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Three-dimensional weld toe magnification factors for various welded joints[†]

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Abstract

To effectively calculate the stress intensity factors in welded components, a weld toe magnification factor is introduced here that will allow for the influence of geometrical effects. This factor was derived from the data obtained in a parametric study performed by FEM. Several sets of weld toe magnification factor solutions have been presented, but these are applicable only to non-load-carrying cruciform or T-butt joints, due possibly to the requirement of very complicated calculations. In the majority of cases for various welded joints such as cruciform, cover plate and longitudinal stiffener joints, the currently used weld toe magnification factors do not adequately describe the behavior of weld toe cracks. In the present study, the weld toe magnification factor solutions with exponents and fractions that have polynomial functions in terms of a/c and a/t - i.e., crack depths normalized by corresponding crack lengths and specimen thickness - were developed through a parametric study using 3-dimensional finite elements for the above mentioned three types of welded joints. These weld toe magnification factor solutions showed a tendency to increase at $a/t < 0.2$. Meanwhile, for $0.2 < a/t < 0.7$, the effect of the attachment on the weld toe magnification factor decreased asymptotically. When the a/t ratio exceeded this range, the weld toe magnification factor became almost one of unity. The fatigue crack propagation life was evaluated by using the proposed weld toe magnification factor and by considering the propagation mechanisms of multiple-surface cracks, and it showed good agreement-to within a deviation factor of 2-between the experimental and calculated results for the fatigue crack propagation life for all welded joint.

Keywords: Mk-factors; Stress intensity factor; Welded joint; Weld toe magnification factor; Weld toe crack; Fatigue crack propagation life

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1. Introduction

The fatigue failure of welded components is caused by multiple surface cracks that initiate along the weld toes. The mechanisms associated with the propagation of these cracks involve the mutual interactions and coalescence of two adjacent cracks. The structural strength of the components subsequently decreases rapidly when the cracks extend through the thickness of their members [1]. An assessment of the fracture mechanics of these weld toe cracks requires accurate stress intensity factor solutions. In welded components, particularly those with complex geometrical shapes, evaluating stress intensity factors is a difficult task.

To effectively calculate the stress intensity factors, a novel weld toe magnification factor was introduced. This factor is defined as the ratio of the stress intensity factor of a cracked plate with a stress concentration to the stress intensity factor of the same cracked plate without the stress concentration [2]. Therefore, the weld toe magnification factor is influenced by the geometry of the structural attachment, the shape of the weld toe, and the size of the weld toe cracks, i.e., 3-dimensional surface cracks having a semi-elliptical shape. In previous studies [3], the required excessive calculations have limited the weld toe magnification factor solutions to several that are applicable only to non-load-carrying cruciform or T-butt joints. In the majority of cases for various welded joints such as cruciform, cover plate and longitudinal stiffener joints, the current solutions do not adequately describe the behavior of weld toe cracks.

The weld toe magnification factor solutions introduced in the present study with exponents and fractions have polynomial functions in terms of a/c and a/t, i.e., crack depths normalized by corresponding crack lengths and specimen thickness, and were developed via a parametric study using 3-dimensional finite elements for the three types of welded joints mentioned above: cruciform, cover plate and longitudinal stiffener joints. The weld toe magnification factors took into account the geometrical characteristics of the welded joints, e.g., the shapes of their attachments, weld toes and toe cracks.

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2. Calculations of weld toe magnification factors

2.1 Definition of weld toe magnification factor

For weld toe cracks, the stress intensity factor K can be described in terms of the weld toe magnification factor that quantifies the change in the K-values as a result of the presence of the weld and the attachment as follows [2]:

$$Weld\ Toe\ Magnification\ Factor = \frac{K_{(in\ plate\ with\ attachment)}}{K_{(in\ same\ plate\ with\ no\ attachmnet)}}. \quad (1)$$

