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Numerical Models Verification of Cracked Tubular T, Y and K-joints under Combined Loads

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ABSTRACT

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This paper summarizes the key steps involved in the construction of an accurate and consistent finite element model for general cracked tubular T, Y and K-joints. The joint under consideration contains a surface crack which can be of any length and located at any position along the brace-chord intersection. Welding details along the brace-chord intersection, compatible with the American Welding Society (AWS) specifications (2000), are included in the geometrical model. In order to develop a systematic and consistent modelling procedure, the whole process is divided into four key steps. They are, namely, (1) construction of a consistent geometrical model of the joint with welding details, (2) determination of cracked surface to define the semi-elliptical surface crack profile, (3) generation of well-graded finite element meshes, and (4) stress intensity factor studies around the crack front. To produce a well-graded finite element mesh, a sub-zone technique is used in the mesh generation whereby the entire structure is divided into several sub-zones with each zone consisting of different types of elements and mesh densities. The stress intensity factors (SIFs) are evaluated using the standard J -integral method. Two full-scale T and K-joint specimens were tested to failure under axial load (AX), in-plane bending (IPB), and out-of-plane bending (OPB). In the tests, the rate of crack propagation was monitored carefully using the alternating current potential drop (ACPD) technique. Using the known material parameters C and m , the experimental SIFs were obtained, and they are found to be in complete agreement with the computed SIFs obtained from the generated models. Hence, the proposed finite element models are both efficient and reliable.

KEY WORDS: Alternating current potential drop (ACPD) technique, crack propagation, J -integral, mesh generation, stress intensity factor (SIF), sub-zones, surface crack, tubular T, Y and K-joints.

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INTRODUCTION

In offshore and petroleum engineering, tubular members, especially hollow circular sections, have been widely used in the construction of a wide range of onshore and offshore structures. They are always subjected to cyclic loads caused by seawater wave, and hence fatigue failure has become a very common phenomenon. In the analysis of these structures, the behaviour of the tubular joints is an essential factor that will affect the overall performance of the whole structure. Thus, it is crucial to be able to estimate the residual life of these damaged joints containing flaws or cracks. The most commonly used method is to employ a fracture mechanics approach, based on accurate estimation of stress intensity factors (SIFs) along the crack front. Generally, the accuracy of the SIF values depends very much on three most important factors, they are, namely,

- (1) the geometrical models used to describe the weld size and the crack details, and
- (2) the grading of the finite element mesh used near the joint intersection and around the crack front, and
- (3) the aspect ratio of the elements along the crack front.

Hence, a consistent geometrical model of the joint with welding and crack details, a well-graded finite element discretization of the geometrical model and low elements' aspect ratio along the crack front are the three most important ingredients in the SIF analyses. A consistent model is even more important when carrying out parametric studies of the behaviour of the joint so that it will allow one to compare the results obtained from other researchers. In the past, a considerable amount of research effort had been directed to this research topic. Detailed geometric analysis for the intersection curve between a brace and a chord without welding details was carried out by Cao et al. (1997). A detailed study for the variation of the dihedral angle for a general tubular Y-joint was carried by Suen and Wu (1993). For the generation of finite element meshes for cracked joints, Cao et al. (1998) developed a procedure for transforming crack elements around a plane curve into crack elements for a doubly curved semi-elliptical surface crack around the joint intersection while Bowness and Lee (1995) developed another mesh generation procedure to discretize the surface

crack. Bowness and Lee (2000) and Cao et al. (1998) have adopted two types of elements to model the crack surface. They used 3D prism singular elements to model the crack front and 3D hexahedral elements at the field far away from the crack front. The problem of using this method is that some generated elements, especially the elements near the crack front, have a very high aspect ratio which in turn produces numerical instability in the SIF values. In practice, using only two types of elements can not produce a good quality mesh for any tubular joint containing a surface crack due to the complexity of the geometry and the weld.

Therefore, a systematic modelling procedure for a general welded and cracked tubular Y-joint is first proposed in this paper. A detailed weld modeling complying to the AWS specifications (2000) and a correct definition of the crack surface are used in the geometrical model. It can cover a wide range of practical tubular joints, including T, Y and K-joints. In the mesh generation, five types of elements, i.e. hexahedral, prism, quarter-point collapsed prism, tetrahedron and pyramid elements, as shown in Table 1, are used to model the surface crack and the other zones of the tubular joint. Previous studies (Chiew et al., 2001, Lie et al., 2003) on tubular T and Y joints have proved that dividing the entire structure into different distinct zones can simplify the mesh generation process drastically. For each zone, the mesh is generated separately using different densities based on mesh quality requirements. After the mesh of all the zones has been completed, they are merged to form the entire structure. Using this method, the field with a high stress gradient is refined with a high quality mesh to ensure a sufficient number of elements in this zone. At the same time, the fields far away from the crack and the weld, which have little effects on the stress intensity factors, have a relatively coarse mesh. The fields of different mesh densities are joined together by some other fields which are called the transition zones. Hence, the density and aspect ratio of the elements can be controlled easily.

