Theoretical and Applied Fracture Mechanics 54 (2010) 54–62

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Application of a stress triaxiality dependent fracture criterion in the finite element analysis of unnotched Charpy specimens

H.L. Yu [a], D.Y. Jeong [b,*]

[a] MacroSys Research and Technology, LLC, 55 Broadway, Cambridge, MA 02142, USA
[b] US Department of Transportation, Volpe National Transportation Systems Center, 55 Broadway, Cambridge, MA 02142, USA

ARTICLE INFO

Article history:
Available online 13 June 2010

Keywords:
Unnotched Charpy specimen
Pendulum impact test
Impact energy
Tank car steel
Stress triaxiality dependent fracture initiation criterion
Strain softening
Finite element analysis

ABSTRACT

Nonlinear dynamic finite element analysis (FEA) is conducted to simulate the fracture of unnotched Charpy specimens of steel under pendulum impact loading by a dedicated, oversized and nonstandard Bulk Fracture Charpy Machine (BFCM). The impact energy needed to fracture an unnotched Charpy specimen in a BFCM test can be two orders of magnitude higher than the typical impact energy of a Charpy V-notch specimen. To predict material failure, a phenomenological, stress triaxiality dependent fracture initiation criterion and a fracture evolution law in the form of strain softening are incorporated in the constitutive relations. The BFCM impact energy results obtained from the FEA simulations compare favorably with the corresponding experimental data. In particular, the FEA predicts accurately the correlations of the BFCM impact energy with such factors as specimen geometry, impactor tup width and material type. The analyses show that a specimen's progressive deterioration through the thickness dimension displays a range of shear to ductile fracture modes, demonstrating the necessity of applying a stress state dependent fracture initiation criterion. Modeling the strain softening behavior helps to capture the residual load carrying capability of a ductile metal or alloy beyond the onset of damage. The total impact energy can be significantly under predicted if a softening branch is not included in the stress–strain curve. This research supports a study of the puncture failure of railroad tank cars under dynamic impact loading. Applications of the presented fracture model in failure analyses of other structures are further discussed.

Published by Elsevier Ltd.

1. Introduction

Tank cars are the most common type of railcar employed in the railroad industry to transport hazardous materials (hazmat). Accidents involving tank cars carrying hazmat are rare occurrences, but their consequences can be severe. A review of freight train derailment and train-to-train collision accidents from 1965 to 2005 indicated that the release of toxic inhalation hazmat, including chlorine and anhydrous ammonia, were usually caused by structural failures in three general locations: tank head, tank shell, and valves and fittings [1]. In three recent accidents, a number of tank cars lost their structural integrity as a result of puncture damages in the head or the shell, and the subsequent release of hazmat led to significant human injuries and fatalities, economic losses and environmental degradation [2–4].

Pendulum impact tests on Charpy V-notch (CVN) specimens are routinely conducted to characterize such fracture properties as lower and upper shelf energies and ductile-to-brittle transition temperature (DBTT). Prior to 1989, tank car steels were typically manufactured without a normalization process that could increase the energies in the DBTT regime. Catastrophic failures featuring brittle fracture and rapidly propagated cracks were observed in one of the three recent accidents [2], and they were attributed to the low CVN impact energies of the involved tank car steels, which were manufactured before 1989. With lowered DBTT and increased impact energies, normalized steels have been used since January 1989 to improve tank car resistance to impact loads.

However, it is questionable whether the fracture toughness or CVN impact energy fully represents the fracture characteristics of a material without preexisting cracks. Numerous studies of CVN or axisymmetric tension specimens demonstrated that the initiation of fracture in metals and alloys depends on multiple factors including stress state, strain rate and temperature (e.g., [5–7]). Post accident examinations of punctured tank car surfaces indicated that the fracture modes ranged from ductile fracture, due to nucleation, growth and coalescence of voids, to shear fracture due to shear band localization [8,9]. These fracture modes correspond to stress states with both positive and negative stress triaxialities. The notched Charpy specimens, however, tend to display a ductile fracture mode (which can transition to brittle fracture under lower temperatures or higher strain rates) with positive stress triaxialities near crack tips. Further, the strain rates in tank car impact

* Corresponding author. Tel.: +1 617 494 3654.
E-mail addresses: Hailing.Yu@dot.gov (H.L. Yu), David.Jeong@dot.gov (D.Y. Jeong).

0167-8442/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.tafmec.2010.06.015

events have not been well documented and may not be as high as those observed in CVN specimens, judged from typical impact duration data. A numerical study by Sih and Tzou [10] demonstrated that a specimen subjected to the same amount of impact energy may or may not be fractured in Charpy tests depending on the loading rate and hence the local strain rate of the material.

Dynamic impact tests have been conducted on tank cars to evaluate their crashworthiness [11]. To help assess the puncture resistance of tank cars, Southwest Research Institute built a pendulum test fixture called the Bulk Fracture Charpy Machine (BFCM) to conduct Charpy style tests on unnotched steel specimens using an oversized, nonstandard pendulum impactor [12]. A series of tests were carried out on the BFCM for specimens made from several types of steel and with different geometric sizes. The typical impact energy to fracture an unnotched steel specimen can be two orders of magnitude higher than the typical CVN impact energy. Much of the increased impact energy may be attributed to the greater plastic energy dissipation in an unnotched specimen.

In addition to experimental studies, finite element analysis (FEA) has been a powerful tool to characterize the fracture mechanics of notched Charpy specimens as well as smooth or notched axisymmetric specimens. Within the continuum damage mechanics framework, ductile fracture models can be formulated on the basis of the thermodynamics theory [13] or the theory of micromechanical void nucleation and growth for porous solids [14]. A critical maximum principal stress criterion can be applied over a representative reference volume to simulate the transition to brittle failure of notched Charpy specimens [15,16].

