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Residual ultimate strength of damaged seamless metallic pipelines with metal loss

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A R T I C L E I N F O

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A B S T R A C T

On the basis of an experimental investigation [1], numerical investigation is conducted in this paper on damaged seamless metallic pipelines with metal loss (diameter-to-thickness ratio D/t around 21) through nonlinear finite element method (FEM). Numerical models are developed and validated through test results by using the measured material properties and specimen geometry, capable of predicting the residual ultimate strength of pipes in terms of bending capacity (M_{cr}) and critical curvature (κ_{cr}). By changing the metal loss parameters, i.e. length (l_m), width (w_m) and depth (d_m), a series of numerical simulations are carried out. Results show that the larger the d_m or l_m is, the less the bending capacity will be. The increase of notch width slightly reduces the pipe strength, presenting a linear tendency. Based on the FEM results, empirical formulas are proposed to predict the residual ultimate strength of metallic pipes with metal loss under pure bending moment. The prediction results match well with the results from the tests, the numerical simulations as well as the theoretical derivation. Such formulas can be therefore used for practice purposes and facilitate the decision-making of pipe maintenance after mechanical interference.

1. Introduction

In previous work [1], an extensive experimental investigation on the structural behavior of damaged seamless metallic pipelines (D/t around 21) subjected to bending moment has been completed. The specimens deployed had an average outer diameter (D) of 168.3 mm and an average thickness (t) of 8 mm. Artificial structural damage was imposed on the surface of specimens including a dent, metal loss in the form of notch, crack and combinations thereof. For intact pipelines, the elastic-plastic failure mode dominates. The structures fail smoothly, initiated in the form of an outward bulge in the area away from the specimen central cross-section. However, the failure of damaged specimens with either a dent or a notch has been accelerated due to the rapid localization of damaged area, with a decrease of both bending capacity and corresponding critical curvature. As one of the numerical investigation series, the present research only concentrates on damaged pipes with metal loss in terms of a notch in order to quantify its effect.

Metal loss is a generalized type of damage that involves partial loss of material in the forms of gouges and notches, etc. In pipelines, metal loss defects due to mechanical interference may compromise structural safety and lead to large loss of assets [2]. Unlike the widely investigation of corrosion on metallic pipes [3–5], the investigation of such metal loss is relative rare due to low probability of mechanical interference. It has been estimated that the failure of oil and gas transmission pipelines that was resulted from structural damage ranges from 55% in the US to around 70% in Europe [6]. Scenarios in practice such as dropping of foreign

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Nomenclature

κ_0	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 damaged pipe [1/m]
λ_l	normalized notch length
λ_w	normalized notch width
ϕ	half angle of metal loss [radians]
σ_y	material yield strength [MPa]
σ_{comp}	compression stress in pipe cross-section [MPa]
σ_{ten}	tensile stress in pipe cross-section [MPa]
θ	angle from bending plane to the plastic neutral axis [radians]
D	outer diameter of pipe [mm]
d_m	metal loss depth [mm]
F	true axial force [N]
k_1, k_2	constants related to notch depth
L_0	length of pipe under pure bending [mm]
l_m	metal loss 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 [kNm]
R	pipe outer radius [mm]
R_a	pipe average radius [mm]
R_m	reduced average pipe radius due to notch, expressed as $R_m = R_a - d_m/2$
S_m	compression area of metal loss region
S_{comp1}	compression area of region without metal loss
S_{loss}	area loss of metal loss in pipe cross-section
S_{ten}	tensile area of pipe cross-section
t	pipe thickness [mm]
t_m	reduced pipe thickness due to notch, expressed as $t_m = t - d_m$
w_m	metal loss width [mm]
Y_m, Y_{comp1}, Y_{ten}	force arms from bending axis to the mass center of respective area segment

objects, fishing equipment, dragging anchors and sinking vessels [7–9] can introduce considerable metal loss on pipes so that the residual ultimate strength of structure may be affected. In this paper, a notch is used to represent such metal loss on the outer surface of metallic pipes.

Considerable research on the ultimate strength behavior of pipes subjected to bending moment has been conducted in the past few decades. In the early time, Bai et al. [10] proposed prediction equations on the ultimate limit states of intact pipes with D/t ratios from 10 to 40 based on an existing experimental database. Experimentally, Es et al. [11] investigated ultimate strength 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 results, Vasilikis et al. [12] conducted a consecutive numerical investigation. Other relevant research can be also seen from literature [13–18].

Nevertheless, most of the investigations focused on ultimate strength of intact metallic pipes. The investigations on pipes with metal loss under bending moment are relatively rare. Levold et al. [19] conducted a test on a damaged pipe with D/t of 26.5, where corrosion damage in terms of gouge was artificially introduced in the inner surface of pipe by Electrical Discharge Machining (EDM) method. In addition, the so-called "neighbor response" effect of finite metal loss has not been fully taken into account in most of the existed research. Zheng et al. [20] used the "effective thickness" to correct such effect. Other investigation on damaged pipes mainly concentrates on the busting of pipes subjected to internal pressure or the collapse capacity of pipes subjected to external pressure, such as Park and Kyriakides [21] and Bjrny et al. [7].

Therefore, the objective of this paper is to investigate the structural behavior of seamless metallic pipes with notch on the compression side and quantify the damage effect. The structure of this paper is arranged as follows. In Section 2, the four-point bending test set-up and the specimens deployed in this research are briefly reviewed. Section 3 comprehensively describes the developed numerical models for simulation of pipes with metal loss. Furthermore, the numerical model is validated through test in terms of failure mode, bending moment-curvature diagrams and ultimate strength in Section 4. In Section 5, the simulation results of notch are investigated and discussed. Analytical solution of residual bending moment accounting for the changing of neutral axis due

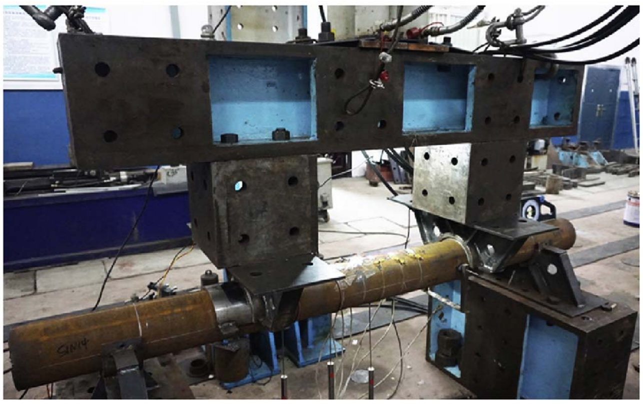

Fig. 1. The configuration of four-point bending test set-up in laboratory [1].