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Determination of two key parameters of a cohesive zone model for pipeline steels based on uniaxial stress-strain curve

Y.J. Wang, C.Q. Ru *

Department of Mechanical Engineering, University of Alberta, Edmonton T6G 2G8, Canada

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ABSTRACT

It is widely believed that maximum traction of traction-separation law (TSL) and cohesive energy are the two key parameters of cohesive zone model (CZM). A method is presented in this paper to determine the two key CZM parameters for pipeline steels. The maximum traction of TSL is given by the critical stress defined based on damage at fracture point from the true stress-strain curve. And the other key parameter, cohesive energy defined as the area under the curve of TSL and usually considered as the critical J-integral, is estimated from a simple tensile test simulation. The two key CZM parameters obtained by the present method are validated for dynamic fracture of pipeline steels. Both load-displacement curves and crack tip opening angle (CTOA)-fracture speed curves showed that the two key CZM parameters determined by the present method are reasonable, and dynamic fracture behavior predicted based on the two predicted key CZM parameters well agree with some known test data and previous work.

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1. Introduction

The Cohesive zone model (CZM) was developed from the Dugdale-Barenblatt model [1,2] for a static crack, and has been widely applied to dynamic fracture of ductile materials [3–5]. A key challenge for CZM is how to determine the CZM parameters based on test data of a real material. Some previous studies [6,7] suggested that the two most important parameters are the maximum traction and the cohesive energy (the area under the curve of traction-separation law (TSL)). Although the cohesive energy has a relatively clear physical meaning and can be calculated by the J-integral [7,8], how to calculate the maximum traction, which is often considered as fracture stress, is still not an easy task. Therefore, it is of great interest to study how to determine the two key CZM parameters based on uniaxial tensile test data of a real ductile material such as pipeline steels.

A common way to determine the two key CZM parameters is based on experiments. For the maximum traction, a notched specimen usually was tested under a tensile machine, the loading force was recorded when fracture happens, and then finite element simulation was used to find the maximum stress [7,8]. Chen and Mai [9] defined the maximum traction equals the tensile strength for an elastic material. For the J-integral, a standard experiment can be used to find the critical J-integral. Cornec et al. [7] used three different methods to determine the critical J-integral based on the J-resistance curve obtained from experiments. Song et al. [10] determined the critical J-integral by using a single-edge notched beam experiment, and calculated the area under the load-crack mouth opening displacement curve and normalized by the cross-sectional area

* Corresponding author.
E-mail address: cru@ualberta.ca (C.Q. Ru).

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Nomenclature

σ_t^f	true stress at fracture point
K	scalar elastic stiffness
T	traction
S	separation
D	damage scalar
S_0, S_m	separations at which the cohesive zone starts being cracked and fully fractured
α	an exponent which controls the damage evolution
J_c	critical J-integral (cohesive energy)
s, e	nominal stress, nominal strain
σ, ε	true stress, true strain
σ_u, ε_u	true stress and true strain at the necking point
σ_c	critical stress
σ_{eq}, σ_m	Von Mises equivalent stress, hydrostatic stress
σ_{eff}	effective stress
d	the ratio of the total area of the voids and the original area of the specimen
f_c	critical void volume ratio
T_m	maximum traction
ε^p	equivalent plastic strain
$\overline{\sigma}, \overline{\varepsilon^p}, \overline{\varepsilon_r}$	equivalent stress, equivalent plastic strain, reference strain
$\dot{\overline{\varepsilon^p}}, \dot{\overline{\varepsilon_r}}$	equivalent plastic strain rate, reference strain rate
σ_y	static tensile initial yielding stress
m, n	material constants

of the beam. Although an experimental method can provide the CZM parameters, it is usually quite complicated and expensive.

An alternative way to determine the two key CZM parameters is to choose the parameters to best fit test data. For this end, an experiment is needed to compare the result of numerical calculation for the load-displacement curve with test data [11]. Scheider and Brocks [12] suggested that the maximum traction is about three times the yield stress, and the critical J-integral is about [50 kJ/m^2, 100 kJ/m^2] for X70 high strength low alloyed ferritic-pearlitic steel. Our previous work [3,5] adjusted their CZM parameters so that the numerical results obtained from the simulation fit test data not only for the load-displacement curve but also for the crack length-time curve and the CTOA (crack tip opening angle)-crack length curve. Xue et al. [13] simulated the tensile behavior of unidirectionally arrayed chopped strand/aluminium fiber metal laminate by adjusting their CZM parameters, and they [14] studied the effect of the CZM shape on the FEA predictions. Yan and Shang [15] used a number of sets of CZM parameters in the interfacial delamination simulation for PZT thin films to best match experimental results. Xu and Yuan [16] introduced a cohesive zone model with a threshold and applied for simulating different mixed-mode cracks in combining with the extended finite element method, in which the maximum traction is related to the tensile strength of the material by an exponential law. Hu et al. [17] obtained their CZM parameters by correlation between simulation and experimental (quasi-static test) failure loads on the single lap joints, and pointed out that the selected CZM parameters sets for the studied adhesives may be not unique. A suggestion for appropriately choosing CZM parameters is given by Wu and Chen [18] after try a number sets of CZM parameters for the single shear test simulation. However, although numerical simulation could offer CZM parameters which fit specific test data, it usually requires extensive calculation time in order to find one proper set of CZM parameters, and sometime even different sets of CZM parameters can fit the same test data.

Therefore an engineering method is used in the present paper to determine the two key CZM parameters for pipeline steels. To this end, the relationship between the TSL and true uniaxial stress-strain curve (SS curve) is studied in Section 2. Under this relationship, the maximum traction and the cohesive energy (critical J-integral) are determined in Section 3, based on the true SS curve and finite element calculation, respectively. In Section 4, a drop-weight tear test (DWTT) is used to validate the two estimated key CZM parameters for pipeline steels X80. And finally, main conclusions are summarized in Section 5.

2. Relationship between true stress-strain curve and traction-separation law

In order to determine the maximum traction and the cohesive energy (critical J-integral) of the CZM by using a true uniaxial SS curve, the connection between the two curves is now clarified.

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