⊙ **Technical Paper**

Establishment of Fracture Mechanics Fatigue Life Analysis Procedures for Offshore Tubular Joints

Part I : The Behavior of Stress Intensity Factors of Weld Toe Surface Flaw

H. C. Rhee*

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해양구조물의 원통형 조인트에 대한 파괴역학적 피로 수명 산출방법

제1부 : 용접부위 표면 균열의 응력확대 계수 거동

이 희 종

Key Words : Off Shore Tubular Joints(해양 구조물의 원통형 조인트), Finite Element Method(유한 요소법), Fracture Mechanics(파괴역학), Stress Intensity Factor (응력확대계수), Fatigue Life(피로수명)

초 록

해양구조물의 원통조인트에 대한 피로 수명 산출이 전통적으로 실험적 방법에만 의존해 왔음은, 원통조인트의 구조가 복잡하여 용접부위 균열의 응력확대 계수 계산이 거의 불가능 했든 것이 주 원인이었다. 최근에 유한요소 3차원 모델을 이용한 계산방법이 개발되어 심히 구조적으로 복잡한 표면 균열의 응력확대계수 산출이 용이하게 되었다. 해양 구조물의 원통조인트에 대한 피로 수명 산출법을 개발하기 위한 연속되는 3부작의 제1부로서 본 논문은 X형 원통 조인트 용접부위 표면 균열의 응력확대계수 거동을 분석하고 있다. 이 연구를 위해 16개의 다른 형태와 크기의 용접표면 균열을 3차원 유한요소 모델에 의해 분석하고, 분석 결과를 이용하여 응력확대계수를 엄격한 방법에 의해 계산하였다. 계산된 응력확대계수를 구조적인 관점에서 해석하고 있다.

1. Introduction

For a fatigue analysis of a conventional tubular joint structure, a fracture mechanics method, which considers the crack geometry explicitly, is the most reliable. The reason is that, in a welded component, weldinng-induced structural discontinuities behave as crack initiators, and thus, the fatigue life consists primarily of the crack propagation life. Although experimental fatigue studies are abundant, however, so far, no rigorous fracture mechanics fatigue crack growth analysis has been performed for surface flaws of offshore tubular joints because of the absence of

* Member, Conoco Inc., U. S. A.

the stress intensity factor solutions, which reflect explicitly both the flaw depth and length,

Experimental fatigue crack growth rate data can be used to calculate a crack driving force parameter, which is expressed in a stress intensity factor equation in terms of the surface crack length[1] (or crack depth[2]) as the crack size parameter. Unless a problem is uncoupled mode (pure mode Ⅰ, Ⅱ, or Ⅲ), such a crack driving force parameter cannot be considered as a stress intensity factor, which represents the magnitude of the crack tip stress singularity. The reason is that such a parameter incorporates all the stress intensity factors existing in the problem, as discussed later. Even for a single-mode problem, such an experimentally calibrated parameter cannot be general as the stress intensity factor of a surface flaw, if it ignores in its expression the other crack geometry parameter, viz., the crack depth[1] or the crack length[2].

Even with today's sophisticated numerical analsyis methods, the complexity in tubular joint structural geometries makes the evaluation of the stress intensity factors of a weld toe surface flaw a significant challenge. As can be seen in Fig. 1 under fatigue loading, a weld toe surface flaw of

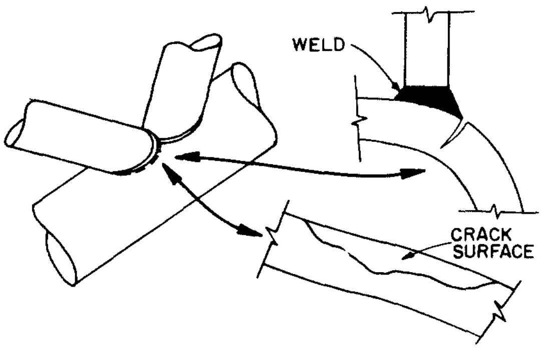

Fig. 1 Tubular joint weld toe surface flaw

a tubular joint tends to grow following the tubular intersection, and its growing path along the tubular-thicknss direction also usually curves. The resulting crack surfaces are doubly warped, in general. For this type of complex flaw geometry, no solution procedure has been established for the stress intensity factors until recently[3].