Two full-scale tubular T and K-joints were tested to failure under axial load (AX), in-plane bending (IPB), and out-of-plane bending (OPB). The crack shape development was monitored step-by-step throughout the test using the alternating potential drop (ACPD) technique. Before the

fatigue test was carried out, static tests were done to assess the stress concentration factors (SCFs) of the joint, and hence the peak hot spot stress (HSS) to determine where to concentrate the majority of the ACPD probes. From the experimental test data, and the material parameters C and m , the stress intensity factors can be deduced accordingly. These experimental SIF values are used to verify the proposed finite element models.

GEOMETRIC MODELLING OF WELD AND CRACK

AWS Specifications (2000) on Weld Profile

Fig. 1 shows the geometry of a Y-joint. It describes the weld path and the definition of the coordinate system. The plan view for the weld path is shown in Fig. 2. The cross section of the intersection is shown in Fig. 3 which indicates the definitions of the inner dihedral angles (γ_i) and outer dihedral angles (γ_o). In order to account for the thickness of the welding, the welded model is obtained by modifying the original inner and outer intersecting curves as shown in Fig. 4. The original contact thickness T_1 is defined as the surface contact thickness at a particular section normal to the intersection at the joint. In general T_1 varies along the joint and depends on the dihedral angle and the curvature of the chord surface. Normally, the thickness of the brace t_b is small compared to the radius of the chord R_1 , and thus T_1 can be approximated as $t_b/\sin(\gamma)$.

To model the weld toe point W_o , a distance of T_2 will shift out from point A_o as shown in Fig. 4. The value of T_2 will depend on the outer dihedral angle γ_o at point A_o . It is suggested that T_2 will vary from a finite value when $\gamma_o = \theta = 30^\circ$ to zero when γ_o increases to 180° . Wong (2001) then proposed the following equations to calculate the T_2 :

$$T_2 = k_2 \times t_2 \quad (1)$$

$$k_2 = F_{OS_{outer}} \left[1 - \left(\frac{\gamma_o - \theta_s}{180^\circ - \theta_s} \right)^m \right] \quad (2)$$

where T_2 is the modified outer thickness, k_2 is the modification factor of the outer intersection curve, $F_{OS_{outer}}$ is a scale factor, m is a constant, and θ_s is the smallest intersecting angle.

The modified equations for the outer intersecting curve (weld toe) can be written as:

$$\begin{cases} Z_{W_o} = Z_{A_o} + T_2 \cos \beta_o \\ Y_{W_o} = Y_{A_o} + T_2 \sin \beta_o \\ X_{W_o} = \sqrt{R_1^2 - Y_{W_o}^2} \end{cases} \quad (3)$$

where point $A_o(X_{A_o}, Y_{A_o}, Z_{A_o})$ is a point on the outer intersecting curve. For the point B_o , as shown in Figs. 5a and 5b, its location can be obtained by displacing the location of A_o a distance of $(T_1 + T_4)$ in the direction of brace axis, and T_4 is defined in the same figure.

For the weld root, a distance of T_3 will shift in and cut inside from point A_i to the point W_i (shown in Fig. 4) when the inner dihedral angle γ_i is inside the range $[30^\circ, 90^\circ)$. For $\gamma_i = 90^\circ$, $T_3 = 0$ and for $\gamma_i > 90^\circ$, point A_i will be shifted out and fill inside to the point W_i . Similarly, T_3 will depend on γ_i at point A_i . The equation for calculation of T_3 can be expressed as follow:

$$T_3 = k_3 \times t_b \quad (4)$$

$$k_3 = F_{OS_{inner}} \left[1 - \left(\frac{\gamma_i - \theta_s}{90^\circ - \theta_s} \right)^n \right] \quad (5)$$

where T_3 is the modified inner thickness, k_3 is the modification factor of the inner intersection curve, $F_{OS_{inner}}$ is a scale factor, n is a constant, and θ_s is the smallest intersecting angle.

Hence the modified equations for the inner intersecting curve (weld root) can be expressed in the same way:

$$\begin{cases} Z_{W_i} = Z_{A_i} + T_3 \cos \beta_o \\ Y_{W_i} = Y_{A_i} + T_3 \sin \beta_o \\ X_{W_i} = \sqrt{R_1^2 - Y_{W_i}^2} \end{cases} \quad (6)$$

where point $A_i(X_{A_i}, Y_{A_i}, Z_{A_i})$ is a point on the inner intersecting curve. For the point B_i , as shown in Figs. 5a and 5b, its location can be obtained by displacing the location of A_i a distance T_4 in the direction of brace axis.

The weld thickness T_w is a combination of the original contact thickness T_1 and the modified outer thickness T_2 and inner thickness T_3 , and it must satisfy the minimum requirement of the AWS specifications (2000). That is:

$$T_w = T_1 + T_2 + T_3 \geq T_{AWS} = k_{AWS} \cdot t_b \quad (7)$$

where k_{AWS} is the welding thickness parameter specified by the AWS specifications (2000).

Wong (2001) had studied the welding thickness of actual tubular T and Y joints and found compared with the AWS specifications (2000), this weld modelling method can be used to model the welded tubular joints safely. Therefore, this method is also used in the present study to model any welded tubular joint.

