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Residual ultimate strength of seamless metallic pipelines under a bending moment-a numerical investigation

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ABSTRACT

Numerical investigation is conducted in this paper on both intact and dented seamless metallic pipelines (diameter-to-thickness ratio D/t around 21), deploying nonlinear finite element method (FEM). A full numerical model is developed, capable of predicting the residual ultimate strength of pipes in terms of bending capacity (M_{cr}) and critical curvature (κ_{cr}). The simulation results are validated through test results by using the measured material properties and specimen geometry. An extensive parametric investigation is conducted on the influences of material anisotropy, initial imperfection, friction of the test set-up and dent parameters. It is found that the structural response is quite sensitive to the frictions that have been introduced by the test configuration. For a pipe with a considerable dent size, the effect of manufacturing induced initial imperfection is insignificant and can be neglected in the FEM simulation. The material yield stress in the pipe longitudinal direction dominates the bending capacity of structures. In the end, formulas are proposed to predict the residual ultimate strength of dented metallic pipes under pure bending moment, which can be used for practical purposes. A satisfying fit is obtained through the comparison between the formulas and FEM methods.

1. Introduction

In previous work of Cai et al. (2017b), an experimental investigation on the bending capacity of the damaged seamless metallic pipelines has been completed. Artificial damage such as a dent, metal loss, a crack and their combinations thereof is properly introduced on specimens. Meanwhile, an initial numerical investigation on the dented pipes has been performed based on a simplified FEM model from the former research of the authors Cai et al. (2018a). However, some influential factors such as the real boundary effect, and the frictions from the test configuration have not been accounted for due to simplifications. As one of the numerical investigation series, the present research focus on both the intact and the dented pipes in order to compare with test and further quantify the dent effect.

In pipelines, structural damage cannot be avoided during their entire life time, which may compromise the structural safety and leads to large loss of assets (Ghaednia et al., 2015; Cai et al., 2017a). It is estimated by PHMSA (2017) that about 23% of all the reported structural damage on pipelines in US in the past 20 years was caused by mechanical interference. Scenarios in practice such as dropping of foreign objects, fishing equipment impact, dragging anchors under water and sinking vessels (Bjørnøy et al., 2000; Macdonald and Cosham, 2005; DNV, 2010) can probably introduce large dent damage to pipes so that the residual ultimate strength of structure may be considerably affected. As simply stated in the rule of DNV (2013a,b), the maximum accepted permanent dent depth due to impact accident should not be larger than 0.05D in a low impact frequency.

Considerable research on the ultimate strength behavior of pipes without structural damage subjected to bending moment has been conducted in the past (Jones and Kitching, 1966; Weiner and Smith, 1976; Sherman, 1976; Gellin, 1980; Murphey and Langner, 1985). During the last twenty years, Bai et al. (1994) proposed prediction equations of ultimate limit states of intact pipes with D/t ratios from 10 to 40 based on an existing experimental database. Gresnigt and Van Foeken (2001) discussed the governing parameters such as geometrical deviations and material properties on pipes with D/t from 22 to 45. It was highlighted that the manufacturing methods had considerable influences on the governing parameters and the pipe local buckling resistance. Experimentally, Es et al. (2016) extensively investigated the ultimate structural behaviors of pipes without structural damage subjected to bending moment, deploying a spiral-welded steel tubes with 42-inch-diameter and D/t between 65 and 120. Based on the test

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Nomenclature

κ_0	the referential curvature of pipe [1/m]
κ_i	critical curvature of intact pipe (either from test or simulation) [1/m]
κ_{cr}	critical curvature of pipe [1/m]
λ_l	normalized dent length
λ_w	normalized dent width
λ_{cl}	critical half-wavelength
ω	dent depth variation [mm]
σ_y	material yield stress [MPa]
σ_h	material yield stress in the pipe hoop direction [MPa]
θ_d	dent angle [deg]
ε_{11}	strain component in pipe axial direction
ε_{22}	strain component in pipe hoop direction
D	outer diameter of pipe [mm]
d_d	dent depth [mm]
L	full length of specimen [mm]
$L1$	half length of specimen under pure bending [mm]
$L2/L4$	length of the loading/support strip [mm]
$L3$	original bending arm [mm]
$L5$	side length of specimen [mm]
l_d	dent length [mm]
M_i	ultimate bending moment of intact pipe (either from test or simulation) [kNm]
M_y	plastic bending moment [kNm]
M_{cr}	residual ultimate bending moment
R	pipe outer radius [mm]
t	pipe thickness [mm]
w_d	dent width [mm]

results, Vasilikis et al. (2016) conducted a consecutive numerical investigation. The effect of spiral-welded manufacturing method has been described in detail. Other relevant research can be seen from literature (Vitali et al., 2005; Guarracino et al., 2009; Hilberink, 2011; Bai and Bai, 2014a; b). Nevertheless, the investigations on the residual ultimate strength of damaged metallic pipes subjected to bending moment are relatively rare. The majority of the research on damaged pipes concentrated on the bursting of pipe subjected to internal pressure or collapse capacity subjected to external pressure, such as Park and Kyriakides (1996) and Bjørnøy et al. (2000).