As a natural consequence of this absence of rigorous stress intensity factor solutions, the prevailing fatigue crack growth model concept for tubular joint structure lacks generality. This lack of generality is obvious in the fact that, so far, the offshore tubular joint fatigue problem has mostly been dealt with in the context of pure mode Ⅰ. This approach is not consistent to the apparent physical characteristics of offshore structural tubular joint weld toe surface cracks whose geometric configurations easily suggest a possibility of predominantly mixed-mode behavior, even for a simple load case. This and other important aspects of offshore tubular joint fracture mechanics fatigue analysis are discussed in detail in reference 3.

Recently, a finite element procedure has been established to calculate the stress intensity factors of a tubular joint weld toe surface flaw with warped crack surfaces[4]. Through this work[4], it has been demonstrated that the evaluation of the stress intensity factors of a tubular joint weld toe surface flaw can be practical and that, for flaws in tubular joints, there exists a strong possibility of predominantly mixed-mode crack tip material behavior. Using this method it is possible to perform detailed fracture mechanics fatigue crack growth analysis for tubular joints which are rare in the offshore industry.

As a preliminary study to develop an engineering model of a fatigue crack growth analysis for a tubular joint, an investigation has been performed on a weld toe surface flaw in an X-joint. For this study, the stress intensity factors of sixteen flaw geometries in the joint were calculated using the previously mentioned methed[4]. These flaw geometries were systematically selected with seven different depths and three different crack lengths. These solutions were compiled consistently with the selected geometries and analyzed to understand fatigue crack growth behavior of a weld toe surface flaw, in conjunction with the detailed stress distributions along the brace-chord intersection and through thickness direction. This stress distributions were obtained through a separate three-dimensional finite element analysis of the joint without the flaw. The results were used to derive a simplified stress intensity factor expression for a weld toe surface flaw using the load and geometric of the joint in a manner similar to the conventional expression for simple flaw geometries.

2. Stress Intensity Factor Solutions of Weld Toe Surface Flaw of X-Joint

Fig. 2 shows two-plane symmetry finite element model of the analyzed X-joint with a weld toe surface flaw near the saddle point of the chord with the dimensions and material properties. The model consists of 490 three-dimensional 20-node isoparametric elements for the area near the crack and the brace-chord intersection area, 5,098-node

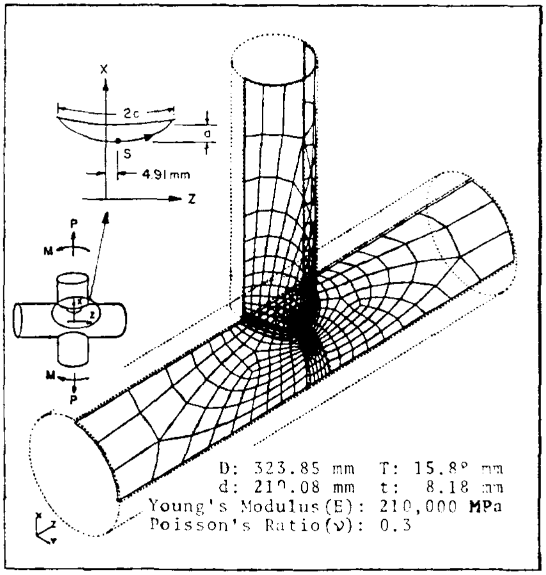

Fig. 2 Finite element model of cracked X-joint

thick shell elements for the other tubular parts, and 5,000 nodes. This model was developed using PRETUBE[5], which is a preprocessing program designed for the finite element mesh development for tubular joints. This program has a built-in capability to develop a finite element mesh for various forms of surface flaws in a tubular joint with crack tip quarter point singular elements[6].