Definition and Determination of Crack Surface at the Weld Toe

When a crack initiates from the surface of the chord of a welded tubular joint, it will propagate through the chord thickness in a special direction in which the energy requirement is minimal (Fig. 6). The crack front will propagate on 3-D curves which together form a surface which is called the crack surface where the crack front lies on. As shown in Fig. 6, the crack surface is formed by joining a series of straight lines W_oD along the weld path. W_oD is passing through the Z-axis and the thickness of the cracked surface is always equal to t_c . $W_o(X_{W_o}, Y_{W_o}, Z_{W_o})$ is the point on the weld profile and on the outer horizontal cylinder, and point D will be located according to the following assumptions that Point D is on the inner horizontal cylinder, $|\overline{W_oD}| = t_c = R_1 - R_2$, and the line $\overline{W_oD}$ will pass through Z-axis.

By using these assumptions (Chiew et al., 2001, Lie et al., 2003), the coordinate of point D can be obtained and expressed as follow:

$$D = \begin{Bmatrix} X_D \\ Y_D \\ Z_D \end{Bmatrix} = \begin{Bmatrix} \frac{R_2}{R_1} X_{W_o} \\ \frac{R_2}{R_1} Y_{W_o} \\ Z_{W_o} \end{Bmatrix} \quad (8)$$

Definition and Determination of Crack Front

After the crack surface is defined, it is necessary to define the crack front which can exist at any location on a surface crack. From past experimental tests on the T-joints (Huang, 2002) as well as the K-joint (Lie et al., 2003), the crack shape resembles a semi-ellipse. Therefore, this assumption is used to model the crack in any tubular joint in the present study. In order to model the crack front conveniently in 3-D space, it is often more convenient to define it on a normalized u' - v' plane and then map it onto the crack surface as shown in Fig. 7. The u' -axis relates to the crack length, l_{Cr} , while the v' relates to the crack depth, d . Apparently, it is easier to define the u' -axis by the polar angle α though it has no direct relationship with the physical length of the crack. In this mapping approach, a crack with any length and size can be modelled at any location. As illustrated in Fig. 8, the two crack tips will be located and defined by the polar angles α_{Cr_1} and α_{Cr_2} in the u - v system.

The coordinates (u', v') are defined as:

$$u' = \frac{(\alpha - \alpha_{Cr_1} - \alpha_{Crange})}{\alpha_{Crange}}, \quad \alpha_{Crange} = \frac{\alpha_{Cr_2} - \alpha_{Cr_1}}{2} \quad (9)$$

$$v' = \frac{d}{t_C} \quad (10)$$

where α is the polar angle corresponding to the point (u', v') , α_{Cr_1} is the polar angle which defines the location of crack tip 1, α_{Cr_2} is the polar angle which defines the location of crack tip 2, d is the depth of the crack, t_c is the thickness of the chord member. Note that $u' \in [-1, 1]$, $v' \in [0, 1)$ and $\alpha_{Cr_1}, \alpha_{Cr_2}, \alpha \in (0^\circ, 360^\circ]$.

In practice, the crack tip positions are frequently described by defining (or measuring) the arc lengths, l_{Cr_1} and l_{Cr_2} on the global X-Y-Z coordinate system as shown in Fig. 9. The crack length, l_{Cr} , will depend on the position of the crack tips and is defined as $l_{Cr} = l_{Cr_1} - l_{Cr_2}$. Since the weld is defined by the polar angles α_{Cr_1} and α_{Cr_2} (Eq. 9), it is required to compute the values of α_{Cr_1} and α_{Cr_2} from l_{Cr_1} and l_{Cr_2} respectively. In this study, the value of α_{Cr_1} and α_{Cr_2} are computed from l_{Cr_1} and l_{Cr_2} by using a sample approximation procedure. For example, in order to compute α_{Cr_1} from l_{Cr_1} , starting from the v' -axis, a sequent of points will be generated by increasing their polar angles gradually in small step equal to $\Delta\alpha$. For each of this point, the corresponding arc length, l^* , is computed until $l^* \geq l_{Cr_1}$. The estimated value for α_{Cr_1} is then defined as the one corresponding to the arc length which is closest to l_{Cr_1} . In practice, it is found that a value of $\Delta\alpha = 0.1^\circ$ will be accurate enough for virtually all applications and the computational cost needed is modest (Wong, 2001).

Suppose that the crack front curve is defined by the point Cr' in the $u'-v'$ space as shown in Fig. 7. For any point (u', v') on the curve, by using Eqs. 9 and 10, the corresponding value of α can be obtained. Once α is known, the coordinates of the point $W_o(X_{W_o}, Y_{W_o}, Z_{W_o})$ could be computed. In order to define the location of the crack front, the point W_o will be further modified. Assume the crack front is defined by the point $Cr(X_{Cr}, Y_{Cr}, Z_{Cr})$ with depth equal to d (Fig. 7), then by using a similar approach for the computation of point D, it can be shown that the coordinates of the point Cr are given by:

$$\mathbf{Cr} = \begin{Bmatrix} X_{Cr} \\ Y_{Cr} \\ Z_{Cr} \end{Bmatrix} = \begin{Bmatrix} \left(1 - \frac{d}{R_1}\right) & 0 & 0 \\ 0 & \left(1 - \frac{d}{R_1}\right) & 0 \\ 0 & 0 & 1 \end{Bmatrix} \begin{Bmatrix} X_{w_o} \\ Y_{w_o} \\ Z_{w_o} \end{Bmatrix} \quad (11)$$

From Eq. 11, any point on the crack front can be determined in a 3-D space.

