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Numerical investigation of speed dependent dynamic fracture toughness of line pipe steels

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ABSTRACT

Recent Drop Weight Tear Test (DWTT) showed that dynamic fracture toughness of line pipe steels depends on fracture speed. Based on a properly designed separation–traction law, standard and modified DWTT of API X80 line pipe steel are simulated by Cohesive Zone Model (CZM) based FEA (finite element analysis). The loading-displacement curve, fracture speed, and crack tip opening angle (CTOA) in FEA simulations are compared with experimental results. The agreement between the present FEA and experimental results shows that the present FEA can well describe high-speed fracture of the standard and modified DWTT of API X80 line pipe steel. The relation between CZM fracture energy, steady-state CTOA and steady-state fracture speed are investigated through two groups of FEA simulations designed for standard and modified DWTT. Our FEA results show that both CZM fracture energy and steady-state CTOA decrease with steady-state fracture speed, and two empirical relations are suggested to describe the dependence of the two toughness measures on steady-state fracture speed.

1. Introduction

For high speed dynamic fracture of gas pipelines, the effect of fracture speed on fracture toughness is an important topic in material selection and crack arrestor design. In general, fracture toughness is often considered as an inherent material property and its value is assumed to be a speed-independent constant for a given material. However, recent Drop Weight Tear Test (DWTT) experiments [1,2] showed that dynamic fracture toughness, defined based on absorbed energy per fracture area or crack-tip opening angle (CTOA), depends on fracture speed of line pipe steels. Although DWTT [3–5] has been widely used to test fracture toughness of line pipes, fracture speed achieved in standard DWTT is far lower than that in full-scale test of high grade line pipes (e.g., X80 and X100 pipes). Therefore, the standard DWTT may be inappropriate for high grade line pipe steels. In order to more accurately test fracture toughness of higher-grade pipes, it is necessary to investigate the dependence of dynamic fracture toughness on fracture speed.

The dependence of fracture toughness on fracture speed has been investigated in the literature. For example, Emery et al. [6] employed the split ring model to investigate the relationship between CTOA and crack velocity of full-scale line pipes. Rudland et al. [1] investigated the fracture speed and CTOA in the DWTT tests of X70 and X80 line pipes, and their experimental results showed that CTOA decreases with fracture speed. Numerical analysis of Kanninen and O'Donoghue [7,8] showed that CTOA of full-scale line pipe increases with fracture speed at first, and then decreases with fracture speed quickly. Lee and Prakash [9] formulated dynamic fracture toughness in terms of critical dynamic stress intensity factor, and showed that critical dynamic stress intensity factor of 4340VAR structure steel under intense stress pulse loading

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Nomenclature

DWTT	Drop Weight Tear Test
CZM	Cohesive Zone Model
FEA	finite element analysis
CTOA	crack tip opening angle
ABAQUS	commercial finite element software

increases with fracture speed, while Pandolfi et al.'s result [10] also showed that critical dynamic stress intensity factor of C300 steel increases with fracture speed. Ma et al. [11] conducted dynamic fracture experiments on thin aluminum, and showed that the CTOA of fatigue precracked aluminum specimens decreased with fracture speed. In addition, Shim et al. [2] compared the absorbed energy per fracture area, CTOA and fracture speed between standard and modified DWTT of X80 line pipes, and found that both absorbed energy per fracture area and CTOA decrease with fracture speed. Based on Shim et al.'s result, Duan et al. [12] formulated a power–law dependence of absorbed energy per fracture area on fracture speed of line pipes.

In spite of the above-mentioned works on speed dependent dynamic toughness, however, the relation between fracture toughness and fracture speed of line pipe steels has not been well addressed with detailed numerical analysis. In this work, the dependence of fracture toughness on fracture speed of line pipe steels is numerically investigated through finite element analysis (FEA) simulation. The Cohesive Zone Model (CZM) will be employed in the present FEA simulations for high-speed fracture of standard and modified DWTT of API X80 line pipe, and the relation between CZM fracture energy, CTOA, and fracture speed of standard and modified DWTT specimens will be analyzed quantitatively. Although various CZMs [13,14] are available in the literature [13,14], it is not a trivial task to identify a specific and reasonably simple CZM suitable for high-speed fracture of line pipes. This paper attempts to achieve this goal. Detailed comparisons of the FEA results with a few known tests indicate that the proposed CZM works reasonably and has the potential to be used for simulating high-speed fracture of line pipes. This offers a useful numerical method to investigate high-speed fracture of line pipes specially when experimental tests are difficult or too expensive.

2. Finite element modeling

DWTT is widely used to test fracture toughness of line pipe steels. In this work, speed dependent fracture toughness of line pipe steels will be numerically investigated through FEA simulations of standard and modified DWTT [2]. FEA simula-

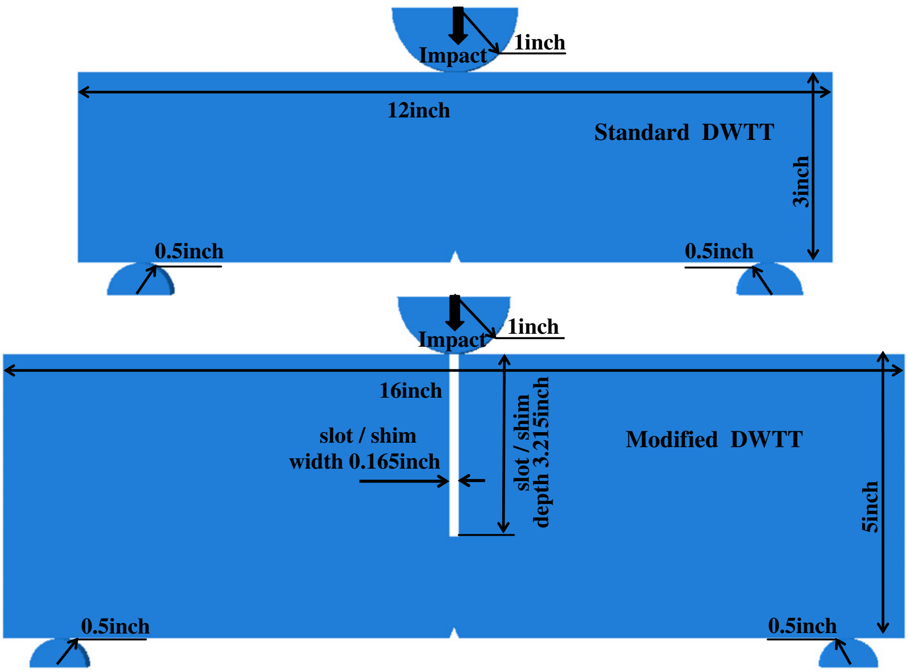

Fig. 1. FEA model of standard DWTT specimen and modified DWTT specimen.