文章编号:0253-2778(2019)09-0723-08

Three-dimensional static linear elasticity crack path prediction

CHEN Chong[1,2], YANG Dapeng[3,4,5]

(1. *Department of Urban Rail Transport, Zhengzhou Technical College, Zhengzhou* 450121, *China*;
2. *School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai* 200240, *China*;
3. *Postdoctoral Mobile Station of Mechanical Department, School of Civil Engineering & Mechanics, Huazhong University of Science and Technology, Wuhan* 430074, *China*;
4. *Department of Material Engineering, Zhengzhou Technical College, Zhengzhou* 450121, *China*;
5. *School of Naval Architecture & Ocean Engineering, Huazhong University of Science and Technology, Wuhan* 430074, *China*)

Abstract: Three-dimensional static stress intensity factors were analyzed for a curved crack by using a second order perturbation method. The method was extended to obtain an approximate representation of a three-dimensional static stress intensity factors at the tip of a curved crack. The criterion of elastic bending crack propagation the three-dimensional body was summarized. The shape parameters of three-dimensional linear elastic bending crack propagation were figured out. A static energy release rate due to three-dimensional curved crack growth could be calculated by using Irwin's formula. Considerations were made for a three-dimensional static curved crack in materials with inhomogeneous fracture toughness. As far as homogeneous matter was concerned, in the framework of the second-order perturbation analysis theory, the two criteria indicated the same three-dimensional static load bending crack propagation path. However, the energy criterion was superior to the stress criterion in materials with non-uniform fracture toughness. Three-dimensional static curved crack path destabilizing factors were compared and analyzed. Critical relations between the material degradation and the static applied stress or the outer static stress for various initial three-dimensional crack lengths have been studied.

Key words: a second order perturbation method; three-dimensional static stress intensity factor; curved crack; fracture toughness; static applied stress

CLC number: TP301 **Document code**: A doi:10.3969/j.issn.0253-2778.2019.09.005

Citation: CHEN Chong, YANG Dapeng. Three-dimensional static linear elasticity crack path prediction[J]. Journal of University of Science and Technology of China, 2019, 49(9): 723-730.
陈冲,杨大鹏. 静载荷作用下三维线弹性弯曲裂纹路径预测[J]. 中国科学技术大学学报,2019,49(9):723-730.

静载荷作用下三维线弹性弯曲裂纹路径预测

陈 冲[1,2],杨大鹏[3,4,5]

Received: 2017-06-08; **Revised**: 2018-01-05

Foundation item: Supported by 2017 Science and Technology Research Plan Project of Science and Technology Department of Henan Province(172102210567).

Biography: CHEN Chong, male, born in 1981, PhD/associate Prof. Research field: Material processing engineering, mechanical properties of materials. E-mail: chongzzy@126.com

Corresponding author: YANG Dapeng, PhD/Prof. E-mail: ydpzpysh@163.com

(1.郑州职业技术学院城市轨道交通系,河南郑州 450121;2.上海交通大学材料科学与工程学院,上海 200240;
3.华中科技大学土木工程与力学学院力学系博士后流动站,湖北武汉 430074;
4.郑州职业技术学院材料工程系,河南郑州 450121;
5.华中科技大学船舶与海洋工程学院,湖北武汉 430074)

摘要:利用二阶摄动方法研究了静载荷作用下结构线弹性裂纹的弯曲扩展问题、裂纹路径预测时的应力准则与能量准则之间的关系,并求解出三维静态应力强度因子.归纳总结出三维线弹性弯曲裂纹扩展的判据,求解出三维线弹性弯曲裂纹扩展过程中的形状参数.利用 Irwin 公式计算出三维弯曲裂纹扩展引起的静态能量释放速率.研究了具有非均匀断裂韧性的材料的三维静态弯曲裂纹.就均匀物质而言,在二阶摄动分析理论的框架内,两种准则指明了相同的三维静荷载弯曲裂纹扩展路径.但在具有非均匀断裂韧度的物质中,能量准则优越于应力准则.对三维静态弯曲裂纹路径失稳因素进行了比较和分析,研究了不同初始三维裂纹长度下材料退化与静施应力或外静应力之间的临界关系.