AUTOMATIC MESH GENERATION FOR A CRACKED TUBULAR JOINT

Mesh Generation Scheme and Element Types

In the present study, a sub-zone technique is used in the mesh generation whereby the entire structure, as shown in Figs. 10a and 11a is divided into three main zones, namely, refined zones (Zone CF, Zone CF1 and Zone CRBLOCK), coarse zones (Zone A, Zone ER, Zone EL, EXTENCHL, EXTENCHR and Zone H) and transition zones (Zone B, Zone D, Zone G1 and Zone G2). In the zones with refined mesh, three layers of elements are generated in the thickness direction so as to model the crack depths. In the coarse mesh zones, only one layer of elements are generated in thickness direction.

Fig. 12 shows the mesh of CRBLOCK in a detailed view. CRBLOCK is extracted from Zone CF1 as shown in Figs. 10b and 11b. It must be noted here that, in Fig. 12, DCUBE-B is part of the sub-mesh in Zone CF1 and DCUBE-A is part of the sub-mesh in Zone D. It also should be emphasized that the number and location of elements extracted from Zone CF1 will depend on the crack length and position. Once the crack length and the crack position are determined, the number of elements to be extracted will be calculated automatically. This means a surface crack with any length at any fixed position can be generated automatically.

After extracting CRBLOCK from Zone CF1, all the elements in Zone CF1 are hexahedral elements since there is no crack in this zone. The mesh of CRBLOCK will be generated separately

since it can be extracted from Zone CF1. The modelling of the surface crack in detail is illustrated in Fig. 13. In the present study, five types of elements, as shown in Table 1, are used to generate the mesh of any cracked tubular joint. The elements in the first ring are quarter-point crack tip elements which consist of the crack front. The second ring consists of prism elements, which are used to connect the crack elements and pyramid elements. SFBLOCK-A, which is to connect with tube elements, consists of pyramid, prism and tetrahedral elements. It is a transition zone. However, as different types of elements are used in this zone, when merging CRBLOCK with Zone CF1 and Zone D, the incompatibility of the surface becomes a big problem. Because of this reason, tetrahedral and pyramid elements are used in DCUBE-A and DCUBE-B. These two blocks are used to link the side faces of block SFBLOCK-A.

After the meshes of all the zones have been generated, they are then merged together to form the mesh of the entire structure. Fig. 14 shows the mesh of typical T and K-joints after merging the meshes of all the zones.

In order to study the convergence of the SIF values of the tubular joint, one uniform refinement is carried out by doubling the mesh density (Lee et al., 2001). During the mesh generation procedure, the mesh generator will always refer to a carefully predefined geometrical model of the joint to capture all the detail features such as welding thickness and surface crack depth of the structures. As it can be seen clearly, the advantage of generating the mesh zone by zone is that only the region near the intersection are required to be modified when the surface crack details are added to the mesh.

The mesh generator has been designed and developed to model a wide range of geometry for tubular joints with a surface crack. In the current implementation of the program, the valid ranges of geometrical parameters which the mesh generator can handle are listed below:

- (1). Intersecting angle: $30^\circ \leq \theta \leq 90^\circ$
- (2). Ratio of brace to chord radius: $0.05 < r_3/R_1 < 0.8$
- (3). Ratio of brace's thickness to brace's radius: $0.03 < t_b/r_3 < 0.3$

ESTIMATION OF STRESS INTENSITY FACTORS

To estimate the remaining life of any tubular joint, the stress intensity factor (SIF) is frequently used by many researchers. In practice, the two most commonly used methods are the J -integral and the displacement extrapolation (Aliabadi and Rooke, 1991). The J -integral has been found to be insensitive to mesh refinement, but it can not be used directly in mixed mode problems. However, the Mode I, II & III SIFs can be obtained from the J -integral using an indirect way by introducing an interaction integral method (Shih and Asaro, 1988). It is also noted that J -integral lacks path independence in the region where the crack meets the weld toe because the stress at the toe and the crack tip is singular. On the other hand, the displacement extrapolation method is based on Westergaard's equations which relate the displacements in the vicinity of the crack front to the stress intensity factors. This method is not applicable for inelastic behaviour.

