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Impact dynamics and puncture failure of pressurized tank cars with fluid–structure interaction: A multiphase modeling approach

Hailing Yu *, David Y. Jeong

Structures and Dynamics Division, Volpe National Transportation Systems Center, U.S. Department of Transportation, 55 Broadway, Cambridge, MA 02142, USA

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ABSTRACT

This paper presents a computational framework that analyzes the effect of fluid–structure interaction (FSI) on the impact dynamics and puncture failure of pressurized commodity tank cars carrying hazardous materials. Shell (side) impact tests have been conducted on full scale tank cars resulting in deformed or punctured tank cars. A finite element (FE) modeling method is applied that explicitly simulates the three distinct phases in a tank car loaded with a liquefied substance: pressurized gas, pressurized liquid and solid structure. Furthermore, an equivalent plastic strain based fracture initiation criterion expressed as a function of stress triaxiality is adopted to depict the fracture behavior of the tank car steel material. The fracture initiation is implemented for ductile, shear and mixed fracture modes and followed by further material deterioration governed by a strain softening law. The force, displacement and impact energy results obtained from the FE analysis show good agreement with the corresponding shell impact test data. The simulations demonstrate that FSI plays a critical role in predicting the correct dynamics of tank car impact. The puncture resistance of a tank car, characterized as limit impact conditions in terms of puncture energy or puncture velocity, is further analyzed in shell impact scenarios. The puncture energy is shown to increase as the initial fluid pressure decreases, the tank car thickness increases or the effective impactor size increases. Quantitative correlations between puncture energy/velocity and each of these factors are obtained using the FE analysis method developed in this paper.

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1. Introduction

Pressurized commodity tank cars are commonly employed in the railroad industry to transport liquefied goods including hazardous materials (hazmat) such as compressed flammable (e.g., propane) or toxic gases (e.g., chlorine). In a number of freight train derailment or collision accidents in recent years, severe impacts led to compromised structural integrity of tank cars that consequently released hazmat into the environment. For instance, tank cars loaded with liquefied chlorine were punctured in some accidents by external objects carrying significant momentum; chlorine gas escaped from the breached tank cars, causing respiratory distresses and sometimes fatality among the population exposed to this inhalation hazmat; as a result, affected residential areas were evacuated, and costly environmental cleanup was often needed [1,2]. The railroad hazmat tank cars displayed apparent vulnerability or inadequate protection under the dynamic impact loads in these accidents.

There has been an ongoing research effort aimed at improving the performance of tank cars subjected to dynamic impact loading and thus preventing the puncture failure observed in the aforementioned freight train accidents. A key task has been to determine the puncture resistance of tank cars subjected to impact conditions representative of those in the field. Puncture resistance may be depicted in terms of limit impact conditions, such as minimum initial impact energy or minimum initial impact velocity, to cause puncture failure. For brevity, they are referred to as the puncture energy and the puncture velocity, respectively. To evaluate the puncture resistance of the existing fleet of railroad tank cars and ultimately seek their improved protection, the U.S. government and railroad industry collaborated on a next generation (NextGen) tank car project in which shell impact tests were conducted on full-scale tank cars [3]. Detailed test setup, impact configuration and main outcome of the tests are described in Section 2. In addition to the physical tests, finite element analysis (FEA) was employed throughout the project to provide pretest prediction, posttest evaluation and design guidance [4–6]. In these analyses, simplified representations of the fluid phases (gas and liquid) and their dynamic effects

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* Corresponding author. Structures and Dynamics Division, Volpe National Transportation Systems Center, U.S. Department of Transportation, 55 Broadway, Cambridge, MA 02142, USA. Tel.: +1 (617) 494 2554; Fax: +1 (617) 494 2113.
E-mail address: hailing.yu@dot.gov (H. Yu).

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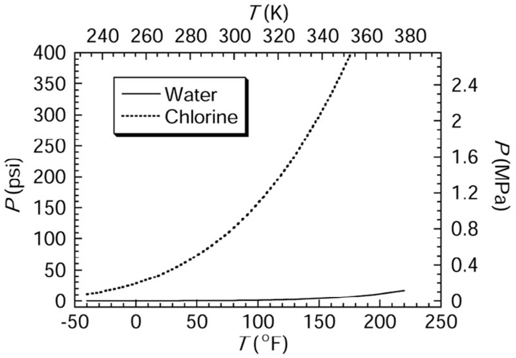

Fig. 1. Vapor pressures of water and chlorine as functions of temperature.

were adopted. Typically, one or both fluid volumes were omitted, and the fluid pressure was simplified as a constant pressure load (equal to the nominal initial fluid pressure) applied directly on a tank car's inner wall. As a result, the interactions between the fluids and the solid structure were not accurately represented in the analyses.