关键词:二阶摄动方法;三维静态应力强度因子;弯曲裂纹;断裂韧度;静施应力

0 Introduction

Perturbation analyses for a quasi-static slightly curved crack were first performed by Banichuk[1], and Goldstein and Salganik[2-3], in which they satisfied the boundary conditions approximately along the slightly curved crack surfaces with the use of Muskhelishvili's complex potentials. Having obtained a rather simple expression of stress intensity factors by using the same method, Cotterell and Rice[4] examined the crack growth path of a semi-infinite crack in an infinitely extended plane. A second order perturbation solution was calculated by Karihaloo et al.[5], in which they considered a straight crack of finite length with slightly kinked-curved extension in an unbounded plane that was subjected to uniaxial tensile stress at infinity. First order perturbation analyses were also performed by Sumi et al.[6-7] for a straight crack in a finite body with a slightly branched and curved extension. The shape of branched and curved extension is approximated by a continuous function with three shape parameters, and the approximate stress intensity factors at the extended crack tip are obtained in terms of these parameters and the near tip stress field parameters ahead of the crack tip prior to its extension, where the effects of the geometry of the domain are also taken into account. Yang et al.[8] have obtained approximate descriptions of the stress intensity factors at the two dimensional curved crack tip, where the cracked body is subjected to dynamic loads. Wu[9], Amestoy and Leblond[10] have acquired the exact asymptotic results of the path of a crack warp ramification and of the stress intensity factors existing in the crack warp ramification tip. But as far as the application of second order perturbation solution is concerned, the research productions were all localized in those of two-dimensional crack warp developments in weldment while enduring loads of static state on linear elasticity conditions[13]. So far, little attempt has been made to study the problem of a three-dimensional, curved and elastic crack developing under static load by means of second order perturbation analysis.

In this paper, static stress intensity factors of three-dimensional curved crack tips have been analyzed and calculated on the basis of the research production of Refs.[6-7]. Furthermore, the shape of a three-dimensional curved crack has been predicted when the crack body is under static load. When enduring multidirectional static loads, the original three-dimensional straight crack will curve because of uneven fracture toughness or material inhomogeneity such as a local degradation zone. Using a second order perturbation analysis solution, fracture behaviors of a three-dimensional brittle curved crack will be studied on.

1 Approximate description of a three-dimensional curved crack in a finite body receiving static load

1.1 Modification of the second order perturbation solution to a three-dimensional curved crack

According to subsistent research products[8,16,17], approximate description of the three-dimensional static stress intensity factor amplitudes, $K_{IZ}^{(\infty)}$ and $K_{IIZ}^{(\infty)}$, are calculated and given as:

$$K_{IZ}^{(\infty)}=\sqrt{F(T_Z)}K_I^{(\infty)}=\sqrt{F(T_Z)}\{(1-\frac{3}{8}\alpha^2)k_I-\frac{3}{2}\alpha k_{II}-[\frac{9}{4}\beta k_{II}+\frac{9}{8}\alpha\beta k_I-2\sqrt{\frac{2}{\pi}}\alpha^2 T]a^{\frac{1}{2}}+[\frac{1}{2}(1+\frac{9}{8}\alpha^2)b_I-\frac{5}{4}ab_{II}-3\gamma k_{II}+\frac{11}{2}\sqrt{\frac{2}{\pi}}\alpha\beta T-(\frac{27}{32}\beta^2+\frac{3}{2}\alpha\gamma)k_I]a\}+O(a^{\frac{3}{2}}) \quad (1)$$

$$K_{IIZ}^{(\infty)}=\sqrt{F(T_Z)}K_{II}^{(\infty)}=\sqrt{F(T_Z)}\{(1-\frac{7}{8}\alpha^2)k_{II}+\frac{1}{2}\alpha k_I+[\frac{3}{4}\beta k_I+\left(\frac{2}{\pi}-\frac{21}{8}\right)\alpha\beta k_{II}-2\sqrt{\frac{2}{\pi}}\alpha T]a^{\frac{1}{2}}+[\frac{1}{2}(1-\frac{27}{8}\alpha^2)b_{II}-\frac{\alpha}{4}b_I+\gamma k_I-\frac{3\sqrt{2\pi}}{4}\beta T-[(\frac{63}{32}-\frac{2}{\pi})\beta^2-\frac{5}{2}\alpha\gamma]k_{II}]a\}+O(a^{\frac{3}{2}}) \quad (2)$$