The J -integral is a measure of the strain energy in the region of the crack tip. Shih and Asaro (1988) had proposed the relationship between the J -integral and the SIFs as:

$$J = \frac{1}{8\pi} \mathbf{K}^T \cdot \mathbf{B} \cdot \mathbf{K} \quad (12)$$

where $\mathbf{K} = [K_I, K_{II}, K_{III}]^T$ and $\mathbf{B}$ is called the pre-logarithmic energy factor matrix. For homogeneous isotropic materials, $\mathbf{B}$ is a diagonal matrix and the above equation can be simplified as:

$$J = \frac{1}{\bar{E}} (K_I^2 + K_{II}^2) + \frac{1}{2G} K_{III}^2 \quad (13)$$

where $\bar{E} = E$ for plane stress and $\bar{E} = E/(1 - \nu^2)$ for plane strain, axisymmetry, and 3D problems.

It is obvious from Eq. 13 that it is easy to obtain the value of J -integral from K_I , K_{II} and K_{III} . However, it is not feasible to obtain K_I , K_{II} and K_{III} from J -integral directly. This means the J -integral method can not be easily used to analyze a mixed mode problem directly. Due to this problem, Shih and Asaro (1988) had proposed an interaction integral method to calculate K from the J -integral.

In the interaction integral method, generally, the J -integral for a given problem can be written as:

$$J = \frac{1}{8\pi} [K_I B_{11}^{-1} K_I + 2K_I B_{12}^{-1} K_{II} + 2K_I B_{13}^{-1} K_{III} + (\text{terms not involving } K_I)] \quad (14)$$

Here, the J -integral is defined as an auxiliary pure Mode-I crack-tip field with stress intensity factor k_I as follow:

$$J_{\text{aux}}^I = \frac{1}{8\pi} k_I \cdot B_{11}^{-1} \cdot k_I \quad (15)$$

Superimposing the auxiliary field onto the actual field yields:

$$J_{\text{tot}}^I = \frac{1}{8\pi} \left[(K_I + k_I) B_{11}^{-1} (K_I + k_I) + 2(K_I + k_I) B_{12}^{-1} K_{II} + 2(K_I + k_I) B_{13}^{-1} K_{III} \right] + (\text{terms not involving } K_I \text{ or } k_I) \quad (16)$$

Since the terms not involving K_I or k_I in J_{tot}^I and J are equal, the interaction integral can be defined as:

$$J_{\text{int}}^I = J_{\text{tot}}^I - J - J_{\text{aux}}^I = \frac{k_I}{4\pi} (B_{11}^{-1} K_I + B_{12}^{-1} K_{II} + B_{13}^{-1} K_{III}) \quad (17)$$

If the calculations are repeated for Modes-II and III, a linear system of equations can be obtained as:

$$J_{\text{int}}^\alpha = \frac{k_\alpha}{4\pi} B_{\alpha\beta}^{-1} K_\beta \quad (\text{on sum on } \alpha = \text{I, II, III}) \quad (18)$$

If the values of k_α are assigned unit values, the solution of the above equations leads to:

$$\mathbf{K} = 4 \pi \mathbf{B} \cdot \mathbf{J}_{\text{int}} \quad (19)$$

Therefore, once $\mathbf{J}_{\text{int}}$ is obtained, $\mathbf{K}$ can be calculated from Eq. 19. The detailed calculations of $\mathbf{J}_{\text{int}}$ can be found in the paper published by Shih and Asaro (1988), and this method has been implemented in the ABAQUS (2001) general finite element software. Figs. 15 and 16 show the computed values of K_I , K_{II} and K_{III} against the angle ϕ , the parametric angle along a crack front, with different mesh density for typical T and K-joints. They show that the SIF values converge as soon as the mesh density is doubled in the finite element model.

Both J -integral and displacement extrapolation methods depend on good quality mesh near the vicinity of the crack front to yield accurate SIFs. Generally, it is a difficult and time-consuming process to model the surface crack. The discontinuity of the curvature at the weld toe and the crack tip makes the mesh near these zones more complicated in the analysis. In practice, the deepest point and the two crack tips are the most important positions in practice. For practical reasons, Bowness and Lee (Bowness and Lee 1998, 2000; Lee and Bowness, 2001) had proposed a simple way to estimate the SIFs at some crucial positions of the surface crack in tubular joints. This method uses the T-butt solutions (Newman and Raju, 1981) in conjunction with the stress concentration factors (SCFs) and the degree of bending (DOB) in the uncracked tubular joints. It avoids generating mesh to model the surface crack. In Bowness and Lee's method, the SIF for a crack in any tubular joint can be approximated by

$$K \approx [M_{km} M_m \text{SCF}(1 - \text{DOB}) + M_{kb} M_b \text{SCF} \cdot \text{DOB}] \sigma_{\text{nom}} \sqrt{\pi a} \quad (20)$$

where a is the crack depth, M_{kj} and M_j are the weld toe magnification factors and plain plate shape factors respectively. The subscripts $j=m, b$ denote membrane and bending loading respectively. SCF is the stress concentration factor and DOB is the degree of bending at the would-be location of the crack, and σ_{nom} is the nominal stress in the reference brace of the joint.

