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Experimental and numerical analysis of dynamic rupture of steel pipes under internal high-speed moving pressures

Majid Mirzaei*, Mahdi Najafi, Hosein Niasari

Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

This paper reports the experimentation and finite element analysis (FEA) of dynamic ductile rupture of steel pipes subjected to high-speed internal moving pressures. The experimentation included the detonations of tiny explosive cords inside small segments of ordinary gas pipes. A number of specific features of the detonation-driven fracture of cylindrical tubes such as; formation of special fracture surface markings due to cyclic crack growth, flap bulging, and crack curving/branching adjacent to the bulged area were identified. In the analysis part, the overall transient dynamic response of the pipe to detonation loading, the detonation-driven crack growth, the cyclic bulging of the crack flaps, and the resultant crack branching were simulated. The blast simulation was performed using a multi-material arbitrary Lagrangian–Eulerian (MMALE) formulation. The fluid–structure interaction (FSI) was simulated using a coupling algorithm that treated the air as a static media and the pipe as a deformable Lagrangian mesh. The accuracy of the FEA results was verified using analytical solutions and data collected from the tested pipes. The experimentation and analysis clearly showed that the self-similar propagation of the initial axial cracks in the pipe was the incremental cyclic growth governed by the structural waves.

1. Introduction

The analysis of deformation and fracture of cylindrical tubes under internal moving pressures has applications in a number of theoretical and practical problems. However, the scope of the current paper is specific to the *high-speed* moving pressures that can cause significant *fluctuating stresses* in the tube wall. A clear example is the occurrence of gaseous detonation inside steel pipes. Based on their relative magnitudes, these dynamic stresses can result in various types of mechanical failures [1]. Grossly, we may define three pressure levels for which three different types of structural response can be expected. These pressures can be classified according to the magnitude of the resultant stresses which can be less than, equal to, or higher than the dynamic ultimate tensile strength of the material. In sequel, we refer to these pressure levels as 1, 2, and 3 respectively.

For relatively low pressures (level 1) the passage of the pressure front results in a pattern of fluctuating *elastic* strains which can exist even after the moving load dies out (see Fig. 1a). An example for the application of this type of loading is the pulse detonation engine (PDE), shown in Fig. 1b [2,3]. For this case a variety of analytical, experimental, and FEA solutions is available for the structural response [4–12].

On the other extreme, the application of very high-amplitude moving pressures (level 3) can result in the fast expansion and *progressive multiple cracking* of the tube wall, leading to severe dynamic fragmentation (see Fig. 1e,f). In practice, nonlinear-explicit finite element codes like AUTODYN, DYNA3D and LS-DYNA provide many capabilities for simulations of such events. However, it should be emphasized that this type of dynamic fracture, which can result from both gaseous detonation [13] and high-explosive detonation [14,15] *is not the scope of this paper.*

The focus of the current investigation is on traveling of medium pressures (level 2) that cause dynamic stresses in the order of the ultimate tensile strength of the material (see Fig. 1c, d). These stresses can initiate axial cracks, which with further propagation can result in partial tearing or *limited* fragmentation of the tube wall. There was no report about this type of *confined* detonation-driven fracture in the open literature, prior to the experimental studies of Chao [16] on aluminum tubes subjected to gaseous detonation loading. Consequently, several researchers carried out

* Corresponding author. Fax: +98 21 82884909.
E-mail addresses: mmirzaei@modares.ac.ir, majidmirzaei@hotmail.com (M. Mirzaei).

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Nomenclature

E	Young's modulus GPa
h	thickness mm
L	pipe length mm
R_{out}	outer radius of the pipe mm
t	time μs
V	detonation speed m/s
V_{bt}	backward crack tip speed m/s
V_{ft}	forward crack tip speed m/s
V_{sw}	structural waves speed m/s
x	axial coordinate mm
ρ	density kg/m^3
ν	Poisson's ratio
σ_u	ultimate strength MPa
σ_y	yield strength MPa
Δa_b	backward crack growth mm
Δa_f	forward crack growth mm

FEA studies to simulate these experiments [17–20]. Nevertheless, it should be emphasized that the numerical simulation of a complicated process like detonation-driven fracture cannot be warranted without *a clear identification of the underlying deformation and fracture mechanisms*.

Although it had already been argued that realistic simulation of such fractures requires the consideration of the entire spectrum of fluctuating strains [17], the concrete evidences of an *incremental crack growth* by flexural waves were found during the failure analysis of an exploded Hydrogen gas cylinder [21,22]. These evidences included the characteristics of special markings found on the fracture surfaces and showed that in this type of fracture a significant portion of the crack propagation can consist of *cyclic* incremental growth (see Fig. 1d) [21]. Thus, realistic crack growth simulations and accurate assessments of quantities like crack speed must involve procedures that are specific to this particular type of growth.