And the finite body corrections of the static stress intensity factors at the three-dimensional curved crack tip are given by:

$$K_{IZ}^{(f)}=F\sqrt{(T_Z)}K_I^{(f)}=\sqrt{F(T_Z)}\{\{[(1-\frac{3}{8}\alpha^2)k_I-\alpha k_{II}]\overline{k}_{11}+[(1-\frac{1}{8}\alpha^2)k_{II}-\alpha k_I]\overline{k}_{12}-\frac{3}{2}\alpha[k_I-\alpha k_{II}]\overline{k}_{21}-\frac{3}{2}\alpha[k_{II}-\alpha k_I]\overline{k}_{22}\}a\}+O(a^{\frac{3}{2}}) \quad (3)$$

$$K_{IIZ}^{(f)}=F\sqrt{(T_Z)}K_{II}^{(f)}=\sqrt{F(T_Z)}\{\{[(1-\frac{7}{8}\alpha^2)k_I-\alpha k_{II}]\overline{k}_{21}+[(1-\frac{5}{8}\alpha^2)k_{II}-\alpha k_I]\overline{k}_{22}+\frac{1}{2}\alpha[k_I-\alpha k_{II}]\overline{k}_{11}+\frac{1}{2}\alpha[k_{II}-\alpha k_I]\overline{k}_{12}\}a\}+O(a^{\frac{3}{2}}) \quad (4)$$

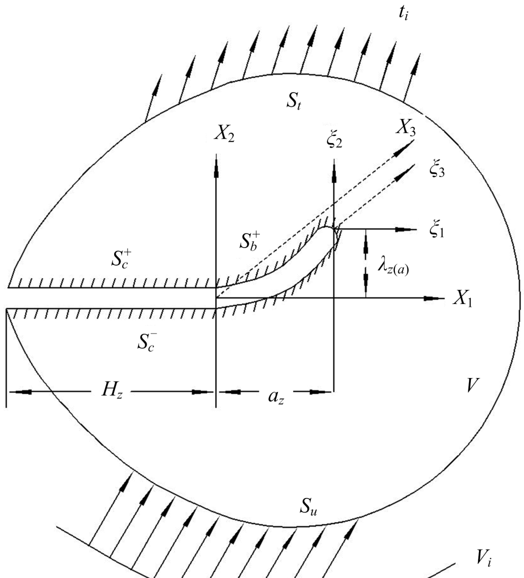

Fig. 1 A three-dimensional curved crack in a finite body enduring static load

Therefore, the three-dimensional static stress intensity factor amplitudes K_{IZ} and K_{IIZ} at the three-dimensional curved crack tip are respectively given by

$$K_{IZ}=\sqrt{F(T_Z)}K_I=\sqrt{F(T_Z)}[K_I^{(\infty)}+K_I^{(f)}]+O(a^{\frac{3}{2}}) \quad (5)$$

$$K_{IIZ}=\sqrt{F(T_Z)}K_{II}=\sqrt{F(T_Z)}[K_{II}^{(\infty)}+K_{II}^{(f)}]+O(a^{\frac{3}{2}}) \quad (6)$$

K_{IZ} and K_{IIZ} are the three-dimensional static stress intensity factors containing three axis stress constraint.

$$F(T_Z)=\frac{2}{3}(1+\nu)+\frac{4}{3}(1-\nu)(1+T_Z)^2/(1-2T_Z)^2 \quad (7)$$

T_Z is off surface confinement factor[16-17]. See Ref. [18] for the meaning of the remaining parameter symbols.

1.2 Criterion of the three-dimensional curved static crack unsteady extending

Let static fracture toughness of the three-dimensional crack body be K_{CZ}, type one static fracture toughness of the three-dimensional crack body be K_{ICZ} and type two static fracture toughness of the three-dimensional crack body be K_{IICZ}. Thereinto: $K_{\mathrm{I}CZ}$, $K_{\mathrm{II}CZ}$ are material constants.