In modeling a surface flaw, the program requires the coordinates of two points at which the curved crack front meets with the tubular surface, and the deepest flaw depth, which is measured at the middle of the crack front which is defined by the two surface points. These three points(two surface points and the deepest point) are then mapped into a parent semiellipse on a flat plane whose axes are defined by the physical distance between the two surface points and the depth at the deepest crack front point. After this parent semielliptical flaw is defined, it is mapped back into the tube through a coordinate transformation between the rectangular coordinates of the parent semiellipse and the curvilinear body coordinates of the tube. The curvilinear body coordinates are defined by the path of the crack mouth on the tube surface, which is determined by the previously mentioned two surface points, and a coordinate along the thickness direction, which is normal to the crack mouth path. At present, the program can model only a straight crack surface along the depth (tube thickness) direction, and thus, a model can have crack surfaces, which are warped along the crack length direction only.

The flaw in the model is slightly offset from the structural symmetry axis (about 2 percent of the brace diameter). Along the crack front, ten three-dimensional collapsed quarter point element clusters, each of which consists of eight elements surrounding the crack front, were modeled to represent the crack tip singularity properly in an analysis. Fig. 3 shows the zoomed view of the finite element mesh near the flaw.

Table 1 lists the dimensions of the analyzed sixteen flaws. The considered loading conditions are a brace tension and an in-plane bending (Fig. 2). This model first was analyzed by TUJAP[7], a general purpose finite element program and then the crack tip $\sqrt{r}$ part displacements, which were extracted from the quarter point elements, were converted into the appropriate stress intensity factors using a computer program developed for this purpose. The details of this conver-

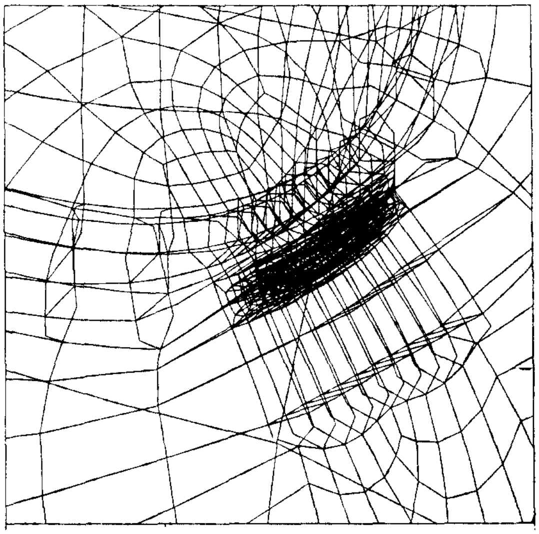

Fig. 3 Finite element mesh near weld toe surface flaw

Table 1 Aspect Ratios of Analyzed Flaws (a/c)

$a(mm)$	a/T	$c(mm)$		
		9.2	13.3	18.4
2.30	0.15	0.25		
3.45	0.22	0.375	0.25	0.1875
4.60	0.29	0.5	0.333	0.25
5.18	0.33		0.375	
6.90	0.44	0.75	0.5	0.375
9.20	0.58	1.0		0.5
9.50	0.60	1.03	0.688	0.516

sion procedure can be found in reference 4.

Fig. 4 and 5 present the resulting stress intensity factor solutions of two of the sixteen flaw geometries. These plots show that the in-plane bending load cases are predominantly mixed mode. All the solutions along the crack front location, where the negative mode I stress intensity factor is developed (for the in-plane bending cases), are not accurate. The negative K_I indicates that crack surface contact and penetration were developed in the analyzed models, which is physically impossible, since a proper multicomponent contact algorithm was not employed. However, solutions far from the locations with negative K_I solutions will be acceptable for engineering purposes.

