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Moment resistance of steel pipes subjected to combined loads

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ABSTRACT

The first part of this paper provides a review of recent investigations on steel pipes subjected to combined loads. Attention is given to studies involving both numerical and experimental components aimed at quantifying the modified moment resistance of pipes subjected to internal pressure and axial force. The comparison of experimental and finite element results indicate that the nonlinear shell finite element analysis is a reliable tool for predicting moment capacities of pipes. The second part of the paper reports two additional full-scale tests recently conducted at the University of Ottawa aimed at expanding the existing experimental database to pipes subjected to more complex load combinations involving twisting moment and shear (in addition to axial force, internal pressure, and bending). The finite element analysis for both tests is shown to provide excellent predictions of pipe moment capacity. The third part of the paper is a systematic parametric study based on the FEA model verified in previous and present investigations, aimed to assess the ability of pipe sections to attain their modified elastic and/or plastic moment resistance as predicted by analytically derived interaction equations. The parameters investigated are the applied torsion, internal pressure, axial force, and the diameter-to-thickness ratio of the pipe.

1. Introduction and scope

Elevated pipes are commonly subject to complex combinations of vertical, transverse, and longitudinal forces in addition to internal pressure. Sources of vertical forces include the self-weight of the pipes, the fluids they convey, insulation, insulation covering, fittings, and valves. Sources of transverse forces include wind, earthquake, and thermal effects. Longitudinal forces can arise in pipes from anchor forces, thermal loads, and Poisson's ratio effect. In addition, pipes are often subject to internal pressure caused by the action of the fluids they convey. Under these load combinations, a straight elevated pipeline is subject to biaxial bending, biaxial shear, compressive or tensile axial forces, as well as tensile hoop stresses. In order to relieve the internal axial forces under thermal effects, it is common practice to introduce horizontal pipe loops into elevated pipelines at regular intervals. The loops provide flexible axial links between straight pipe segments and allow the pipeline to expand or contract longitudinally without generating excessive internal axial forces. However, the presence of loops introduces twisting moments in the loop arms of the same order of magnitude as that of the bending moments in the straight section. Current pipeline codes, e.g., Refs. [1,2] recognize the additional capacity of pipe sections with relatively low diameter-to-thickness ratio which can be developed by deforming into the plastic range of deformation but do not provide simple design rules to predict pipe section capacity under general load combinations. In this context, recent work in Refs. [3–5] have resulted in developing general plastic and elastic interaction relations for pipe sections under general load combinations. However, it is not known under which geometric and loading conditions, pipe sections are able to develop their modified plastic moment M_{pm} or their modified elastic moment resistance M_{em} (both moment resistances M_{pm} and M_{em} are defined in Appendix A), or possibly undergoing local buckling prior attaining any of these limits. The objective of the present study is to assess the conditions under which the above two limits are attained for commonly used pipes with X65 material 508 mm diameter, and a diameter-to-thickness ratio of 80.

2. Review of related research

A series of seven tests subjected to internal pressure, axial force, and bending moments on 1.220 mm diameter pipes with a $D/t = 104$ was conducted in Ref. [6]. The flexural behavior of 19 tube sections with a D/t ranging between 18 and 102 beyond the ultimate moment capacity was reported in Ref. [7]. Pipe deformational behavior and capacity under combined loads were investigated by conducting approximately 70 small-scale and two full-scale tests [8], which had a diameter of 610 mm with