Under normal operating conditions, both liquid and vapor forms of a substance being transported coexist in a tank car. The pressure of a gaseous vapor in dynamic equilibrium with its liquid form at a given temperature is called a vapor pressure. For instance, the Antoine equation calculates the vapor pressure P as a function of the temperature T as follows:

$$\log_{10}(P) = A - B/(T + C) \tag{1}$$

where A, B and C are Antoine coefficients. Based on Eq. (1) and with Antoine coefficients given in reference 7, vapor pressures of water and chlorine are plotted against temperature in Fig. 1. At normal temperatures, the water vapor pressure appears to be negligible, but the chlorine vapor pressure is significant, rendering the chlorine tank cars pressure containers.

Fig. 2 depicts the three interacting phases in a typical chlorine tank car across the longitudinal section: solid structure, liquid and gas. The liquid and gas phases are also referred to as the fluid phases. The fluids transmit pressure onto the tank inner wall, which reacts with balancing internal forces and deflections. Under external impact loading, the tank car structure in the impact zone further responds with elastic–plastic deformations that can be ultimately stretched to a state of failure. Significant structural deformations reduce the volume that the gas occupies and increase its internal pressure, which in turn is imposed upon the tank structure and further affects the structural response. This is a typical fluid–structure interaction (FSI) phenomenon, as the fluid pressure influences the structural response and vice versa.

FSI can have various effects on the dynamics of a closed fluid container, including added fluid mass on the structure; added stiffness to the structure due to fluid pressure; fluid pressure variation with structural deformation; and structural failure. Computational modeling methods have been employed to account for some of these FSI effects in several pressure or non-pressure container applications, such as cargo ship collision, seismic nuclear reactor response and beverage can puncture (e.g., refs. 8–10). In contrast to these applications, the tank car impact problem is unique in that there are two fluid phases in the container and that the fluid pressure is significant enough to affect the structure's susceptibility to failure. As opposed to the simplified fluid modeling approaches adopted in previous tank car studies, this paper presents a multiphase modeling method that addresses all aspects of the FSI effects described above by explicitly modeling all three interacting phases in a tank car: solid structure, pressurized liquid and pressurized gas. Section 3 describes the multiphase FE model development, including constitutive relations, FSI modeling and key FE simulation techniques employed in the study. For the solid phase, in particular, a stress triaxiality dependent fracture initiation criterion, validated with unnotched Charpy impact test data on railroad tank car steel specimens [11–13], was employed to predict the onset of tank car fracture. Section 4 presents the analysis results obtained using the multiphase FE model. The FE model was first validated with the NextGen shell impact test data. The validated model was then used to study the puncture resistance and its dependence on various factors in shell impacts.

It is noted that fluid cavitation can strongly affect FSI in dynamic loading, examples of which were demonstrated in the experimental and numerical studies of marine structures subjected to underwater blast loading [e.g., refs. 14,15]. However, fluid cavitation has not been an observed or reported factor in the impact events of pressurized tank cars. This is partly due to the fact that fluid flow speeds in tank car impact events are considerably lower than those normally associated with cavitation formation. While the duration of a typical underwater blast event was no more than several milliseconds [14,15], the duration of a typical tank car impact event was several hundred milliseconds. This roughly translates into fluid flow speeds that are two orders of magnitude lower in tank car impact than in underwater blast, making it unlikely for low pressure zones to form or cavitation to occur in the former case. In addition, in the tests and FE simulations conducted in this paper, water in the tank cars was pressurized initially to 100 psi (689.5 kPa), a pressure amount significantly higher than the vapor pressure of water at normal temperatures (see Fig. 1). This again deprived the low pressure condition for water to vaporize and form cavitation. For these reasons, no fluid phase transition or cavitation was modeled in this paper.

The Lagrangian formulation was employed to describe both the solid and the fluid domains. In the side impact tests and simulations presented in this paper, there were only small to moderate amounts of fluid sloshing occurring in the tank cars, resulting in moderate fluid mesh deformations. The Lagrangian approach was convenient to implement and sufficient to deal with these deformations and account for the corresponding sloshing effects. More sophisticated alternative methods, such as Arbitrary Lagrangian–Eulerian method and coupling of structural mechanics and fluid dynamics codes, can be considered in cases of significant sloshing (and consequently excessive Lagrangian mesh distortion) but were not necessary in this study.

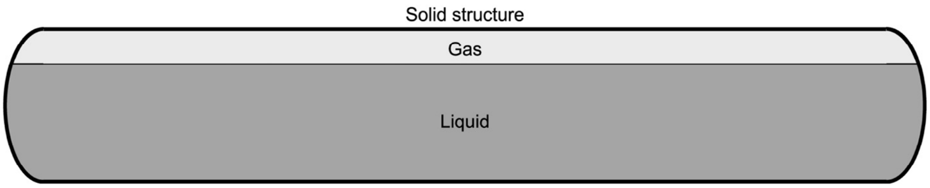

Fig. 2. Illustration of the three interacting phases in a typical chlorine tank car.