In these plots, the data represented by the solid dots are the equivalent stress intensity factors, K_e, which are converted from the appropriate energy release rate, G.

$$\frac{K_e^2}{E} = G = \frac{1-v^2}{E}\left(K_I^2 + K_{II}^2 + \frac{K_{III}^2}{1-v}\right) \qquad (1)$$

This equivalent stress intensity factor can be interpreted as a crack driving force which incorporates all the K_I, K_{II}, and K_{III} components of a mixed-mode problem. For a mixed-mode problem, any single component of the stress intensity fac-

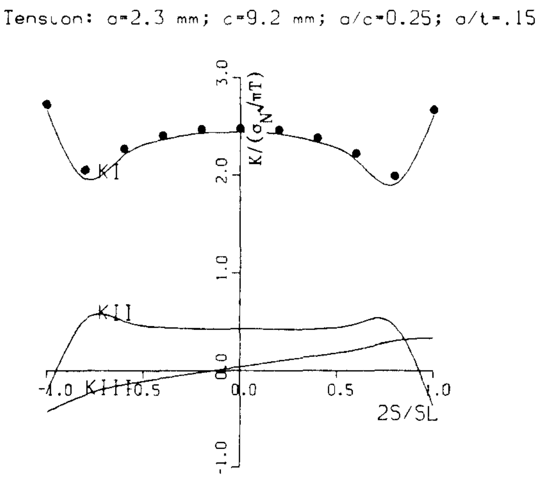

Fig. 4a Normalized stress intensity factors of shallow flaw (tension)

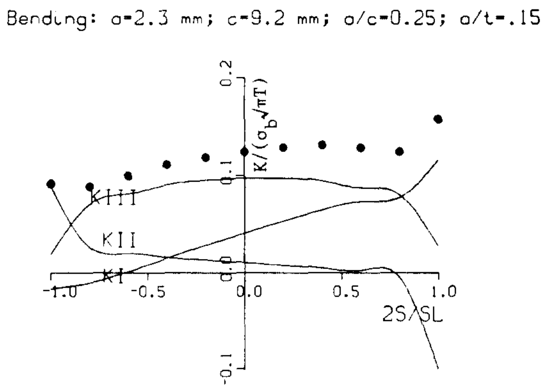

Fig. 4b Normalized stress intensity factors of shallow flaw (bending)

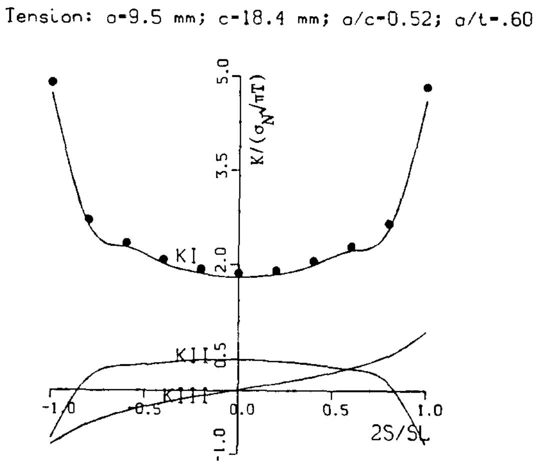

Fig. 5a Normalized stress intensity factors of deep flaw (tension)

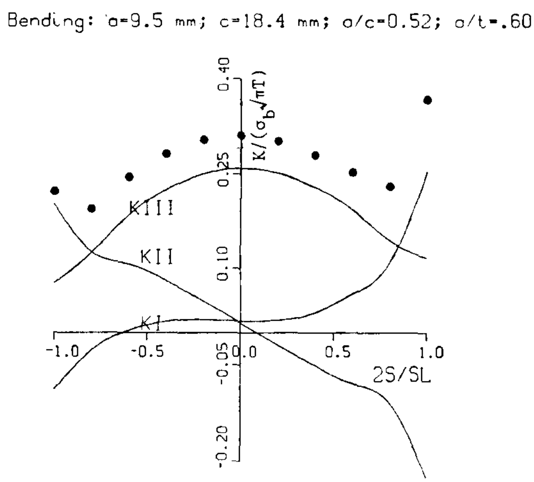

Fig. 5b Normalized stress intensity factors of deep flaw (bending)

tors cannot represent the crack driving force properly since crack propagation is a combined result of the contributions of all three stress intensity factors of the problem. A comparison between K_e and any individual component of K_I, K_{II}, and K_{III} can indicate the contribution of such an individual component to crack propagation.

