Theoretical and Applied Fracture Mechanics 80 (2015) 121–132

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Unified correlation of in-plane and out-of-plane constraints with cleavage fracture toughness

M.Y. Mu, G.Z. Wang *, F.Z. Xuan, S.T. Tu

Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

ARTICLE INFO

Article history:
Available online 30 October 2015

Keywords:
In-plane constraint
Out-of-plane constraint
Cleavage fracture toughness
Unified correlation
Equivalent plastic strain

ABSTRACT

Extensive three-dimensional finite element analyses have been conducted for a large amount of experimental specimens with a wide range of in-plane and out-of-plane constraints. The capability of the new constraint parameter A_p for establishing a unified correlation of in-plane and out-of-plane constraints with cleavage fracture toughness of a reactor vessel steel were comparatively investigated with the conventional constraint parameters Q and T-stress. The results show that the parameter A_p can characterize both in-plane and out-of-plane constraints and their interaction. Based on the parameter A_p, the unified correlation of a wide range of in-plane and out-of-plane constraints with cleavage fracture toughness of the steel has been obtained. In structural integrity analyses based on fracture mechanics incorporating constraint effects for improving accuracy, the unified correlation may be used to determine constraint-dependent or structurally relevant fracture toughness of specimens or cracked components with a wide range of in-plane and out-of-plane constraint levels.

1. Introduction

Brittle cleavage fracture and constraint effects play important roles in structural integrity assessment and design, such as for integrity analyses of reactor pressure vessels [1–3]. To achieve integrity analyses based on fracture mechanics incorporating the constraint effects, the correlation of crack-tip constraint with cleavage fracture toughness of steels needs to be accurately established.

Constraint is the resistance of a structure against plastic deformation [4]. The constraint contains in-plane and out-of-plane components. The in-plane constraint is directly affected by specimen dimension in the direction of growing crack, that is, the length of the un-cracked ligament, while the out-of-plane constraint is affected by the specimen dimension parallel to crack front, that is, the specimen thickness. Because the material's fracture toughness is dependent on the constraint, it is necessary to develop a clear understanding of the constraint effect on the fracture behavior of materials and incorporate the constraint effect in fracture assessments for improving accuracy.

The quantification of constraint has been studied for a long time, and different constraint parameters and fracture theories have been put forward in the last few decades, such as the single-parameter K [5] and J [6], two-parameter-concepts K–T [7], J–Q [8,9], J–A_2 [10], J–T_Z [11–13] and J–h [14]. Most of these parameters were only used to quantify the in-plane or out-of-plane constraint separately, but not the interaction between them. In the two-parameter-concept K–T, the T-stress constraint parameter is usually referred to the in-plane component T_{11}-stress which is always used to describe the in-plane constraint effect [15]. The out-of-plane component T_{33}-stress is also known to be an important parameter for characterizing the out-of-plane constraint effect [15–21]. In some recent work [16,21], it has been shown that the T_{33}-stress could characterize the out-of-plane constraint effect on the cleavage fracture toughness of steels. The T-stress solutions for different specimens and structures also have been studied in some recent work [15,20].

However, in the actual engineering structures (such as reactor pressure vessels or pipes), both in-plane and out-of-plane constraints exist simultaneously. In order to describe the interaction between in-plane and out-of-plane constraints and the overall levels of constraints, a unified constraint parameter which can characterize both constraints together is required [22,23]. Mostafavi et al. [24–26] have suggested a unified constraint parameter φ which was defined as the size of plastic region at the onset of fracture normalized by the plastic region size of a standard test:

$$\varphi = \frac{A_c}{A_{ssy}} \tag{1}$$

* Corresponding author. Tel./fax: +86 21 64252681.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

