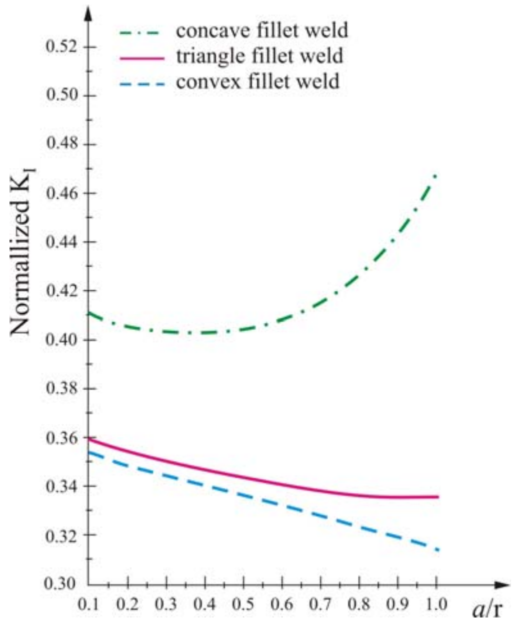

Figure 2. The normalized Mode I SIF vs. normalized crack length.

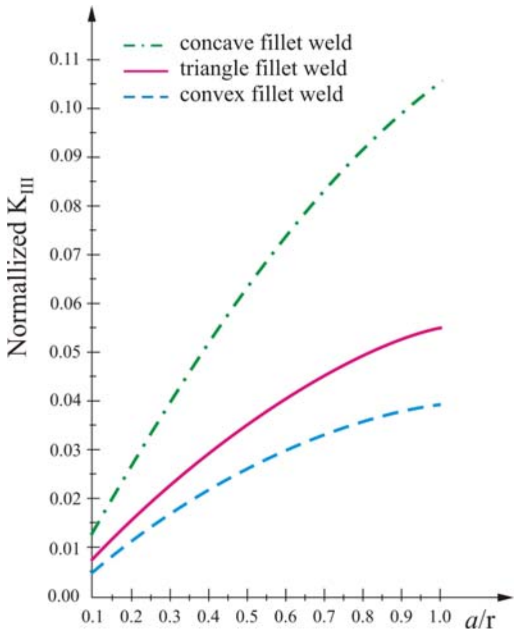

Figure 3. Normalized Mode III SIF vs. normalized crack length.

From Fig. 3, one can notice that the normalized Mode III stress intensity factor increases with crack length for all three shapes of the fillet welds. From Figs. 2-3 one can conclude that the convex weld has the highest fracture resistance.

In Fig. 4 the change of Mode I stress intensity factor $\Delta K = K_{max} - K_{min}$ is presented in terms of crack length, for three different fillet weld geometries. It is taken that $h/r = w/r = 1$. The bending moment is constant and it amounts to $M = 1$ kNm. Axial force changes from $F_{min} = 1$ kN to $F_{max} = 10$ kN. Material properties are $E = 210$ GPa, and $\nu = 0.3$.

Based on Figs. 4 and 5 it can be concluded that the convex fillet weld has the highest fracture resistance in the case of cyclic loading, as well.

Figure 5 shows the variation of crack length in terms of number of load cycles, based on Eq.(13) for three different weld geometries. It is taken that $h/r = w/r = 1$. The bending moment is constant and it amounts to $M = 1$ kNm. The axial force changes from $F_{min} = 1$ kN to $F_{max} = 10$ kN. Material properties are $E = 210$ GPa and $\nu = 0.3$, while the material constants necessary for calculating the life are: $m = 3$, $C = 2.974 \times 10^{-10}$.

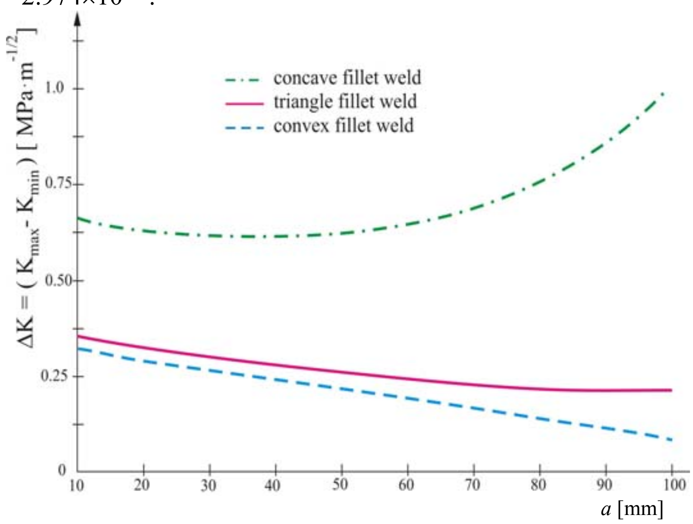

Figure 4. Variation of $\Delta K = K_{max} - K_{min}$ with crack length for $F_{min} = 1$ kN to $F_{max} = 10$ kN.

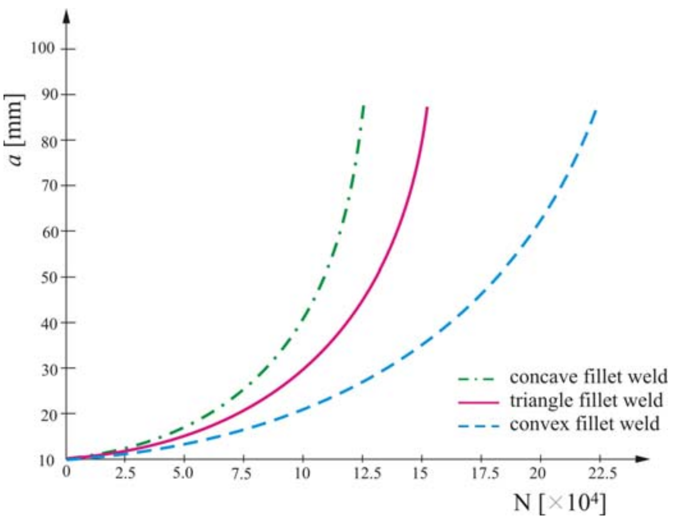

Figure 5. Fatigue crack growth curve: crack length vs. number of load cycles, a vs N.

CONCLUSION

In this paper the welded joints of two cylindrical parts with three different fillet weld shapes are analysed: triangular and rounded convex and concave. The welded joints are subjected to combined loading consisting of axial tensile force, bending moment and torque. The normalized Mode I stress intensity factor decreases with crack length, while Mode III stress intensity factor increases with crack length both for cases of triangular and convex fillet welds. For the case of concave weld, both stress intensity factors increase with crack length.

From the aspect of fracture resistance, the best characteristic is found for the rounded convex fillet weld. The same conclusion can be drawn from the case of the cyclic loading of fillet welds.

ACKNOWLEDGEMENT

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