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List of symbols

α	indicator measuring how apart M_{FEA} is from the modified plastic moment M_{pm} and/or the modified elastic moment M_{em}
τ_r	shear ratio parameter which intrinsically relates the twist and shear force ratios (Eq. (A2)) to the moment, axial force, and internal pressure ratios (Eq. (A1))
A	applied axial force
A_r	ratio of axial force applied to yield axial resistance
A_y	yield axial resistance $A_y = 2\pi rtF_y$
D	measured pipe diameter
D/t	diameter-to-thickness ratio
E	modulus of elasticity of the pipe material
F_y	measured yield strength
L_p	length of the pipe specimen
M_b	maximum moment at the location of the buckle as measured during the experiments of this study
M_e	elastic moment capacity of a pipe calculated in the absence of other internal forces
M_{em}	modified elastic moment capacity of a pipe predicted by elastic interaction relations (Appendix A)
M_{FEA}	maximum moment at the location of the buckle predicted by FEA
M_p	plastic moment resistance a pipe calculated in the absence of other internal forces $M_p = 4r^2tF_y$
M_{pm}	modified plastic moment capacity as predicted by the plastic interaction relations (Appendix A)
M_{test}	maximum moment measured during the tests in precious studies
OD	nominal outer diameter
p	applied internal pressure
p_r	ratio of applied internal pressure p to internal pressure p_y which causes the hoop stresses to attain the yield stress F_y
p_y	internal pressure which causes the hoop stresses to attain the yield stress F_y
SMYS	specified minimum yield strength
r	radius of pipe mid-surface
t	pipe wall thickness
T	applied twisting moment
T_p	plastic twisting moment resistance calculated in the absence of other internal forces $T_p = (2\pi r^2tF_y)/\sqrt{3}$
T_r	ratio of applied twisting moment T to plastic twisting moment resistance T_p
V	applied shear force
V_b	shearing force at the location of the buckle as measured during the experiments
V_p	plastic shear resistance calculated in the absence of other forces
V_r	ratio of applied shear force V to the plastic shear resistance V_p
z	vertical distance between the center line of the actuators to the location of the buckle

a $D/t = 95$. In these full-scale tests, curvature was applied to the pipes along with external pressure. In Ref. [9], the authors suggested that tubular members under longitudinal force and bending with D/t ratio higher than 35 are susceptible to local buckling within their compressive side before they reach their fully plastic resistance. In contrast, in Ref. [10], the authors suggest that when tension is a dominating load, it is more likely that pipes will develop higher capacity than their plastic resistance due to tensile stresses and strain-hardening effects. A series of tests was conducted on large fabricated tubes with a diameter of 450 mm and D/t ratio ranging from 51 to 100 subjected to combinations of axial load and bending [11]. A numerical and experimental study [12] investigated the inelastic shear behavior of large diameter pipes subjected to transverse loads by conducting two tests on pipes with 1.270 mm diameter and $D/t \approx 400$. An interaction equation for the bending and shear was proposed based on regression analysis of test results. Since 1992, several experimental and numerical studies were conducted on pipe sections at the University of Alberta. This includes the work in Ref. [13] involving full-scale tests on seven pipe specimens subjected to internal pressure, axial force, and bending moments. Subsequently, the authors developed interaction expressions [14] including internal pressure, axial force, and bending moments. The experimental results in Ref. [14] demonstrate the validity of these interaction relations for pipes with a D/t ratio of 51 and 64. The validated equations were subsequently adopted in the design rules for submarine pipelines in Ref. [2]. The experimental study was later extended in Ref. [15] to investigate the effect of the girth-weld on pipe specimens subjected to the combinations of internal pressure, axial force, and bending. Further testing on pipe segments subjected to internal pressure, axial force, and bending moments for pipes with $D/t = 92$ were reported in Ref. [16]. In their study, it was observed that specimens pressurized up to 80% of their specified minimum yield strength (SMYS) were able to develop their modified plastic moment capacity. Another series of tests was conducted at the Centre for Engineering Research (C-FER). Published work from this series include the work in Ref. [17] which reports an experimental and numerical program on pipes with $D/t = 87$ subjected to internal pressure and bending and the study [19] which reports a series of tests on 762 mm diameter spirally welded pipes with D/t ratios of 82 and 48 and material grades of X70 (483 MPa) and X80 (552 MPa) under combinations of internal pressure and bending. Recent work at the University of Ottawa [19] included an experimental study on six pipes with $D/t = 43$ subjected to bending, shear, and torsion. Most recently, another series of tests was conducted on pipes under bending, axial force and tension [20]. The tests in Refs. [19,20] showed that the interaction relations developed in Refs. [3,4] were able to accurately predict the moment capacity for the pipes tested.

3. Comparison of previous experimental and numerical results

Among the many research programs reported in the previous section, the ones selected in this section meet two criteria: a) They involve a recent full-scale testing component on pipes subjected to combined loads, b) They involve a finite element analysis (FEA) component based on shell elements, including material and geometric non-linear effects. These include the studies reported in Ref. [11] and their FEA modeling in Refs. [21], [13] and [18] which report the experimental and numerical components, [16] and its FEA modeling as reported in Refs. [21,22], as well as the study reported in Refs. [22] and [23]. The summary of the tests is provided in Table 1. Column 1 of this table cites the main publication in which the test series is documented. Column 2 assigns a serial number for each specimen. Column 3 provides test descriptor as used in the relevant publication. Columns 4, 5, and 6 respectively provide the