For the brace tension cases, it is apparent from Fig. 4 and 5 that, throughout the crack front, the fatigue crack propagation will be dominated by the mode I stress intensity factor K_I. However, for the in-plane bending cases, the K_I contribution to K_e is negligible except for a small area near the surface. In other areas, one of K_{II} and K_{III} is the dominant component. Therefore, if the considered flaw geometry is practical for a fatigue load system which consists of a significant contribution of in-plane bending, a fatigue crack growth analysis should consider all the three K_I, K_{II}. and K_{III} components.

In the next section, the behavior of the crack driving force parameter of the weld toe surface flaw is discussed using the solutions of the sixteen different flaw geometries. In this discussion, as the crack driving force parameter, K_I will be used for the brace tension load case and K_e for the in-plane bending because of the reasons stated above.

For all discussions, only the right-half part solutions of each flaw will be used. Since the offset of the flaw symmetry axis from that of the structure is small, the right-half part solutions will be sufficient to properly relate the fatigue crack growth behavior of the entire flaw for the brace tension. For the in-plane bending, such a symmetric nature is not directly applicable. In addition, it should be realized that a crack driving force parameter such as K_e has yet to be established as a parameter through which the fatigue crack growth behavior of a mixed-mode flaw can be directly calculated in a manner similar to the K_I of a mode I problem. Expressions similar to the present K_e have been studied for limited mixed-mode problems[8,9], such as problems with K_I and K_{II} mixed and with K_I and K_{III} mixed; however, few fully mixed-mode problems, such as the present in-plane bending, have been studied. For the purpose of this study on the behavior of a crack driving force parameter of a tubular joint weld toe surface crack, using K_e for the in-plane bending case is sufficient.

3. Behavior of Crack Driving Force in X-Joint

In the conventional S-N curve approach to tubular joint fatigue analysis, the stress concentration factor (SCF) is used as a primary load parameter. In this approach, all the structural characteristics of a joint, viz., the geometric and loading conditions, are reflected in an analysis through this parameter and the S-N curve used. Similarly, in a fracture mechanics fatigue analysis of a mode I problem, all the structural characteristics which affect the fatigue crack growth behavior can be incorporated through the stress intensity factor, as can be seen in the following fatigue crack growth equation:

$$\frac{da}{dN}=C(\Delta K_I)^m \qquad (2)$$

where a is the crack depth, N is the number of fatigue loading cycles, C and m are material parameters, and ΔK_I is the range of K_I for the instantaneous flaw under a specified fatigue load. It is so because the stress intensity factor, K_I, which can define the stress state near the crack is a function of all the relevant structural parameters, viz., the load, the structural and flaw geometries.

While the one-dimensional SCF parameter cannot represent a three dimensional stress state completely and remains constant for a specified load throughout an analysis, ΔK_I varies continuously with the size and the shape of the growing flaw. The stress distribution along the crack growing path is an important parameter through which crack behavior can be understood. Fig. 6 shows the through-the-chord thickness distributions of the normalized principal stresses, which were sampled at various locations along the brace-chord intersection, for the brace tension case. These solutions were obtained by a TUJAP analysis of the X-joint without a crack using a model used in reference 3. The through-wall stress distribution is primarily in bending mode. The magnitude of the outer surface stress decreases, keeping the similar through-wall distribution pattern, as the location moves toward the crown point from the saddle point.