Steady condition or criterion of the three-dimensional static curved crack:

$$(K_{IZ})_{\max} < K_{ICZ} \text{ and } (K_{IIZ})_{\max} < K_{IICZ} \quad (8)$$

Condition or criterion of three-dimensional static curved crack unsteady extending:

$$(K_{IZ})_{\max} \geqslant K_{ICZ} \text{ or } (K_{IIZ})_{\max} \geqslant K_{IICZ} \quad (9)$$

Combining (5), (6), (7), (8) and (9), we can know the extending state of the three-dimensional static curved crack.

2 Discussion on static crack path criteria

2.1 Static energy release rate

Based on the research production of Bilby and Cardew[11], the static elastic energy release rate G_Z, due to the slightly branched and curved crack extension in homogeneous materials under static load can be calculated as

$$G_Z = \frac{1-\nu}{2\mu}(K_{IZ}^2 + K_{IIZ}^2) \quad (10)$$

in which μ and ν are shear modulus and Poisson's ratio respectively, and K_{IZ} and K_{IIZ} are the three-dimensional static stress intensity factors at the extended crack tip. According to subsistent research products[8,16], G_Z is given by

$$\begin{aligned} G_Z = {} & G_{0Z}[\alpha_Z; k_{IZ}, k_{IIZ}] + \\ & G_{\frac{1}{2}Z}[\alpha_Z, \beta_Z; k_{IZ}, k_{IIZ}, T_Z] a_Z^{1/2} + \\ & G_{1Z}[\alpha_Z, \beta_Z, \gamma_Z; k_{IZ}, k_{IIZ}, T_Z; \\ & b_{IZ}, b_{IIZ}; \bar{k}_{ij}] a_Z + O(a_Z^{3/2}) \end{aligned} \quad (11)$$

The three-dimensional static energy release rate of the three-dimensional curved crack is initially governed by the first term G_{0Z} which is written as

$$G_{0Z}[\alpha_Z; k_{IZ}, k_{IIZ}] = \frac{1-\nu}{2\mu}\left[\left(1-\frac{\alpha_Z^2}{2}\right)k_{IZ}^2 - 2\alpha_Z k_{IZ} k_{IIZ} + \left(1+\frac{\alpha_Z^2}{2}\right)k_{IIZ}^2\right] \quad (12)$$

The first and second variations of G_{0Z} are calculated as

$$\delta_{\alpha_Z}(G_{0Z}) = -\frac{1-\nu}{2\mu}[(k_{IZ}^2 - k_{IIZ}^2)\alpha_Z + 2k_{IZ}k_{IIZ}]\delta\alpha_Z \quad (13)$$

$$\delta_{\alpha_Z}^2(G_{0Z}) = -\frac{1-\nu}{2\mu}(k_{IZ}^2 - k_{IIZ}^2)(\delta\alpha_Z)^2 \quad (14)$$

As far as the condition $(k_{IZ})_{\max} \gg (k_{IIZ})_{\max}$ holds, Eqs. (13) and (14) indicate that the branch angle α_Z is given by

$$\alpha_Z = -\frac{2k_{IZ}k_{IIZ}}{k_{IZ}^2 - k_{IIZ}^2} = -\frac{2k_{IIZ}}{k_{IZ}} + O\left[\left(-\frac{2k_{IIZ}}{k_{IZ}}\right)^3\right] \quad (15)$$

which gives rise to the three-dimensional maximum static elastic energy release rate of the crack body.

One of the criteria often used in crack path prediction is the condition of local symmetry, which requires that k_{IIZ} vanish along curved crack[8]. When the crack body is receiving static load, these criteria will demand that the discretionary k_{IIZ} due to static loads all vanish along curved crack extension. This means that in homogeneous materials both criteria designate equivalent crack paths within the second order approximation theory.