Therefore, in the present research, on the basis of both the experimental investigation and the former research of the dented pipes, the simulations of intact seamless metallic pipes and pipes with artificial dent are conducted in order to compare with test and further quantify the dent effect on pipes under pure bending moment. The full numerical models are developed, capable of accounting for the variation of possible parameters such as material, geometrical nonlinearality, damage type and damage size in an efficient way. The nonlinear finite element method (FEM) is deployed for the simulation.

The structure of this paper is arranged as follows. In Section 2, the test set-up and the specimens that are deployed are briefly reviewed. Section 3 comprehensively describes the developed full numerical models for simulation of different types of specimens, including intact model without damage and the dented model. Furthermore, the numerical predictions are validated by the test results in terms of structural failure modes, strain variation, and bending moment-curvature diagrams in Section 4. In Section 5, a parametric investigation is performed, accounting for the influential parameters such as material anisotropy, initial imperfection and friction of the set-up that have been observed in the physical test. Afterwards, the effects of dent parameters including dent depth, length and width are analyzed and discussed in Section 6. Empirical formulas are then proposed to predict the residual ultimate strength of metallic pipes under bending moment. Finally, this paper ends with some concluding remarks.

2. Tests and specimens overview

In this section, the set-up of four-point bending tests and specimens are briefly reviewed. The details of the pipe test have been presented in the relevant experimental investigation part of Cai et al. (2017b).

Fig. 1 shows the designed four-point bending test set-up. The principal dimensions and specific geometrical distribution of specimens are listed in Table 1. During the physical test, 39 seamless specimens in terms of both intact and the ones with artificial damage on their surface were used. The D/t ratio of the specimens varied around 21 due to the manufacturing deviation. The deployed specimen material is Q345B (GB/T 1591, 2008), which is a typical material for transmission pipes with a minimum yield stress of 345 MPa.

Four specimens are intact with no structural damage, whereas 35 specimens are intentionally damaged through carefully designed test in the laboratory. All the structural damage is introduced properly on each specimen before the strength test, located at the center of specimen either on the compression side or on the tensile side. The test data are measured and documented extensively. In this paper, only the type of dent structural damage, as shown in Fig. 2, has been accounted for. Other types of damage have been investigated separately by the authors Cai et al. (2018b, c). As seen in Fig. 3, the dent is introduced by a quasi-static indentation with different types of indenters. In this paper, the dent on specimens is produced by the indenter with an arc-shape.

The specimens that will be deployed for the following validation are categorized into two groups (all the series numbers of specimens in this paper are exactly the same with the ones in the experimental investigation of Cai et al. (2017b)): (a) specimens within the first group without artificial structural damage, including S1N1, S1N2, S1N3 and S1N4; (b) dented specimens within the second group with dent in different dent angle and size, including S2N1, S2N2, S2N3 and S2N5.

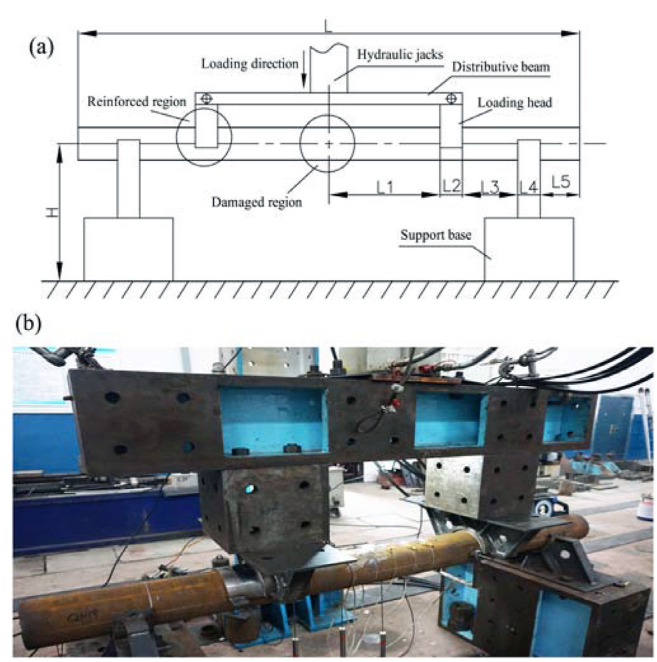

Fig. 1. The configuration of four-point bending test: (a) the sketch of test set-up; (b) the real test set-up in laboratory.