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Unified constraint parameter based on crack-tip opening displacement

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ABSTRACT

To develop new fracture assessment methodology to incorporate both in-plane and out-of-plane constraints, it is desirable to develop unified constraint parameters convenient for engineering calculation and application. In this work, a new unified constraint parameter A_d based on crack-tip opening displacement (CTOD) was proposed, and the capability of A_d to characterize both in-plane and out-of-plane constraints has been investigated by a comparison with the unified constraint parameter A_p. The results indicate that the parameter A_d can quantify both in-plane and out-of-plane constraints and their change with load levels. A unified correlation line between the normalized fracture toughness J_C/J_{ref} and A_d (toughness locus) can be established for both ductile and brittle fracture. The parameter A_d based on CTOD has clear physical and geometric meaning, and it can be easily measured and determined in FEM analyses. Therefore, the A_d may be an appropriate engineering unified constraint parameter, and it may be adopted in fracture assessments of cracked structures for incorporating both in-plane and out-of-plane constraints.

1. Introduction

The fracture criterion based on traditional fracture mechanics assumes that the cracked structures have the same fracture resistance as the laboratory fracture toughness specimen at fracture initiation [1]. However, cracks in actual structures (such as pipes and vessels) often have lower crack-tip constraint than those in laboratory fracture specimens [2]. Thus, the fracture assessment for lower constraint structures using conventional fracture mechanics may produce excessive conservative results. This conservative assessment may lead to unnecessary replacement or repairs of in-service components. On the other hand, if the crack-tip constraint in structures is higher than that in laboratory fracture specimens, non-conservative assessment results (unsafe) may be produced. Therefore, the constraint effects need to be considered in fracture assessment for cracked structures.

Constraint is related to the hindrance of the crack tip deformation induced by a structure [3]. The constraint is usually composed of in-plane constraint and out-of-plane constraint. The former is directly affected by the length of the un-cracked ligament or crack depth, and the latter is affected by the specimen thickness. During the past decades, different constraint parameters have been proposed, such as T-stress [4], Q [5,6], A_2 [7], T_z [8–10], stress triaxiality factor h [11], K_P [12], A [13–16] and A_p [17–22], etc. In current fracture assessment procedures, such as in the R6 [23], SINTAP [24] and FITNET FFS [25] procedures, the constraint effects have been considered by adopting the constraint parameters T and Q. However, in recent work [20–27], it has been shown that the parameters T-stress and Q only can quantify the in-plane constraint effect. But for practical engineering structures, in-plane constraint coexists with out-of-plane constraint [28,29]. In order to improve the accuracy of fracture assessments, it requires developing new

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Nomenclature

A_p	a unified parameter for quantifying both in-plane and out-of-plane constraints
A_{PEEQ}	area surrounded by equivalent plastic strain isoline in a specimen or component
A_{ref}	area surrounded by equivalent plastic strain isoline in a standard test at fracture
J	J-integral
J_C	fracture toughness characterized by J-integral
J_{ref}	fracture toughness measured in a standard test at fracture
A_d	a new unified parameter for quantifying both in-plane and out-of-plane constraints
δ	crack-tip opening displacement
δ_{ref}	crack-tip opening displacement at fracture measured in a standard test
a	crack length
W	specimen width
B	specimen thickness
K	stress intensity factor
T	T-stress constraint parameter under elastic condition
Q	a constraint parameter under elastic-plastic condition
A_2	parameter quantifying second and third term of stress relative to the first term in a cracked elastic-plastic body
T_Z	factor of the stress-state in 3D cracked body
h	stress triaxiality factor
K_P	plastic stress intensity factor
A	second (constraint) parameter in J–A crack-tip fields
φ	a unified constraint parameter defined by plastic region area
ε_p	equivalent plastic strain isoline
E	Young's Modulus
ν	Poisson's ratio
σ_0	yield stress
σ_b	tensile strength
ψ	reduction of area
δ_{90}	crack-tip opening displacement based on the 90° intercept procedure
δ_C	crack-tip opening displacement at fracture
$U1$	displacement in the direction of X
r_0	initial root radius of blunt crack-tip
J_{ave}	average J-integral along crack front
J_{mid}	J-integral at middle plane
z	distance from middle plane in three-dimensional specimen
$A_{d\text{-}mid}$	value of A_d at middle plane
$A_{p\text{-}mid}$	value of A_p at middle plane
$A_{d\text{-}ave}$	average A_d along crack front
$A_{p\text{-}ave}$	average A_p along crack front

Abbreviations

CTOD	crack-tip opening displacement
SEN(B)	single edge notched bend
2D	two-dimensional
3D	three-dimensional
FEM	finite element method
SSY	small scale yielding
PEEQ	equivalent plastic strain in ABAQUS code

fracture assessment methodology to incorporate both constraints.

Mostafavi et al. [30,31] suggested a unified constraint parameter φ based on the crack-tip plastic zone size. However, the parameter φ has its limitation on characterizing constraint at higher load level for the ductile material with higher fracture toughness [17]. Recently, Yang et al. [17,18] have proposed a unified constraint characterization parameter A_p by modifying the parameter φ as follows:

$$A_p = \frac{A_{PEEQ}}{A_{ref}} \tag{1}$$

where A_{PEEQ} denotes the area surrounded by the equivalent plastic strain (ε_p) isoline ahead of a crack tip in a specimen or structure, and A_{ref} denotes the reference area surrounded by the ε_p isoline in a standard plane strain specimen with high constraint at fracture. It has been shown that the parameter A_p can capture both in-plane and out-of-plane constraints, and there exists a sole linear relation between the normalized fracture toughness J_{IC}/J_{ref} and $\sqrt{A_p}$ regardless of the in-plane constraint, out-of-plane constraint and the selection of the ε_p isolines [17]. The FEM simulations with the GTN damage model (local approach) can be used in obtaining the unified $J_{IC}/J_{ref} - \sqrt{A_p}$ reference line for materials under ductile fracture condition [17]. In the work of Yang et al. [18], the specimens with different geometries and loading configurations were used to study the unified correlation of in-plane and out-of-plane constraints with ductile fracture toughness. The results showed that a sole linear relation between J_{IC}/J_{ref} and $\sqrt{A_p}$ for these specimens also can be obtained. The unified $J_{IC}/J_{ref} - \sqrt{A_p}$ correlation line can be used to determine constraint dependent fracture toughness of materials. The results also demonstrate that the out-of-plane constraint effect is related to the in-plane constraint effect, and there exists interaction between them. The further work of Yang et al. [19] shows that the parameter A_p also can characterize the combining constraint composed of in-plane, out-of-plane and material constraints (induced by local strength mismatch in welded joints). The study of Mu et al. [20] showed that the parameter A_p has a good correlation with brittle fracture toughness K_{Jc} and J_c of various specimens with different constraint levels, and it is also a unified measure parameter of in-plane and out-of-plane constraint for brittle fracture. In the further study of Mu et al. [21], extensive three-dimensional finite element analyses were conducted for a large amount of experimental specimens with various constraint levels. The results showed that the parameter A_p can characterize a wide range of in-plane and out-of-plane constraints and their interaction under brittle fracture condition. In a recent study [22], the capability and applicability of five constraint parameters (namely T-stress, Q, h, T_z and A_p) for characterizing in-plane and out-of-plane crack-tip constraints and establishing unified correlation with fracture toughness of a steel were investigated. The results showed that the four