2.2 The effects of inhomogeneous distribution of three-dimensional static fracture toughness

Here a crack under pure static loading condition is considered, whose tip intersects a specially oriented line degradation zone at angle α_Z^* (see Fig. 2), and where the critical static energy release rates for the base material and the degraded material are G_{CZ} and G_{CZ}^*, respectively. The three-dimensional static stress intensity factor at the instance of fracture is calculated from Eq. (12) and given by

$$k_{IZ} = \sqrt{F(T_Z)}\, k_I = \sqrt{F(T_Z)}\sqrt{\frac{2\mu G_C}{1-\nu}} \quad (16)$$

By comparison, if the crack extends in the degraded zone, the kink angle is α_Z^* and the static

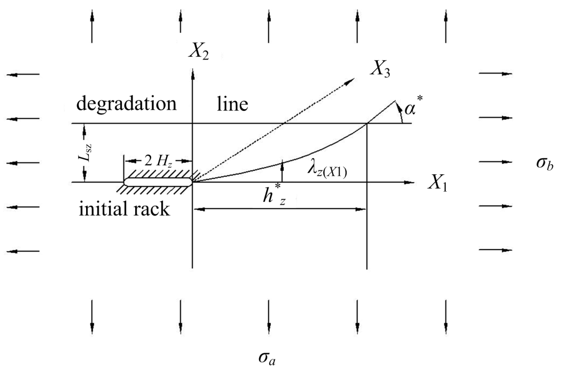

Fig. 2 A mathematical modeling of three-dimensional curved crack propagation along a welded joint under static load

stress intensity factor prior to the crack extension is also calculated from Eq. (12) as

$$k_{IZ}^{*}=\sqrt{F(T_Z)}k_I^{*}=\sqrt{F(T_Z)}\sqrt{\frac{2\mu G_C^{*}}{(1-\nu)[1-(\alpha_Z^{*})^2/2]}} \quad (17)$$

The three-dimensional static curved crack can extend in the degraded zone under the condition

$$(k_{IZ}^{*})_{\max}<(k_{IZ})_{\max} \quad (18)$$

Substitution of Eqs. (16) and (17) into (18) results in the following relation between the angle of inclination and the material properties.

$$G_{CZ}^{*}<[1-\frac{(\alpha_Z^{*})^2}{2}]G_{CZ} \quad (19)$$

3 The three-dimensional curved crack path prediction of brittle fracture in weldment under static load

3.1 An analytical model of a linear elasticity crack in weldment

Based on the aforementioned static crack analysis, researches have been made on a transverse welded joint in an infinite plate under a uniaxial tensile stress σ_a and the longitudinal component of welding static residual stress σ_b which is acting parallel to the welded joint, the stresses are accordingly static in the region. As shown in Fig. 2 the initial crack of length $2H_z$ is assumed to be parallel to the welding line. Material deterioration is observed along the heat affected zone, which is modeled as a line degradation being also parallel to the welded joint with the distance L_{SZ} from the initial crack line. The resistance forces of three-dimensional static curved crack propagation can be denoted by G_{CZ} for base and weld metals, and G_{CZ}^{*} for the heat affected zones respectively. Brittle static crack propagation is assumed to occur from the right hand side of the crack tip where the origin of the Cartesian coordinate system $O\text{-}X_1X_2X_3$ is established. Since a slightly warp ramification extension under static stresses may be expected, the static crack intersects the degradation line at angle α_Z^{*} with $x_1=h_z^{*}$.

The stress field parameters at the original crack tip are obtained as

$$\left.\begin{aligned}
&k_{IZ}=\sqrt{F(T_Z)}k_I=\sigma_a\sqrt{\pi HF(T_Z)},\\
&T_Z=\sqrt{F(T_Z)}T=\sqrt{F(T_Z)}(\sigma'_r-\sigma_a),\\
&b_{IZ}=\sqrt{F(T_Z)}b_I=\frac{3}{4}\sigma_a\sqrt{\pi F(T_Z)/H_Z},\\
&(k_{IIZ})_{\max}=(b_{IIZ})_{\max}=0,\ (k_{IIZ})_{\min}=(b_{IIZ})_{\min}=0,\\
&\bar{k}_{11}=\bar{k}_{22}=-\frac{1}{8H_Z},\ \bar{k}_{12}=\bar{k}_{21}=0
\end{aligned}\right\} \quad (20)$$