In Eq. 20, the weld toe magnification factors M_{kj} can be obtained from equations provided by Bowness and Lee (2000). Plain plate shape factors M_j may be obtained from standard T-butt solutions by Newman and Raju (1981). DOB is a parameter to judge the bending degree of tubular joints which is defined by Lee and Bowness (2001) as follow:

$$\text{DOB} = \frac{\sigma_b}{\sigma_b + \sigma_m} \quad (21)$$

where σ_b and σ_m are bending stresses and membrane stresses respectively. Parametric equations of DOB are available in Morgan and Lee (1998). The values of these parameters can also be obtained from numerical analysis of uncracked tubular K-joints.

EXPERIMENTAL TESTS OF T AND K-JOINTS

In order to check the accuracy and validity of the proposed numerical model, a full-scale T and K-joint, were each tested to failure under combined loads. The basic dimensions of the joints are given in Fig. 17. Structural steel pipes to API 5L Grade B specifications were used for the specimens. A specially designed test rig was used to test the tubular joints under AX, IPB, and OPB. The rig is capable of applying static loading on a joint specimen to determine the HSS distributions in the joint, as well as cyclic loading to study the fatigue performance and fracture behaviour of the joint. Two 250kN (numbers 1 and 2) and one 100kN (number 3) capacity servo-hydraulic actuators were installed to apply the three basic load cases using the Instron Labtronic 8800 digital controller. The loads were applied along the two mutually perpendicular axes. The actuators can also be operated individually or concurrently to enact a multi-axis loading condition. Both the 250kN and 100kN actuators were used to apply AX, IPB and OPB respectively. A tension loading is defined as positive load and compression is defined as negative load for all the actuators. The chord ends of the specimen were rigidly mounted on the rig using eight bolts per chord end, creating a fixed condition for the chord ends. In the experimental tests, a distance greater than 6 chord diameters between the support and connection was used to ensure that the stresses at the brace-chord intersection are not affected by the end conditions.

Fatigue cracks on these joints generally initiate from the location of peak hot spot stress (HSS). Therefore, static tests were first carried out to investigate the stress distribution around the brace-chord intersection of T and K-joints specimens subjected to basic and multi-axis load cases, and determine the peak HSS position on the joints before fatigue testing. In this study, a small chord diameter/thickness ratio of $D/t=14$ was used for tubular T-joint specimen, and a ratio of $D/t=10.75$ was used for tubular K-joint specimen. These ratios are slightly out of the normal range ($15 \leq D/t \leq 64$). Joints with such small chord diameter/thickness ratio of $D/t=10.16 \sim 14.12$ had been used in practice (Schumacher et al., 2001). Hence, the static test can also be used to investigate the validity

of the existing stress concentration factor (SCF) equations if the chord diameter/thickness ratio (D/t) of the joint is slightly outside the valid range.

For the fatigue test, the specimens were tested in air under a sinusoidal constant amplitude loading until failure using the test rig. A stress ratio of $R=0$ and a frequency of 0.2-1.0Hz was used throughout the test. The cyclic loading patterns applied to the specimen are shown in Figs. 18 and 19. The maximum/minimum values of the AX, IPB, and OPB are 100kN/0kN, 8kN/0kN, 4kN/0kN for the T-joint, and 150kN/0kN, 15kN/0kN, 0kN/0kN for the K-joint respectively. During the test, all the actuators were preset under the load control condition.

Stress Distribution along the Weld Toe

In order to measure the stress distribution along the weld, strain gauges were placed around the entire chord-brace intersection on both brace and chord at 15° intervals. At each spot, a pair of strain gauges was used to measure the distributions of the strain components perpendicular to the weld toe. The arrangement of the two strain gauges followed the linear extrapolation region recommended by CIDECT (Zhao et al., 2000). The hot spot strain was obtained by linear extrapolation of the results from these two strain gauges to the weld toe. In order to monitor the actual brace load, four additional strain gauges were placed at the midpoint of the brace. They were placed at 90° intervals around the outer surface so that the two of them were in the in-plane positions while the other two were in the out-of-plane positions.

An AX, IPB, OPB of 100kN, 8kN, 4kN, and 150kN, 15kN, 0kN were applied at the brace end of the T and K-joints respectively. The hot spot stress distribution along the chord weld is plotted and shown in Figs. 20 and 21. It is apparent that the hot spot stress lies at the crown on the chord, with a value of about 182MPa and 279MPa for the T and K-joints respectively. The definition of some critical positions such as crown, heel and saddle is shown in Fig. 22. Because the stress distribution along the chord weld is almost symmetrical, it is likely that the crack will initiate at the crown and

propagate along the weld toe symmetrically. Therefore, the ACPD probes should be concentrated at this region to monitor the fatigue crack development of the tubular specimens.

