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Computational investigation of lateral impact behavior of pressurized pipelines and influence of internal pressure

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ABSTRACT

This paper presents a computational study to examine lateral impact behavior of pressurized pipelines and to determine influence of internal pressure on the pipelines on their impact behaviors. A total of more than 300 numerical simulations were carried out on mild steel pipe models with different internal pressure levels and were struck at the mid-span and at the one quarter span positions. These numerical simulations of the impact tests were performed using 3D dynamic nonlinear finite element analysis (FEA) through LS-DYNA, where both geometrical and material nonlinearities were considered. The computational results for the first time systematically revealed the effects of internal pressure, impact position, and outside diameter on the lateral impact behavior of the pipeline models. The outcomes of this study will have potential benefits on research of safety and reliability of civil pipelines and development of advanced pipeline materials.

1. Introduction

Dynamic responses and failure modes of pipelines subjected to low-velocity lateral impact were studied and described by Jones' and other researchers [1–11] through a series of experimental and theoretical analyses. In Jones work [1–3,9], pipelines with different sizes were fully clamped at both ends and a rigid indenter struck transversely at the pipe center, quarter span and near to the support at velocities ranging up to 14 m/s. Important experimental results (deformation mode, maximum permanent transverse displacement, threshold failure energy, etc.) were observed and associated with size of the pipelines, initial kinetic energy of the indenter, its impact velocity, and its impact position. In addition, properties of material of the pipelines were also considered and the influences of material strain hardening, strain rate sensitivity, and elasticity on the impact behavior of the pipelines were included in their analytical models. Pressurized pipelines were also tested in Jones' and Ng's work [8,9] but the influence of internal pressure on the impact behavior of the pipelines has not been explicitly demonstrated. In reality, the internal pressure is a critical factor in the design and assessment of pipelines because in civil applications, most pipelines convey gases and liquids under high pressures over long distances.

In this study, the dynamic inelastic behavior of clamped thin-walled pipes with internal pressure impacted transversely by a rigid, knife-edge indenter at the pipe center and quarter span is modeled and examined computationally through more than 300 simulations. The obtained numerical results are validated by comparing to several previously published experimental data. Effects of internal pressure on the lateral impact response of the pipelines as well as influences of other impact conditions such as dimensions of the pipelines and impact location are revealed from those simulation results. An explicit FEA solver, LS-DYNA is employed to create the FEA models and run the numerical analyses. The rest of this paper is organized as follows: Section 2 describes the impact problem investigated in this study. Section 3 introduces material properties of the pressurized pipelines. Section 4 demonstrates computational modeling techniques employed in this study; important numerical results are presented in Section 5 and discussed in Section 6. Section 7 concludes this paper.

2. Problem description

The indenter geometry is selected as a fairly severe test of a pipeline and is an idealization of the edge of a flange which could be dropped accidentally onto a pipeline. The pressurized pipes are made from seamless cold drawn mild steel with outside diameters of 22, 42, 60, 80, 100, and 120 mm with a fixed ratio of $2L/D=10$, where $2L$ is the distance between the two supports and D is the outside diameter. The selected ratio of $2L/D=10$ is currently being used in most research laboratory and industry plant as the largest

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Notation

2L	distance between two supports of a pipeline
D	outside diameter of a pipeline
σ_y	static uniaxial yield stress of pipe
σ_u	static ultimate tensile stress of pipe
ε_r	static uniaxial rupture strain of pipe
p	internal pressure
W_f	the maximum permanent transverse displacement
W_l	the local permanent transverse displacement
W_g	the global permanent transverse displacement
F_{max}	maximum impact force
F_m	average impact force
v_i	initial velocity of indenter
v_r	rebound velocity of indenter
E_p	absorbed impact energy
E_f	threshold failure energy

unsupported pipe length ratio [5]. The cold worked mild steel pipes have a 2 mm wall thickness, and the mechanical properties in the axial direction of the pipe are: static uniaxial yield stress $\sigma_y=663$ MPa, static ultimate tensile stress $\sigma_u=823$ MPa, and static uniaxial rupture strain $\varepsilon_r=6$–7%. Several internal pressures will be applied in addition to the tests without any internal pressure in order to find out the influence of internal pressure on the lateral impact behavior of the pipelines. In this study, the internal pressure p varies from 0 to 150 bar. Specifically, 6 different pressures, 0, 30, 60, 90, 120, 150 bar are applied on inner surface of the pipelines separately in order to achieve a complete understanding of how the internal pressure affects the lateral impact behavior of the pipelines.