3.2 Three-dimensional static crack path prediction

As was discussed in the previous subsection, in the case where the initial crack tip is contained in a homogeneous material under static load, a static crack path can be determined by the local symmetry criterion, which is equivalent to the condition $K_{IIZ}=0$ along the curved trajectory. The three-dimensional static curved crack path is approximated by Eq. (22), and the shearing mode of stress intensity factor can be approximated by the first order terms of Eq. (6). Putting the equation to be identically zero and disregarding the second order terms, the shape parameters of the static curved crack path are determined as

$$\left.\begin{aligned}
&\alpha_Z=-\frac{2k_{IIZ}}{k_{IZ}},\\
&\beta_Z=\frac{8}{3}\sqrt{\frac{2}{\pi}}\frac{\alpha_Z T_Z}{k_{IZ}},\\
&\gamma_Z=-(k_{IIZ}\bar{k}_{22}+k_{IZ}\bar{k}_{21}+\frac{b_{IIZ}}{2})\frac{1}{k_{IZ}}+\\
&\{[k_{IZ}(2\bar{k}_{22}-\bar{k}_{11})+\frac{b_{IZ}}{2}]\frac{1}{2k_{IZ}}+4(\frac{T_Z}{k_{IZ}})^2\}\alpha_Z
\end{aligned}\right\} \quad (21)$$

Substituting (20) into (21), $\alpha_Z=\beta_Z=\gamma_Z=0$ will be obtained.

This three-dimensional straight static crack extension could occur only in the perfect system, which means that the loading condition and the geometry have the perfect symmetry with respect to the crack line . Let us study the case in which non-collinear crack propagation is caused by some load induced disturbances in the system with a small initial three-dimensional kink angle α_Z at the original crack tip used as the imperfection parameter of the system.

The shape of the three-dimensional static crack growth is acquired in the following form[8]:

$$\lambda_Z(x_1)=\alpha_Z x_1+\beta_Z x_1^{3/2}+\gamma_Z x_1^2+O(x_1^{5/2}),\ x_1\geqslant 0 \tag{22}$$

where α_Z, β_Z and γ_Z are the shape parameters.

The three-dimensional static crack path stability is then examined by considering the second and third terms of (22). The effect of static crack path stability should be examined by means of the rest of the terms being proportional to α_Z. So the three-dimensional static crack path stability should be evaluated by the quantity range D_{SZ} that is expressed as:

$$\left.\begin{aligned} &D_{SZ}=B_{SZ}+C_{SZ}\sqrt{h_Z/L_{SZ}}<0, && \text{stable;}\\ &D_{SZ}=B_{SZ}+C_{SZ}\sqrt{h_Z/L_{SZ}}>0, && \text{unstable}\end{aligned}\right\} \tag{23}$$

B_{SZ} and C_{SZ} are the three-dimensional parameters representing the destabilizing effect against the static curved crack:

$$\left.\begin{aligned} &B_{SZ}=\frac{8}{3}\sqrt{\frac{2}{\pi}}\frac{T_Z L_{SZ}^{1/2}}{k_{IZ}};\\ &C_{SZ}=\{[k_{IZ}(2\bar{k}_{22}-\bar{k}_{11})+\frac{b_{IZ}}{2}]\frac{1}{2k_{IZ}}+\frac{4T_Z^2}{k_{IZ}^2}\}L_{SZ}\end{aligned}\right\} \tag{24}$$

Fig. 3 shows the crack path destabilizing factors B_{SZ} and C_{SZ} for the present analysis model, where the ratios of applied static stress and the sum of the outer static stress and the residual stress are chosen as 0. 25 and 0. 5. In the case where the applied static stress level is relatively low compared with the sum of the outer static stress and the residual stress, and where the size of the initial crack is relatively small, these parameters have large values. This means that static crack paths of low stress brittle fracture initiated from a small initial crack at weldment can most probably be branched into the base metal approximately when the static crack path destabilizing factors get up to maximum .

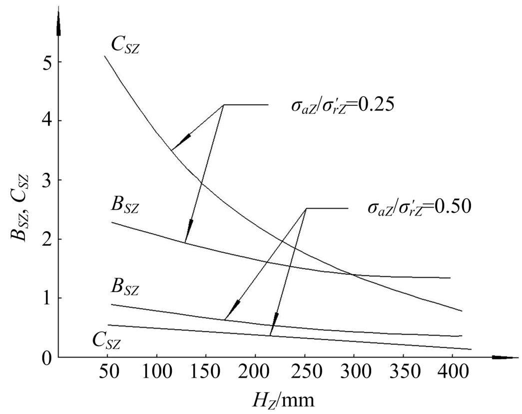

Fig. 3 Three-dimensional static curved crack path destabilizing factors

As the static crack further extends, it begins to intersect the line degradation zone. Here the question presents itself of whether the static crack intersects the zone and penetrates into the base metal, or whether it branches to the heat affected zone, where the fracture toughness is lower than that of the base metal. For the sake of solving the question, the angle α_Z^* is calculated, which is shaped by the static crack and the degradation line by means of (22)～(24). The condition of three-dimensional static crack extension along the degradation line could be acquired by using (21) .