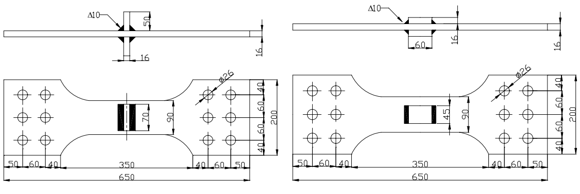
Previous studies calculated the weld toe magnification factor mostly by treating a 3-dimensional surface crack as a 2-dimensional through-crack. BS 7910 [4] provided the weld toe magnification factor solutions for welded joints, e.g., butt, cruciform and T-joints, by using 2-dimensional finite elements. Lie et al. [5] presented the weld toe magnification factors of semi-elliptical cracks in non-load-carrying cruciform joint using 3-dimensional finite elements, in which the two-dimensional weld toe magnification factors over- and under-estimated the 3-dimensional weld toe magnification factors at both the deepest and surface points by approximately 15 and 65%, respectively. However, the 3-dimensional weld toe magnification factor solutions were, for the most part, found only in the case of the non-load-carrying cruciform joint. In the majority of cases for various welded joints such as cruciform, cover plate and longitudinal stiffener joints, these solutions do not adequately describe the behavior of weld toe cracks.

2.2 Selection of welded joints

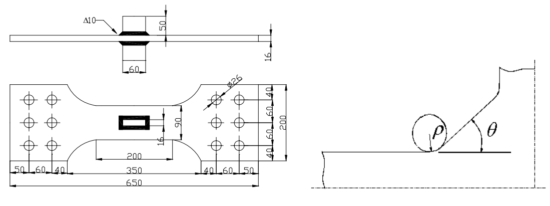
Three types of joints that are widely used in welded components were considered: non-load carrying cruciform, cover plate, and longitudinal stiffener joints. The material used in the welded joints was SM490B, and its manufacturing process is described in detail in the literature [6]. Fig. 1 shows the configurations of the three types of joints. The geometry of the weld toes for the three types of joints can be presented by statistical characteristics of the representative geometrical parameters such as the notch radius, ρ, and flank angle, θ, as shown in Fig. 1(d).

2.3 Parametric numerical study

To account for the influence parameters on the weld toe magnification factors such as the shape of the weld toe and the size of the cracks, a parametric study was performed using the finite element method. For modeling cracked bodies with a semi-elliptical shape and calculating K-values, a module of displacement extrapolation technique loaded on ANSYS was applied. One of the main difficulties in the numerical analysis involved generating adequate finite models. A batch program was developed to automatically create such finite models for cracked bodies using APDL language in ANSYS, where the element type used was a 20-noded solid element. The parameters covered are based on the crack shapes-crack depth a/t and crack aspect ratio a/c (see Fig. 2 for notations) - where the range of the a/t and a/c was selected as 0.01~0.7 and 0.2~1.4, respectively. In addition, the parameters of the weld toe shapes - ρ and θ values - were taken into account. The parametric study enabled calculation of the weld toe magnification factors through comparison of the K-values with or without attachment via Eq. (1).



(a) Cruciform joint (b) Cover plate joint



(c) Longitudinal stiffener joint (d) ρ and θ

Fig. 1. Configuration of welded joints and geometrical parameters (unit : mm).

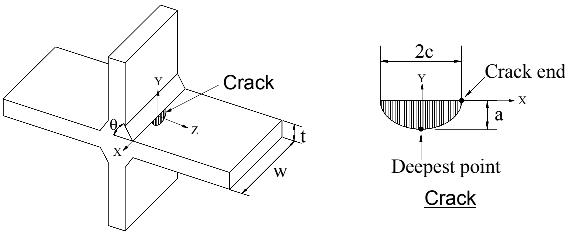
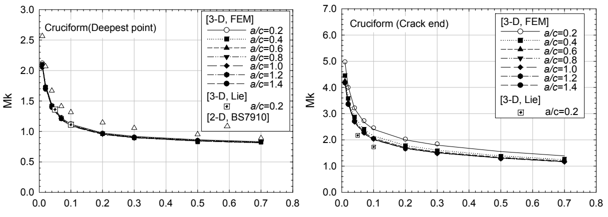


Fig. 2. Configuration of a semi-elliptical surface crack.