From these stress distributions, it is clear that

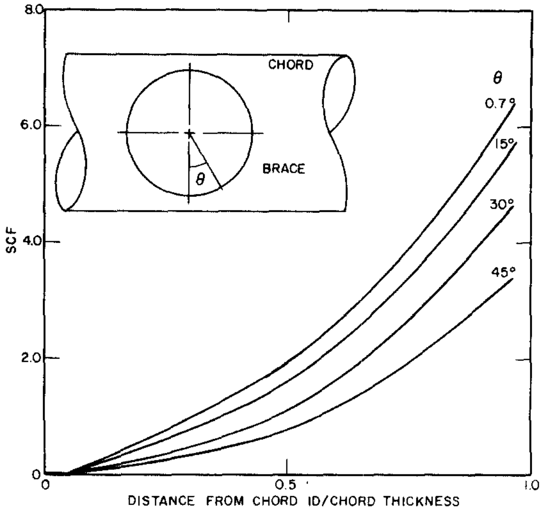

Fig. 6 Chord through thickness stress distributions at various locations (uncracked X-joint)

there exists two factors which tend to reduce each other's effects on the magnitudes of the stress intensity factors of a growing surface flaw starting from the saddle point. The growth of the flaw size will make the stress intensity factor larger. However, while the flaw grows deeper along the thickness and longer along the surface, the crack front moves to areas with low stress level so that the resulting stress intensity factors become smaller. Fig. 7 shows the variations of the normalized K_I values with respect to the crack length (c) for various flaw depths (a). For a specified depth as the flaw length increases, the K_I value measured at the chord surface decreases for all the flaw with $a/T \leq 0.44$. For the deepest flaw ($a/T=0.6$), the effect of the crack elongation on the K_I variation first overcomes that of the stress reduction. However, as the crack grows longer, the trend is dominated by that of the stress reduction to result in low K_I values for higher c/T values. For a specified flaw length, the surface K_I increases with the flaw depth. At the deepest point of the crack front, K_I increases with the crack length for a specified flaw depth. However, the K_I decreases with increasing flaw depth for a fixed flaw length, reflection the through-wall bending stress effect.

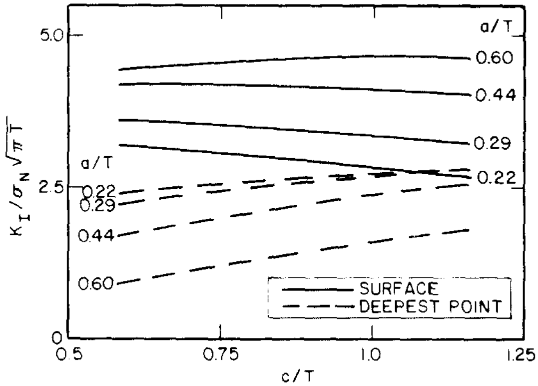

Fig. 7 Normalized stress intensity factor, K_I (tension)

In many laboratory tests, it has been observed that the crack propagation rate on the tube surface of a weld toe surface flaw of tubular joints (X or T type) decreases as the crack grows longer under brace tension fatigue loading. The stress intensity factor behavior discussed above is consistent with this laboratory observation, as well as with the stress distribution presented in Fig. 6. Further, as can be observed from the curve for $a/T=0.6$ (Fig. 7), the surface K_I variation is flat. This indicates that, at a certain flaw depth, the fatigue crack growth rate of Eq. (2) can be independent of the flaw length.

For the in-plane bending case, the situation is slightly different from the brace tension. As shown in Fig. 8, K_e increased monotonically as the flaw grows longer and deeper. For the in-plane bending, the hot spot is near the crown point. Therefore, this trend of K_e is likely to continue as the crack grows longer to approach near to the crown point.

