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Numerical prediction on dynamic fracture of tubes subjected to internal gaseous detonation

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ABSTRACT

Gaseous detonation-driven fracture is a strongly coupled fluid-structure-fracture problem which involves fluid motion, chemical reaction as well as structural large deformation and fracture. In our work, a stability-based coupling approach which couples a Lagrangian structure solver with fracture capability and an Eulerian fluid solver with detonation computation capability was developed to achieve the fluid-structure interaction (FSI) simulation of tube fracture due to internal gaseous detonation. Different from an assumed fracture strain or stress, a rate-dependent failure criterion for metal materials at high strain rate conditions was employed in the simulation to account for the failure of the tubes. The interaction between detonation wave and tube, dynamic crack propagations, strain responses, crack speeds and the venting of detonation products were obtained and discussed. The simulated final fracture patterns were compared with experiments and the numerical results from other literatures. It is found that our approach reproduces the experimental crack propagations quite well, and it gives a more reliable prediction of the fracture patterns of tubes subjected to gaseous detonation loads compared with other literatures.

1. Introduction

Tube fracture due to internal gaseous detonation has continued to draw attention because of its engineering importance and research interests [1,2]. It is a hazard that is often encountered in the chemical [3], nuclear [4] and transportation industries [5], e.g., the pipe rupture at Hamaoka Nuclear Power Plant (NPP) in Japan [6] (see Fig. 1). Its research can benefit the hazard analysis of pipeline explosion and the failure-based design for pressure vessels under explosive loading [7,8].

A representative experimental study of tube fracture due to internal gaseous detonation was conducted by Chao T W and Shepherd J E [9,10], where ethylene-oxygen detonation waves were sent through aluminum tubes with different initial flaw lengths and the crack propagation behaviors were observed. In addition, detailed analyses on the fracture of gas cylinder, CNG fuel tank and steel pipes induced by internal deflagration/detonation were conducted by Mirzaei M [11–13], where specific features of deflagration/detonation-driven fracture were identified. Besides experiments, numerical methods are exploited for a more realistic simulation of this complicated phenomenon. Involvement of various mechanical behaviors in different fields, such as fracture mechanics, gas dynamics and chemical/mechanical behavior of detonation has made the simulation of gaseous detonation-driven fracture as one of the most difficult engineering simulations [10].

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Fig. 1. Pipe rupture due to internal hydrogen-oxygen detonation at Hamaoka NPP [6].

Generally, numerical simulation of gaseous detonation-driven fracture can be achieved through a decoupled or a coupled analysis. The decoupled analysis first calculates the pressure loads on the structure by simulating the detonation process as if the structure was rigid. Then the pressure loads are applied to the failure model of the structure as boundary conditions to model structural fracture. Examples are Mirzaei M [11,14,15], Song J H [16,17], Gato C [18] and Liu S J [19]. The fluid-structure interaction (FSI) effect is ignored in this kind analysis, and the pressure loads are often over-calculated especially if significant motion or failure of the structure occurs during the loading period [20]. In fact, gaseous detonation-driven fracture is a strongly coupled fluid-structure-fracture problem [21]. The pressure generated by gaseous detonation induces structural deformation, which provides the driving force for crack propagation. The opening cracks and large structural deformation in turn govern the gas dynamics. However, due to large deformations, local topology changes and complicated coupling approaches, coupled analysis of gaseous detonation-driven fracture is a highly challenging task and the related open literature is quite limited. Cirak F etc. [22] developed a level-set-based approach which was successfully applied in the FSI simulation of gaseous detonation-driven fracture. Wang K G [23] also presented a computational framework for the simulation of FSI problem with dynamic fracture. Additionally, Mirzaei M [12] used the ALE (arbitrary Lagrangian-Eulerian) method to study the detonation-driven fracture of steel pipes deeply.

On the other hand, the structure subjected to detonation loading will suffer 10^1–10^6 s^{-1} high strain rates, which makes its failure mode and crack propagation behavior quite different from that under static or quasi-static loading. In many simulations [12,16–19,21,23], a fixed value of equivalent or average strain/stress is assumed as the critical failure strain/stress to model structural fracture. However, many studies [24–26] and our previous rupture experiments on explosion containment vessels (ECVs) [27,28] have revealed that many metal materials tend to fail by adiabatic shear band (ASB) when under loading of sufficiently high rate, and the strain at fracture varies depending on the strain rate of the material.

In this paper, a stability-based coupling approach which couples a Lagrangian structure solver with fracture capability and an Eulerian fluid solver with detonation computation capability was proposed and applied to the FSI simulation of gaseous detonation-driven fracture of tubes. A rate-dependent failure criterion for metal materials at high strain rate conditions was employed in the simulation to account for the failure of the tubes. The interaction between detonation wave and tube, dynamic crack propagations and the venting of detonation products were showed and discussed. The simulated final fracture patterns were compared with experiments and the numerical results from other literatures. It is found that the approach is able to reproduce the experimental fracture patterns quite well.

2. Numerical analysis

2.1. Numerical model

The numerical models are established based on the experiments performed by Chao T W and Shepherd J E [8,9,21]. The schematic setting of the experiments is given in Fig. 2. The preflawed tube specimen is made of aluminum 6061-T6 and is connected

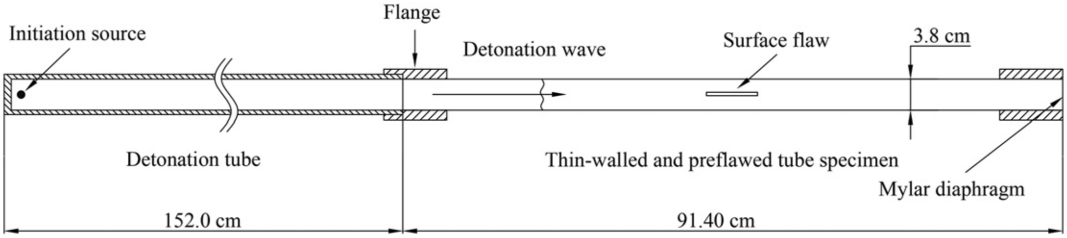

Fig. 2. Experimental setup for the preflawed tube under internal gaseous detonation loading.