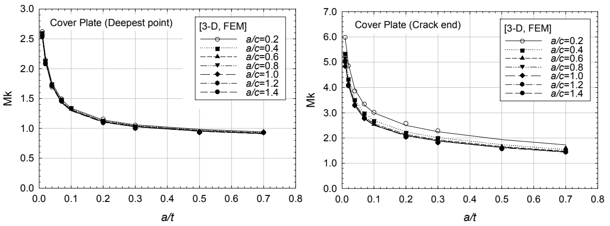
3. Numerical results

3.1 Results of a parametric study

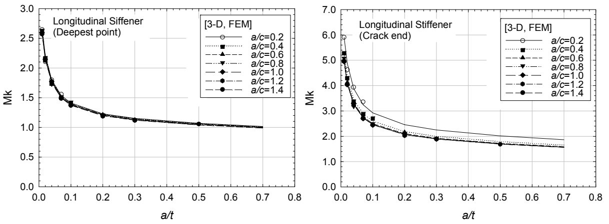
A parametric study was used to obtain the weld toe magnification factors at the deepest points and at the ends of cracks. The results are plotted in Fig. 3, where Mk designates the weld toe magnification factor. For all welded joints, the calculated weld toe magnification factors showed a marked tendency to increase at smaller a/t ratios, i.e. $a/t < 0.2$. If the crack length was small, the weld toe magnification factors were influenced significantly by the attachment and the shape of the weld toe. For $0.2 < a/t < 0.7$, the effect of the attachment on weld toe magnification factors was reduced asymptotically. The weld toe magnification factors at the crack ends were more than two-times larger than at the deepest points. This indicated that the attachment of the welded joints influenced



(a) Cruciform joint



(b) Cover plate joint



(c) Longitudinal stiffener joint

Fig. 3. Weld toe magnification factors at the deepest points and at the end points of cracks.

the weld toe magnification factors at the crack ends to a greater extent than at the deepest points. The influence of the a/c ratio on the Mk-a/t curves at the deepest points showed no effect, while the weld toe magnification factors at the crack ends varied slightly in a range from 0.2 < a/c < 0.4.

3.2 Solutions for weld toe magnification factors

A commercial spreadsheet program was used to regress the data generated from the parametric study into the form of equations for the weld toe magnification factors. The equations with exponents and fractions that had a polynomial function in terms of a/t and a/c, are shown in Eq. (2)

$$\left\{A + B\cdot e^{-C(a/c)}\right\}\left\{\frac{D+E\cdot(a/t)}{1+F\cdot(a/t)+G\cdot(a/t)^2}\right\}. \tag{2}$$

The coefficients A~G were determined by means of minimizing the differences between the finite element data and the equation predictions. Table 1 shows the determined coefficients.

4. Fatigue crack propagation life for welded joints

The fatigue failure of welded components is caused by multiple surface cracks that are initiated along weld toes. The mechanisms associated with the propagation of such cracks involve mutual interactions and the coalescence of the two adjacent cracks. These significantly affect the stress intensity factors at each crack tip. In the present paper, an empirical approach is applied whereby mutual interactions of adjacent 3-dimensional semi-elliptical cracks are taken into account as those of 2-dimensional through-cracks to compensate for differences [7]. The stress intensity factors at the crack ends, therefore, can be calculated for the cracks in the outer areas and in the areas between adjacent cracks, as follows:

Table 1. Coefficients of equation for weld toe magnification factors.

	Cruciform		Cover plate		Longitudinal stiffener	
	I*	II**	I*	II**	I*	II**
A	4.16	2.05	4.99	2.52	4.97	2.47
B	2.30	0.09	2.69	0.14	3.17	0.19
C	5.19	1.36	5.029	1.76	6.06	0.45
D	1.45	2.85	1.429	1.33	1.38	1.38
E	27.38	49.08	28.86	18.56	21.89	25.72
F	72.32	60.03	71.19	51.94	60.18	62.97
G	45.19	4.89	49.10	5.25	20.25	10.90

* I : Coefficients for crack end
** II : Coefficients for crack deepest point

$$(K_I)_{outer\ cracks\ without\ interaction} = Mk\cdot S_t\sqrt{\pi c}\cdot F_{Fett}\ , \tag{3}$$

$$(K_I)_{between\ cracks\ with\ interaction} = Mk\cdot S_t\sqrt{\pi c}\ \{1+r_m(F_{2D}-1)\}\cdot F_{Fett} \tag{4}$$

where S_t is the nominal tensile stress and F_{Fett} is the extended shape correction factor [8], as modified from Newman-Raju's formula by Fett. F_{2D} is the coefficient of mutual interaction of adjacent 2-dimensional through-cracks in an infinite plate. The r_m is an interaction factor to compensate for differences in the interaction effect between 2- and 3-dimensional cracks. It was determined to be 0.2 through a series of fatigue crack growth tests using standard plate specimens with various numbers and sizes of surface cracks.