Moreover, phenomenological fracture models based on macroscopic strains and stresses have been proposed for various fracture modes (e.g., [17]) and were adopted in the FEA of unnotched Charpy specimens in this paper. Some of these models require the identification of the equivalent plastic strain at the onset of fracture, or fracture initiation strain, as a function of stress triaxiality, strain rate and temperature. Wierzbicki et al. [18] summarized seven different fracture initiation models and compared their respective merits and limitations. For instance, the constant equivalent strain criterion independent of stress triaxiality is easy to implement but overly simplified; the Johnson–Cook model [19] has received wide applications and is most accurate for ductile fracture; and the maximum shear stress criterion is most suitable for predicting shear and mixed fracture modes. This study is focused on the application of the Bao–Wierzbicki criterion [20] because it covers the fracture modes across the full stress triaxiality spectrum. Further, the Bao–Wierzbicki model parameters can be calibrated from basic material test data for industrial applications.

This paper presents an FEA framework that realistically simulates the failure of initially uncracked steel specimens in the BFCM impact tests by incorporating the stress triaxiality dependent Bao–Wierzbicki criterion for fracture initiation and a strain softening law for fracture evolution. The paper is organized as follows. First, the impact tests of unnotched Charpy specimens are described and the impact energy results analyzed. Second, constitutive relations governing the elastic–plastic, fracture initiation and fracture evolution behaviors are presented, and FE models are developed to simulate the impact tests. Third, FEA results are verified with experimental data, and additional analyses are conducted to better understand the involved fracture mechanics. Last, conclusions are drawn from the study, and broader applications of the computational method are discussed.

2. Experimental study

The physical interpretation of a pendulum impact test is straightforward. A pendulum impactor is raised to an original height at the beginning of a test and released. It impacts with and fractures the test specimen placed on its swinging path before recovering to a secondary lower height. The height difference multiplied by the impactor weight is taken as the impact energy needed to fracture the specimen.

Fig. 1 shows photographs of the BFCM for testing unnotched steel specimens and a post-impact, zoomed-in view of the fixture holding a fractured specimen. To withstand the higher amounts of impact energy needed to fracture unnotched specimens, the BFCM has a much larger test frame than that of a standard Charpy test.

Fig. 2 shows the geometry of a typical test specimen in a plane perpendicular to the thickness dimension denoted as t. The specimen has a rectangular shape in the center section with a height h and a length $2l$, and it transitions to two trapezoidal ends that enable the specimen to be engaged with and fully constrained by the test fixture. The transitional arc has a radius r and a central angle α, and the total specimen length is $2L$.

Two impactor tups with cross sections shown in Fig. 3 were applied in the tests. The contact surface width w_{tup} was 3.175 mm

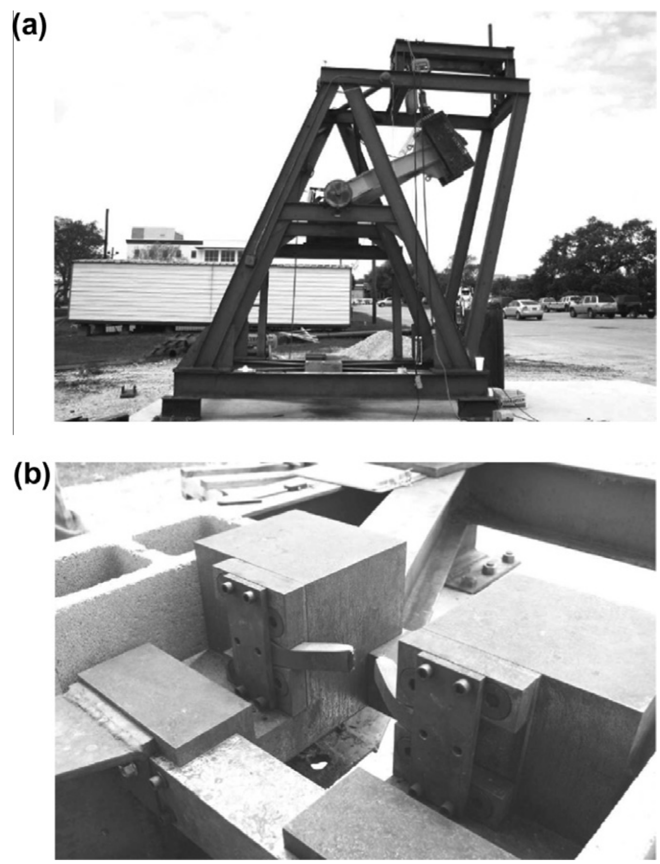

Fig. 1. Bulk Fracture Charpy Machine (BFCM) for testing unnotched steel specimens, and zoomed-in view of the test fixture holding a fractured specimen.

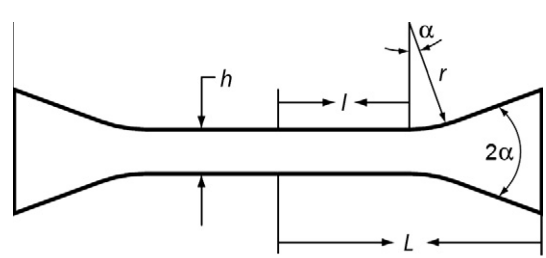

Fig. 2. Geometry of a BFCM specimen in a plane perpendicular to the thickness dimension t.