Crack Growth Rate of a Surface Crack

The ACPD technique is a well-established technique (Dover et al., 1995) which can be used to monitor the depth and shape of growing fatigue cracks in any tubular joint. It was used to monitor the fatigue crack development of the K-joint specimen. Basically, it uses an alternating current (a.c.) with a high frequency of about 5k Hz, induced on the surface of any ferromagnetic material. When this alternating current passes through a conductor, the so-called “skin effect” forces the current to flow in a thin layer on the outer surface. This concept can be illustrated in Fig. 23 where V_R is the reference potential drop, V_C is the cross-crack potential drop, Δ_R is the reference probe gap, Δ_C is the cross-crack probe gap, and d_1 is the crack depth at that particular probe or site. If Δ_R and Δ_C as shown in Fig. 23 used are the same ($\Delta_R = \Delta_C = \Delta$) (Huang, 2003), then the crack depth is given by:

$$d_1 = (\Delta/2) \{V_C/V_R - 1.0\} \quad (22)$$

Thus, only reference probe gap Δ is necessary to determine d_1 . Fortunately, Δ is easier to measure accurately since it does not lie across the re-entrant corner of the weld toe. The probes were equally spaced at every 10mm around the connection at the hot spot site as shown schematically in Figs. 24 and 25. A special ACPD instrument called a U10 Crack Microgauge with an integral 128 channel multiplexer unit (Technical Software Consultant Ltd, 1991) was connected to these probes. A single ACPD site requires two channels, one each for the crack and reference readings resulting in a total capacity of 64 fixed ACPD sites. These 64 ACPD sites can be divided equally or weighted towards the hot spot region. A maximum of four fields can be used simultaneously in a test, but the total ACPD sites can not exceed 64 numbers. In the present study, each field had 8 ACPD sites resulting in the total number of 32 ACPD sites only. The fatigue crack

development shape was recorded at every 225 cycles using the Flair software (Technical Software Consultant Ltd, 1998). Once the surface crack had penetrated the chord thickness, the whole test and scanning stopped automatically.

Experimental Observations and Results

A FORTRAN program had been written to analyze the ACPD raw crack depth readings, and to calculate the initial and final crack depth readings from all the scans. The modified ACPD crack development plots of two specimens are plotted in Figs. 26 and 27. In order to check the crack shapes physically after the specimens had failed, the joints were split into two parts along the crack surface. It is found that in the T-joint specimen, several small cracks first initiated and then coalesced one by one. As expected, the crack tends to initiate at the crown and propagate through the chord thickness and along the weld toe. The crack deepest point always lies nearly at the crown during the crack propagation because the hot spot stress is located at this point.

The crack growth curves at these positions, at which the cracks penetrated the chord wall according to the ACPD readings in the two specimens, were kept, and a Fortran program was developed to smooth out these data by a polynomial fitting technique. In the program, a polynomial was used to fit the crack depth data, and then the crack growth rate can be determined from differentiation of this polynomial. The crack growth rates da/dN of these deepest points are shown in Figs. 28 and 29 for the T and K-joints respectively.

The rate of crack propagation at the deepest point for the K-joint is quite similar to that of the T-joint after the crack depth exceeds half of the chord thickness. It increases more rapidly after a/T equal to 0.8. This means that the fatigue behaviour of a tubular K-joint is not entirely the same as that of a tubular T-joint. This is possibly due to the fact that the other brace provides compressive restraint at the hot spot stress region.

The earlier proposed mesh generation technique is then used to produce the finite element models for simulating the tested specimens. The experimental SIFs are validated against the

computed SIFs obtained from these models directly. The geometry and the material properties of the models are the same as those of the specimens used in the tests. The crack locations, crack deepest point positions and the applied loads of the models are all based on the information obtained from the specimens and experimental settings where a/T is the ratio of crack depth a to chord thickness T , c is the half-length of crack on the chord surface, and the applied loadings were obtained from the readings of strain gauge on the brace directly. The boundary conditions are that the two ends of the chord are fixed rigidly against any displacements and rotations, and the end of the brace is free.

The crack surface of the T and K-joints under combined AX, IPB and OPB loads is a mixed mode, and generally Mode I is the dominant one. Therefore, previous studies have concentrated on the calculation of K_I only. For the sake of comparison, K_I , K_{II} and K_{III} are combined together and they are represented by an equivalent stress intensity factor called K_e , which is the crack driving force parameter for a mixed mode fracture problem. This parameter was proposed by Chong Rhee (1991) and it is expressed as:

$$K_e = [K_I^2 + K_{II}^2 + K_{III}^2 / (1 - \nu)]^{1/2} \quad (23)$$

where ν is Poisson's ratio. From Figs. 15 and 16, it is obvious that the values of K_I and K_e are very similar, while K_{II} and K_{III} only occupy a small percentage of K_e . This means that for any tubular joint under combined AX, IPB and OPB loads, the relative movement between the two crack surfaces is mainly opening.

The experimental stress intensity factors can be obtained from the well known Paris' equation:

$$da/dN = C(\Delta K)^m \quad (24)$$

where da/dN is the crack growth rate which are already obtained from the experimental tests, ΔK is the range of the stress intensity factor, C and m are material constants. These values of C and

m supplied by the steel manufacturer, are $1.45 \times 10^{-11} \text{ (m/cycle)(MPa}\cdot\text{m}^{1/2})^{-2.75}$ and 2.75 respectively.