For the convenience of a fatigue crack growth analysis, which requires a large amount of data, it is useful to express the stress intensity factor in a simple form in terms of easily measurable loading and geometric parameters, such as the nominal stress and crack dimensions. As previously stated, the stress intensity factor of Eq. (2) incorporates all the structural properties of a joint to be analyzed. Therefore, the functional form of the stress intensity factor can be expressed as

$$K_I = K_I(a, c, s, g, l) \tag{3}$$

where g and l represent the geometric and loading characteristics of a cracked tubular joint, respectively. For the convenience of an analysis, for

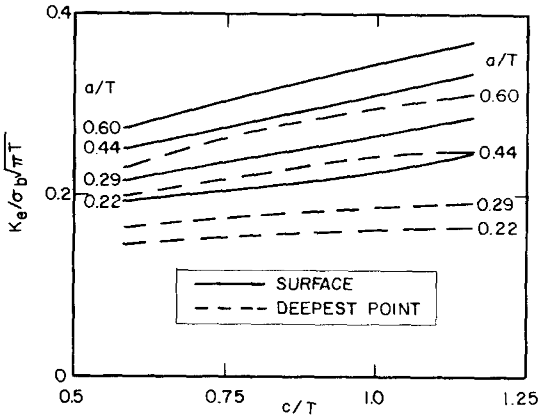

Fig. 8 Normalized effective stress intensity factor, K_e (bending)

the present brace tension case, the stress intensity function is expressed as:

$$K_I = \sigma_n F\sqrt{\pi c} \tag{4}$$

where, σ_n is the brace nominal stress and F is the magnification factor.* In the above equation, the load parameter σ_n can be selected consistent with that of the conventional S-N curve approach, the crack length, c, in the square root was selected as a parameter representing the crack geometry. The load parameter can easily be replaced by the SCF, which is the S-N curve load parameter. Using this simplified expression, which is defined in the conventional stress intensity factor expression for a one-dimensional flaw geometry with a straight crack line, the crack driving force

* Also it takes the identical form, the nature of the F function of Eq. 4 is significantly different from that of $K_I=\sigma F\sqrt{\pi a}$ of the conventional stress intensity factor expression of a simple one-dimensional crack geometry.

behavior of a tubular joint weld toe surface flaw with curved crack surfaces can be conveniently analyzed. In this expression, the conventional flaw shape function for a planar elliptical flaw was not included and the two-dimensional structural flaw geometry form (the flaw itself in one-dimensional) was adopted since, for a tubular joint weld toe surface flaw, the depth parameter is difficult to measure, while the surface flaw length is easily measurable.

Fig. 9 and 10 present the plots of the stress intensity magnification factors of the flaws under the brace tension for various a/T ratios and a/c ratios, respectively. Contrary to a simple flaw geometry, the magnification factor, F, of the present X-joint surface flaw decreases, in general, except for the deepest point of deeper flaws (a/T ≥ 0.44), as the crack grows in the length. This indicates that the F factor for the tubular joint, as defined in Eq. (4), is a function of the load as well as of the geometry. Due to the complexity in a tubular joint geometry, it seems that the load effect cannot be easily decoupled from the magnification factor, F, which is readily possible for other simple flaw geometries. Therefore, while it can be referred to as a geometric correction factor in a simple structural flaw geometry, the magnification factor of a tubular joint surface flaw, F, should be referred to as a structural correction factor due to its dependency on the load as well as the geometry.

Fig. 11 and 12 show the F factors for K_eS of the in-plane bending, which were defined consistently with Eq. (4). In this case, the brace bending stress, σ_b, was used as the loading

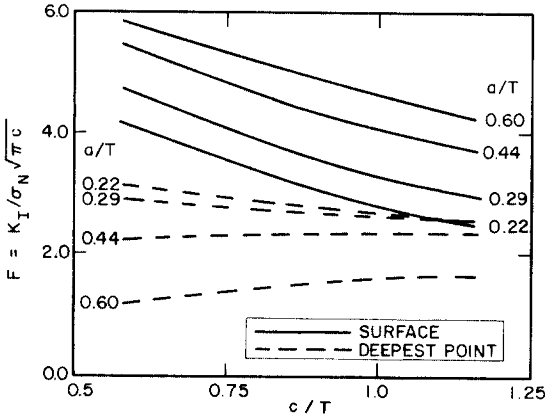

Fig. 9 K_I magnification factors for various crack depths (tension)