http://dx.doi.org/10.1016/j.tafmec.2015.10.005
0167-8442/

Nomenclature

a	crack depth
A_2	parameter quantifying second and third term of stress relative to the first term in a cracked elastic–plastic body
A_c	area of the plastic region at fracture
A_{PEEQ}	area surrounded by equivalent plastic strain isoline
A_p	a unified characterization parameter of in-plane and out-of-plane constraint
A_{ref}	area surrounded by equivalent plastic strain isoline at fracture measured in a standard test
A_{ssy}	area of the plastic region at fracture measured in a standard test
b	ligament size
B	specimen thickness
E	elastic modulus
h	stress triaxiality factor
J	J-integral
J_{ave}	average J-integral
J_c	fracture toughness characterized by J-integral
J_{ref}	reference fracture toughness J_c measured in a standard test
K	stress intensity factor
K_e	linear elastic K contribution to J_c
K_{Jc}	fracture toughness
K_{ref}	reference fracture toughness K_{Jc} measured in a standard test
L	characteristic length
P	load
Q	a constraint parameter
Q^{BLA}	the Q parameter determined from a FE small scale yielding reference field
r	distance from a crack tip, or initial root radius at the crack tip
S	loading span
T	non-singular term of stress (T-stress for elastic condition)
T_{11}	in-plane component of T-stress
T_{33}	out-of-plane component of T-stress
T_z	out-of-plane constraint factor
U_p	plastic area under P–Δ curve
W	specimen width
z	distance from specimen center along specimen thickness
ε_p	equivalent plastic strain
θ	polar coordinate at the crack tip
σ_0	yield stress
$\sigma_{\theta\theta}$	opening stress
υ	Poisson's ratio
φ	a unified constraint parameter defined by plastic region area
η	dimensionless parameter relating U_p to the plastic component of J
Δ	load point displacement

Acronyms

ASTM	American Society for Testing and Materials
C(T)	compact tension
CC(T)	center-cracked tension
FEM	finite element method
SEN(B)	single edge-notched bend

where A_c is the plastic region area at fracture load and A_{ssy} is the reference plastic region area at fracture load for a standard specimen in plane strain condition. They argued that there is no evident difference on the plastic zone size at fracture between in-plane and out-of-plane constraints, and the parameter φ is equally sensitive to in-plane and out-of-plane constraints. However, in finite element method (FEM) calculations of the authors [27–29], it has been found that for the materials with higher toughness, the specimens reached general yielding before ductile fracture. The plastic region at the crack tip expanded to the specimen's surface, and interacted with the plastic region in the loading region. So it is impossible to calculate the size of crack-tip plastic region accurately under this condition, and the constraint parameter φ has its limitation in characterizing constraint. Thus, Yang et al. defined a new unified constraint parameter A_p by modifying the parameter φ as follows [27,28]:

$$A_p = \frac{A_{PEEQ}}{A_{ref}} \tag{2}$$

where A_{PEEQ} is the area surrounded by the equivalent plastic strain (ε_p) isoline ahead of a crack tip in the under evaluated specimen and A_{ref} is the reference area surrounded by the ε_p in a standard specimen. To obtain unified correlation of in-plane and out-of-plane crack-tip constraints with fracture toughness of a steel by using the A_p parameter in Eq. (2), the area A_{PEEQ} and A_{ref} at fracture load needs to be calculated by FEM. The ε_p isoline is dependent on the fracture toughness of materials and is determined by FEM calculation [27,28]. It has been shown that the parameter A_p can characterize both in-plane and out-of-plane constraints for ductile materials with higher fracture toughness, and based on the A_p the unified correlation of in-plane and out-of-plane constraints with ductile fracture toughness of the reactor vessel steel A508 [27,28] and a dissimilar metal welded joint [29] were obtained. In the previous work of authors [30], the capability of the parameter A_p for characterizing in-plane and out-of-plane crack-tip constraint effects under brittle fracture condition has been investigated. The results showed that for the specimens with different geometries (C(T), SEN(B) and CC(T)) in the work of Hebel et al. [31], the parameter A_p has a good correlation with brittle fracture toughness K_{Jc} and J_c of various specimens, and it is a unified measure parameter of in-plane and out-of-plane constraints for brittle fracture. However, the actual engineering structures (such as reactor pressure vessels or pipes) may have a wide range of in-plane and out-of-plane dimensions, and thus contain a wide range of in-plane and out-of-plane constraints. It has not been investigated and understood whether or not the parameter A_p is suitable to be as a unified constraint parameter for a wide range of in-plane and out-of-plane constraints, and whether or not a unified correlation of a wide range of in-plane and out-of-plane constraints with cleavage fracture toughness of steels can be established.

In this work, the equivalent plastic strain ε_p distributions ahead of crack tips for a large amount of experimental specimens with a wide range of in-plane and out-of-plane constraints in the work of Rathbun et al. [32] under cleavage fracture condition were calculated by three-dimensional FEM. The constraint parameter A_p was comparatively analyzed with the conventional constraint parameters Q and T-stress (the T-stress in this paper is referred to the in-plane component T_{11}-stress). The capability and applicability of the parameter A_p for characterizing a wide range of in-plane and out-of-plane crack-tip constraints and establishing a unified correlation with cleavage fracture toughness of a reactor vessel steel were investigated.