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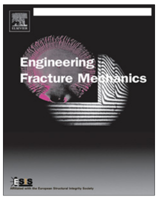

Analysis of energy absorptions in drop-weight tear tests of pipeline steel

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ABSTRACT

The energy absorptions of drop-weight tear tests (DWTT) are analyzed using a finite element model based on the cohesive zone model. The parameters in the traction–separation law for the cohesive zone are validated by matching the simulation results to test data of standard specimens of DWTT. Based on the simulations the fracture energy (defined as the adhesion energy plus the plastic energy surrounding the crack tip) is quantified from the total energy absorption in the standard specimen. A ratio of the fracture energy to the total energy absorption for the steady-state crack propagation in the standard specimen is obtained which could be used to estimate the energy-based toughness of pipeline steel based on the measurable total energy absorption in DWTT.

1. Introduction

The drop-weight tear test (DWTT) has been widely used to measure the dynamic fracture resistance of pipeline steels [1–3]. Combining with high-speed camera and instrumented tup, the crack speed, crack tip opening angle (CTOA) and energy absorption in the DWTT specimen are captured during the crack propagation [4]. According to the physical mechanism of dynamic fracture, the energy consumption for crack growth – referred to as the fracture energy – is essential for the fracture resistance and should be defined as the dynamic fracture toughness. However, in DWTT it is difficult to distinguish the fracture energy from the total energy absorption which inevitably includes the toughness-unrelated energy consumed by impact, friction, plastic deformation in the entire specimen out of crack tip. Therefore, CTOA has served as the suboptimal choice to define the dynamic fracture toughness in engineering practice of tests and simulations [2,4–7] due to its measurability.

Although CTOA is related to the fracture energy and has been widely used for assessment of fracture, there are still a few noticeable limitations of the CTOA-criterion. First of all, from the viewpoint of material selection, for two different materials the one who has higher CTOA does not necessarily have higher fracture toughness than the other. For example, the CTOA of aluminum could be greater than that of steel, but it is not expected that the aluminum has a higher fracture toughness that the steel. Even though, CTOA is used as a promising assessment for the dynamic fracture toughness of pipeline steel due to the convenient measurability. Moreover, the correspondence between the CTOA and the fracture energy or other toughness-related parameters should be clarified which would be helpful to understand the definition of fracture toughness. In

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Nomenclature

CZM	cohesive zone model, see Fig. 2
D	damage scalar in traction–separation law, see Eq. (1)
DWTT	drop-weight tear test
FE	finite element
G_{adhesion}	adhesion energy, see Eq. (1)
G_{f}	fracture energy, see Fig. 11
G_{im}	total imported energy in DWTT
$G_{\mathrm{A+C}}$	plastic energy absorbed induced by the impact of hammer and the supporting anvils in the specimen
G_{t}	total energy absorption, see Fig. 11
K	elastic stiffness in traction–separation law, see Eq. (1)
T	traction stress in cohesive zone, see Eq. (1) and Fig. 3
TSL	traction–separation law
α	exponent in traction–separation law, see Eq. (1) and Fig. 3
σ_{y}	static tensile yielding stress
δ	separation in cohesive zone, see Eq. (1)
δ_0, $\delta_{\max}$	separation corresponding to the maximum traction and maximum damage, see Eq. (1)

addition, although the energy absorption in DWTT is calculated by integrating the area of the loading–displacement curve of the instrumented tup, it is not surprising that the energy per unit crack area also strongly depends on specimen types even for the steady-state crack growth [3,8]. Meanwhile, the true fracture energy – which eliminates the fracture-toughness-unrelated energy in the specimen – is still difficult to measure directly in DWTT.

In this paper, the energy absorption in the DWTT specimens is systematically analyzed using finite element (FE) simulation combined with the cohesive zone model (CZM) [9–12]. Firstly, the total energy absorption in the specimen obtained by FE simulation is verified by some available test data of standard specimens of DWTT [3] including the crack speed, CTOA and loading–displacement of the impact tup. Then the distribution of energy consumed by different areas of the specimen is obtained from the simulation results. Upon that the fracture energy is quantified, which defined as the sum of adhesion energy of cohesive elements and the plastic energy surrounding the crack tip [13–15]. Finally, the ratio of fracture energy to the total energy absorption for the steady-state crack growth in DWTT is analyzed by FE simulations of DWTT.

2. The FE models of DWTT specimens

2.1. Geometries of specimens

According to the API 5L3 specifications [1], the standard DWTT specimen is a rectangular plate of the dimension of 305 mm × 76 mm with a pipe-wall-dependent thickness, and an initial static-precracked V-notch with an angle of 45° and a depth of 5 mm is introduced at the middle of bottom, as shown in Fig. 1. However, due to the limitation of impact velocity (5–9 m/s) in DWTT [1], the crack speed in the standard specimen is typically 15–20 m/s which is almost one order of magnitude lower than that in the full-scale pipes of 90–300 m/s [3]. Therefore, some non-standard (modified) specimens are developed to achieve higher crack speed which is close to the fracture speed in full-scale pipes. One of the simple and effective ways to improve the fracture speed in DWTT is to machine a back-slot in the specimen and insert a clearance-fitted

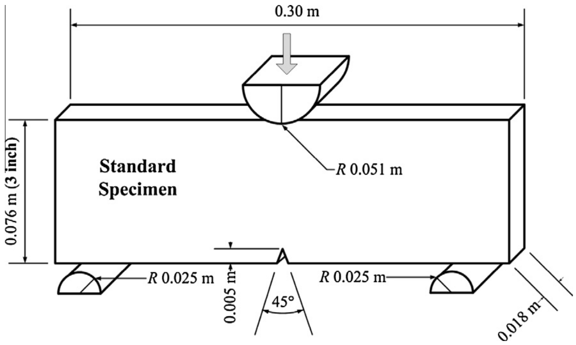

Fig. 1. Geometries of the standard specimen of DWTT.