3.3 Results and discussions

In this subsection static crack paths of brittle fracture in weldments are analyzed based on the numerical results. Numerical calculations are performed for the cases in which the initial half crack length is chosen as H_Z = 50, 100, 150, 200, 250, 300, 350, and 400 mm. Since the distance L_{SZ} , between the initial crack line and the degradation line is of the order of the bead widths, it is chosen as 25 or 50 mm . The imperfection parameter α_Z is selected as 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 degrees.

Based on the theory presented in the previous subsection, the critical curves could be determined, which distinguish the static crack propagation in the base metal and in the degraded zone respectively. Fig. 4 represents such curves for the cases $\alpha_Z = 2.5$ degrees and $L_{SZ} = 25$ and 50 mm. And σ_{rZ} is very small, that is to say, $\sigma_{rZ} \ll \sigma_{aZ}$. The figure illustrates that if the ratio of the applied static stress and the sum of the outer static stress and the residual stress, σ_{aZ}/σ_{rZ}', and the ratio of the critical static energy release rate of degraded zone and base metal, G_{CZ}^*/G_{CZ}, fall on the lower right hand side of the respective curves, a static brittle crack can probably propagate along the degradation line. From Fig. 4, it can be concluded that if the sum of the outer welding static stress and the welding residual stress acting parallel to the welded joint is relatively small, and if the decrease of critical static energy release rate in the degraded zone is comparatively large, three-dimensional static curved cracks can probably propagate in the degraded zone. These results qualitatively interpret the difference of static linear elasticity fracture behavior observed in welded mild steel plates and high tensile steel plates. As can be seen from Fig. 4, static linear elasticity fracture starting from a longer straight crack has a tendency to propagate along the degraded zone. This means that once a static linear elasticity crack has begun to extend in a welded joint, it could not be expected to turn off the welding line and to penetrate into the base metal.

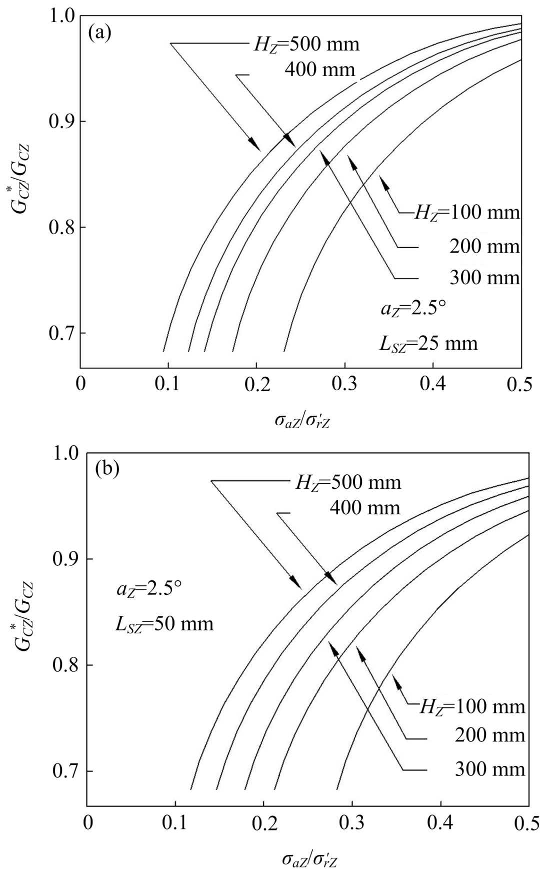

Fig. 4 Critical relations between the material degradation and the static applied stress or the outer static stress for various initial three-dimensional crack lengths

4 Conclusion

In this article, three-dimensional static brittle crack development in a finite body is analyzed by means of a second order perturbation solution. And it is applied to examine the relation between the static energy criterion and the static stress criterion for static crack path prediction. As far as homogeneous materials are concerned, both criteria designate equivalent static crack paths according to the second order approximation theory. It should be contrasted for static crack paths in materials with inhomogeneous fracture toughness, in which the energy criterion predominates over the stress criterion. As a practical application of the method, morphological characteristics of three-dimensional static linear elasticity fracture in weldment are studied, and the critical curves for the three-dimensional static crack propagation in the degraded zone have been acquired considering many factors such as applied static stresses, welding residual stresses, localized material deterioration and defect sizes.