Nevertheless, the majority of the reported FE simulations of detonation-driven fracture of cylindrical tubes lack the above considerations [16,18–20,23]. In a most recent study, Choi et al. [23] investigated the deformation and fracture of thin expanding tubes by detonation of MDF (mild detonation fuse) cords filled with hexanitrostilbene. They managed to create local ruptures in *oval* steel tubes under the explosive propagation velocity of 7030 m/s. They also performed numerical simulations of the process using the explicit dynamic code AUTODYN. Although the numerical results of their pressure histories clearly showed the traveling of a high-speed moving pressure inside the tube, they neither considered nor discussed the effects of structural waves on the stress and failure analysis of the tubes.

In the view of the above arguments, the current study was aimed at characterization of the effects of *structural waves on dynamic deformation and rupture* of steel pipes under internal high-speed moving pressures through a systematic experimental and numerical analysis.

2. Materials and methods

The experimental specimens were small segments of steel pipes (ASTM A284 Grade D) with dimensions and material properties listed in Table 1.

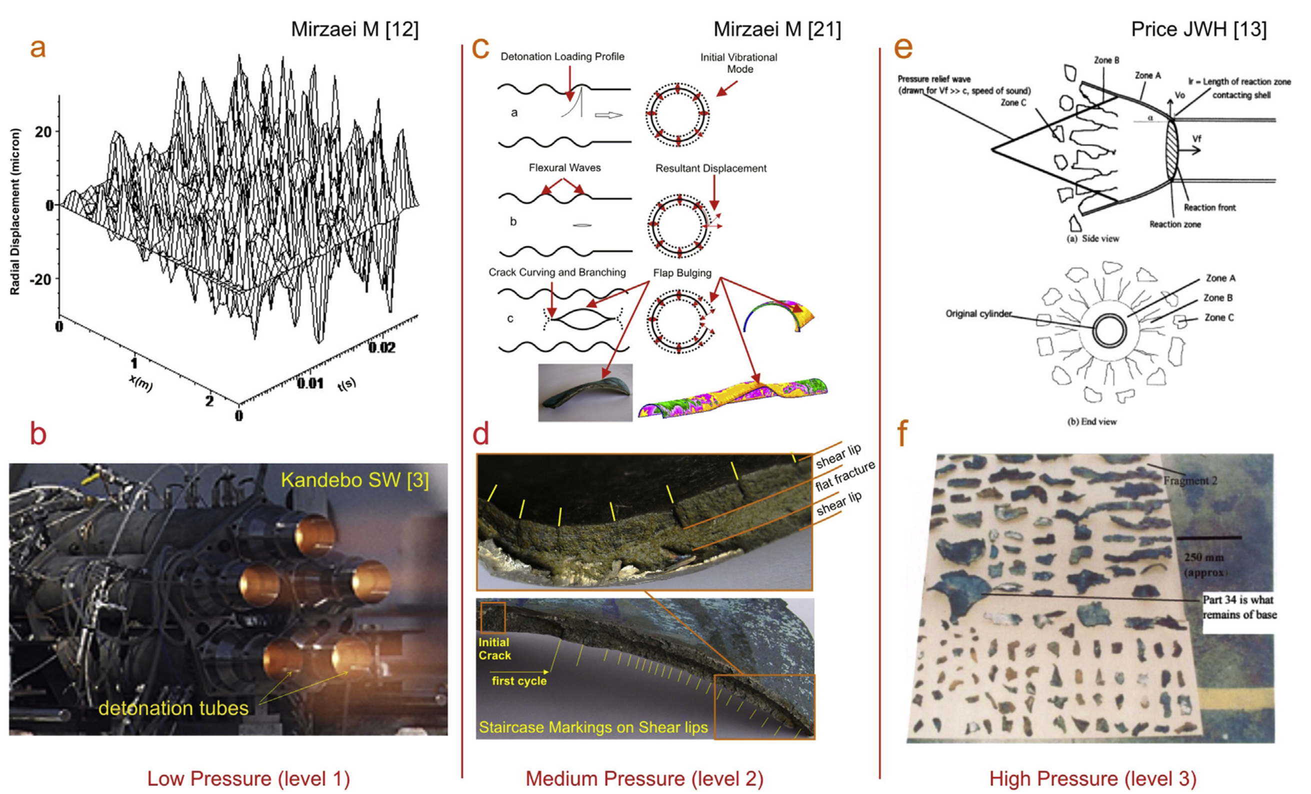

Fig. 1. (a) A 3D plot showing the vibrational behavior of an experimental tube under sequential detonations [12] (b) A five-tube PDE test rig [3]. (c) Formation of flexural waves by a moving detonation front and the resulting crack growth characteristics [21] (the picture of the finite element simulation is for an aluminum tube [17]). (d) The upper crack initiation site of an exploded Hydrogen gas cylinder and special markings on conjugate fracture surfaces [22]. (e) The hypothesized process of fragmentation in a cylindrical shell loaded by a high-pressure detonation [13]. (f) Fragments of an exploded acetylene gas cylinder [13].