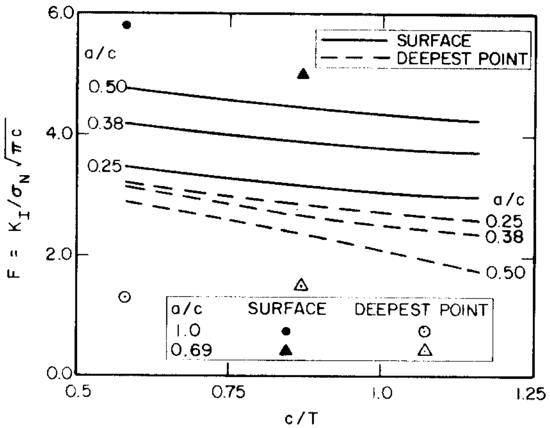

Fig. 10 K_I magnification factors for various aspect ratios (tension)

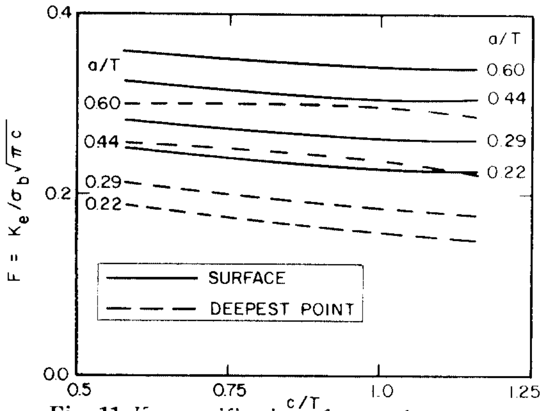

Fig. 11 K_e magnification factors for various crack depths (bending)

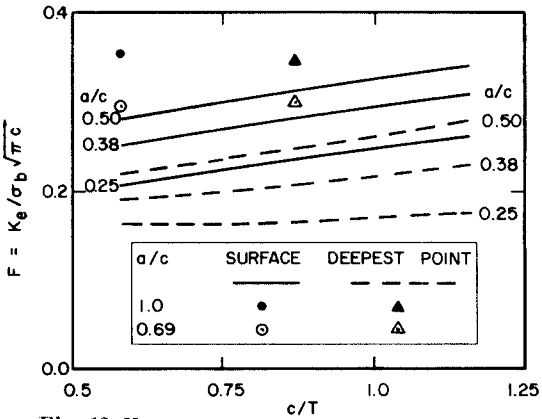

Fig. 12 K_e magnification factors for various aspect ratios (bending)

parameter. As in the brace tension case, the structural correction factor F is a coupled function of the geometry and loading conditions for the in-plane bending.

4. Conclusions

The following conclusions can be drawn from the present study.

1) Using the finite element method, the evaluation of the stress intensity factors for a weld toe surface flaw of tubular joints can be practical.
2) Depending on the loading condition, the crack tip material behavior of a weld toe surface flaw can be predominantly mixed-mode, even for a simple tubular joint geometry.
3) The crack driving force behavior of the weld toe surface flaw of an X-joint under a brace tension indicates that as the crack grows under fatigue loading, the crack growth rate on the surface generally decreases due to the stress reduction along the crack growing path. This is consistent with many laboratory tests on tubular joints.
4) The crack driving force behavior also indicates that the lengthwise fatigue crack growth rate can be independent of the crack length at a certain crack depth for the brace tension case.
5) The structural magnification factor of a stress intensity factor expression of a weld toe surface flaw cannot be defined independently of the load because of the complexity in the stress distribution. When the expression is cast into a form similar to that of a simple flaw geometry, the magnification factor seems to be a strong function of the load, as well as of the geometry.

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