After simulations, important numerical data are measured or estimated in order to describe the plasticity mechanisms and impact behavior of the pressurized pipelines. Those data include W_f, the maximum permanent transverse displacement, W_l and W_g, local and global permanent transvers displacement respectively, maximum impact force F_{max} and average impact force F_m, rebound velocity of the striker when it separates from the pipe v_r, impact energy absorbed by the pipes E_p and the threshold failure energy E_f, etc. Fig. 1 defines W_f, W_l and W_g, from which the relationships among the three displacement components can be defined as

$$W_f = W_l + W_g \quad (1)$$

3. Definition of material properties

In creating FEA models used for impact analysis that involves large strain and high strain rate problems, the material properties have to be carefully defined to correctly capture the impact. Here, elastic plastic material law with kinematic isotropic hardening is chosen to model the pipeline material (cold drawn steel). Dynamic effects of strain rates are taken into account by scaling static yield stress with a factor with the assumption of Cowper–Symonds relation [12,13]

$$\sigma'_0 = \sigma_0\left(1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}\right) \quad (2)$$

where $\dot{\varepsilon}$ is the strain rate and Eq. (2) shows that during dynamic crushing, the original yield strength σ_0 should be replaced by the dynamic flow stress σ'_0 due to the strain rate effects. C and P are constants of Cowper–Symonds relation, which are used to define the influence of material strain rate sensitivity in this study.

The pipelines are made of cold drawn steel, whose material properties are listed in Table 1 and were implemented into the FEA models through the card *MAT_PLASTIC_KINEMATIC. The indenter is assumed to be rigid during the impact simulation and was defined using *MAT_RIGID.

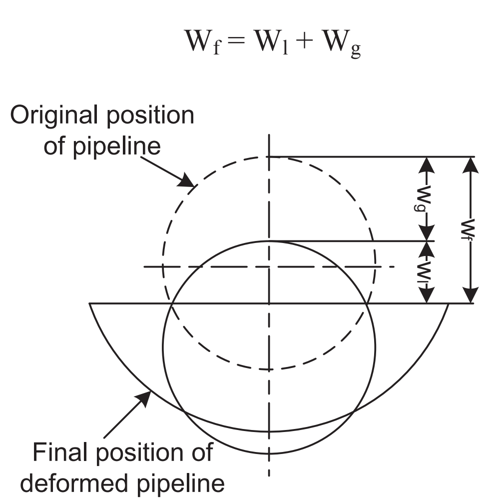

Fig. 1. W_f, W_l, and W_g for the idealized deformed cross-section of a pipeline.

4. Computer modeling and analysis

72 FEA models were created for the pressurized pipelines and one for the rigid knife-edge indenter. The pipelines were modeled using 4-node Belytschko–Tsay shell elements with five integration points through the thickness. The indenter was modeled using rigid elements with rigid material properties assigned and its mass is set as 17.48 kg. It has the same shape and mass as the indenter used by Jones [9]. The contact between the pipelines and the indenter was defined through automatic surface to surface contact algorithm. Within the defined contact pair, the impact face on the pipeline was chosen as master contact surface and the impact face on the indenter the slave surface. Boundary conditions were applied on the FEA models by fully constraining both ends of those pipeline models (Fig. 2). An initial speed of 10 m/s along the impact direction was defined through the LS-DYNA initial velocity generation card and applied on the impactor, at which it impacted onto the pipeline.

Two loading curves were developed to define the internal pressure and gravity, which were applied onto the pipeline model

Table 1
Plastic kinematic material properties for the LS-DYNA pipeline models.

Material properties	Value
Density ρ	7800 kg/m^3
Young's modulus E	200 GPa
Poisson's ratio ν	0.29
Yield stress σ_y	663 MPa
Ultimate tensile stress σ_u	823 MPa
Tangential modulus K_T	583 MPa
uniaxial rupture strain ε_r	6–7%
Failure strain ε	0.72
Hardening index	0.169