Based on the research results of this paper, the next research goal should focus on the calculation of the stress intensity factor of the three-dimensional linear elastic crack with sharp bending, the plastic zone of the three-dimensional large bend elastic-plastic crack, the opening displacement, the Jz integral and other fracture characteristic parameters, the determination of the shape parameters of the crack growth path, etc.

References

[1] BANICHUK N V. Determination of the form of a curvilinear crack by small parameter technique[J]. Izv An SSSR MTT, 1970, 7(2): 130-137. (in Russian)

[2] GOLDSTEIN R V, SALGANIK R L. Plane problem of curvilinear cracks in an elastic solid[J]. Izv An SSSR MTT, 1970, 7(3): 69-82. (in Russian)

[3] GOLDSTEIN R V, SALGANIK R L. Brittle fracture of solids with arbitrary racks[J]. Int J Fracture, 1974, 10: 507-523.

[4] COTTERELL B, RICE J R. Slightly curved or kinked cracks[J]. Int J Fracture, 1980, 16: 155-169.

[5] KARIHALOO B L, KEER L M, NEMAT-NASSER S, et al. Approximate description of crack kinking and curving[J]. J Appl Mech, 1981, 48: 515-519.

[6] SUMI Y, NEMAT-NASSER S, KEER L M. On crack branching and curving in a finite body[J]. Int J Fracture, 1983, 21: 67-79; Erratum [J]. Int J Fracture,1984, 24: 159.

[7] SUMI Y. A note on the first order perturbation solution of a straight crack with slightly branched and curved extension under a general geometric and loading condition [J]. Engng Fracture Mech, 1986, 24: 479-481.

[8] YANG Dapeng, ZHANG Xueyan, ZHAO Yao, et al. Crack path prediction of brittle fracture in weldment under dynamic loads[J]. Journal of Ship Mechanics, 2012, 16(3): 254-270.

[9] WU C H. Explicit asymptotic solution for the maximum-energy-release-rate problem[J]. Int J Solids Structures, 1979, 15: 561-566.

[10] AMESTOY M, LEBLOND J B. On the criterion giving the direction of propagation of cracks in the Griffith theory[J]. Comptes Rendus, 1985, 301: 969-972. (in French)

[11] BILBY B A, CARDEW G E. The crack with a kinked tip[J]. Int J Fracture, 1975, 11: 708-712.

[12] SUMI Y, NEMAT- NASSER S, KEER L M. On crack path stability in a finite body[J]. Engng Fracture Mech, 1985, 22: 759-771.

[13] RICHARD H A, FULLAND M, SANDER M. Theoretical crack path prediction [J]. Fatigue and Fracture of Engineering Materials and Structures, 2005, 28: 3-12.

[14] WANG Lei, WU Jiankang. Flow behavior in microchannel made of different materials with wall slip velocity and electro-viscous effects[J]. Acta Mechanica Sinica, 2010, 26(1): 73-80.

[15] ZHANG Weifeng, FENG Hua. The wavelet analysis of vibration detection for structure's crack fault[J]. Mechanics in Engineering, 2010, 32 (1): 20-23.

[16] ZHAO Xinwei, LUO Jinheng, YANG Zheng, et al. 3D fracture mechanics characteristics and criterion for pipeline steel with surface crack under fatigue load[J]. Journal of Mechanical Strength, 2009, 31(4): 654-660. (in Chinese)

[17] QI Guiying. Study on 3D-fracture behavior in CTS-specimen with inclined crack [D]. Harbin: Harbin Engineering University, 2011. (in Chinese)

[18] YANG Dapeng. Research on fracture behaviors of slightly curved extension crack[D]. Wuhan: Huazhong University of Science and Technology, 2006. (in Chinese)