The comparisons of the numerical and experimental results at the deepest position are shown in Figs. 30 and 31. From these graphs, it appears both the results from Bowness & Lee's Equation (Eq. 20) and the computed numerical results obtained in this study are conservative compared to the experimental results in the sense that the predicted SIFs are higher than the experimental results. (A higher SIF will lead to a lower value of estimated number of cycles before failure according to Eq. 24.) Thus, numerical results obtained from the proposed generated model are safe to be used for estimating the residual life of the K-joint. It can also be seen that the two values of K_I and K_e are very close to each other. This means that crack Mode I is dominant in the mixed mode crack growth case. Another important point to observe is that the stress intensity factors modelled using the actual weld size are different from the results obtained using the AWS specifications (2000). The estimated relative errors are approximately 10%. From Fig. 31, the SIF results obtained using the AWS specifications (2000) are higher than the corresponding SIF values obtained using the actual weld size. This means the weld size will influence the numerical results, and the numerical results obtained using the actual weld size are closer to the experimental results for the K-joint.

SUMMARY AND CONCLUSIONS

In this paper, a sub-zone technique to generate consistent and accurate geometrical finite element models for general cracked tubular welded joint is proposed. The models generated by this technique can include a surface crack of arbitrary length and location along the intersection of the brace and chord. This modelling technique is then used to analyze tubular T and K-joint specimens to obtain the stress intensity factors along the crack front using the J -integral method. Full-scale T and K-joint specimens were fabricated and tested to failure under axial load (AX) and in-plane bending (IPB), and out-plane-bending (OPB) combined loads. Static tests were first carried out to

determine the peak hot spot stress (HSS) and its location when the joint was subjected to these load cases. The peak HSS location was used to determine the placement of the crack growth monitoring probes. An alternating current potential drop (ACPD) technique was then employed to monitor the crack growth and crack shape development on the joint at a preset number of cycles. The crack growth curves and crack growth rate of the specimen were analyzed, and using the Paris' equation, the experimental stress intensity factors were obtained at the crack deepest point. The numerical SIFs were then compared with the experimental ones based on the Paris' law equation for the purpose of validating the models. Generally, the agreement between the numerical and experimental results is good and reasonable. It confirms that the generated finite element model of the cracked welded tubular joints is both consistent and reliable.

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Fig. 1 Definition and geometry of a welded tubular Y-joint

Fig. 2 Inner and outer intersecting curves with the weld path

Fig. 3 Inner and outer dihedral angle

Fig. 4 Enlarged view of geometry and modelling of the weld path

(a) Modelling of welded joint ($30^\circ \le \gamma < 90^\circ$) – Section 1–1 in Fig. 2

(b) Modelling of welded joint ($90^\circ \le \gamma < 180^\circ$) – Section 2–2 in Fig. 2

Fig. 5 Modelling of a welded tubular joint

Fig. 6 Definition of a crack surface

Fig. 7 Mapping a surface crack from a 2-D plane to a 3-D surface

Fig. 8 Location of surface crack on a local polar u-v coordinate system

Fig. 9 Location of surface crack defined on global X-Y-Z coordinate system shown on Y-Z plane

(a) Zones of the different regions

(b) Zone CF1 and zone CRBLOCK

Fig. 10 Generated mesh of a T-joint with a surface crack

(a) Zones of the different regions

(b) Zone CF1 after extracting zone CRBLOCK

Fig. 11 Generated mesh of a K-joint with a surface crack

Fig. 12 CRBLOCK extracted from Zone CF1 and Zone D

Fig. 13 Detailed mesh along the crack front

(a) T-joint

(b) K-joint

Fig. 14 The mesh of the joints after merging all the zones

Fig. 15 SIF results along a crack front with different mesh density for a T-joint

(a) K_I results

(b) K_I , K_{II} , K_{III} and K_e results

Fig. 16 SIF results along a crack front with different mesh density for a K-joint

(a) T-joint

(b) K-joint

Fig. 17 Specimen dimensions of the full-scale joints

Fig. 18 Cyclic loads applied to the T-joint specimen

Fig. 19 Cyclic loads applied to the K-joint specimen

Fig. 20 Hot spot stress distribution along the chord weld for the T-joint

Fig. 21 Hot Spot stress distribution along the chord weld for the K-joint

Fig. 22 Definition of some critical positions

Fig. 23 ACPD theory and notation

Fig. 24 Schematic siting of the probes in the T-joint

Fig. 25 Schematic siting of the probes in the K-joint

Fig. 26 Crack shape profile of the T-joint plotted using an interval of 45000 cycles

Fig. 27 Crack shape profile of the K-joint plotted using an interval of 10000 cycles

Fig. 28 Crack grows rate at the deepest point for the T-joint

Fig. 29 Crack grows rate at the deepest point for the K-joint

Fig. 30 Comparison of SIFs from experimental test of the T-joint

Fig. 31 Comparison of SIFs from experimental test of the K-joint

Element Types		No. of Nodes	
1.	Hexahedral / Cubic Element – (H20)	20
2.	Prism/Wedge – (P15)	15
3.	Quarter Point / Crack Element – (QP15) (Collapsed Prism)	15
4.	Tetrahedron – (T10)	10
5.	Pyramid – (PR20) (Collapsed Hexahedral)	20

Table 1 Element types used in the mesh generation for cracked tubular joints