Estimation of the fatigue crack propagation life for welded joints was carried out using an in-house code based on Paris's equation with the material constants C and m for the a and 2c determined experimentally, C_a= 5.85×10^{-13} and m_a= 3.82; and, C_{2c}= 9.55×10^{-13} and m_{2c}= 3.59. To run the in-house code, input data of the number and location of multiple cracks and the shapes of each crack were required. The weld toe magnification factor using Eq. (2) and the stress intensity factors considering the interaction effect using Eqs. (3) and (4) then followed in succession. Via the Paris' equation, the incremental growth of each crack was calculated and provided a recharacterization of the crack size in the direction of the depth and the surface. According to the coalescence of each of the cracks based on the surface connection theorem [9], an iterative operation or re-characterization of the multiple cracks was se-

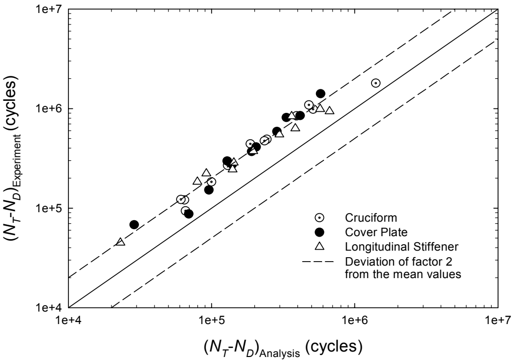


Fig. 4. Experimental and calculated results showing the fatigue crack propagation life for welded joints.

lected.

Fatigue tests were performed for the three welded joints under constant load amplitude conditions with R (= P_{min}/P_{max}) = 0.1 and a loading frequency of 10Hz in a servo-controlled hydraulic test machine. During the fatigue test, an ink stain technique was carried out to permit measurement of the crack sizes and distribution of multiple surface cracks by fractographic analysis performed after the test. The ink stains on the fracture surfaces provided the characteristics of multiple cracks: numbers, sizes and locations, when the ink stain technique applied, i.e., N_D. The crack sizes a and c were arranged due to non-dimensional variable N_D/N_T, where N_T denotes the total fatigue life.

The input data for the in-house code were collected from the experimental results by applying the ink stain technique to run the solving program. These were capable of simulating the fatigue crack increments. The difference between total fatigue life and the number of cycles when applying the ink stain technique, i.e., N_T - N_D, also was estimated using the in-house code. A comparison of the experimental and simulated results of the N_T - N_D for the welded joints is plotted in Fig. 4. This shows good agreement, to within a deviation factor of 2, between the results of the simulation and those found in the experiment. The proposed techniques, including the weld toe magnification factor and the behavior of collinear multiple surface cracks, are tenable methods that can be used to reliably estimate the fatigue crack propagation life.

5. Conclusions

(1) The weld toe magnification factors of cruciform, cover plate and longitudinal stiffener welded joints can be reliably estimated using an equation that includes exponentials and fractions with polynomial functions in terms of a/t and a/c; this equation was determined via a parametric study of 3-dimensional finite elements.

(2) These weld toe magnification factors showed a marked tendency to increase at a/t < 0.2. Meanwhile, for 0.2 < a/t < 0.7, the effect of attachments on the weld toe magnification factors was reduced asymptotically.

(3) The weld toe magnification factors at the crack ends were more than 2 times larger than those at the deepest points. This indicated that the attachment of the welded joints influenced the weld toe magnification factors at the crack ends to a greater extent than at the deepest points.

(4) The experimental and calculated results for the fatigue crack propagation life of all welded joints were in good agreement within a deviation factor of 2.

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