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A load–indentation formulation for cement composite filled pipe-in-pipe structures

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ABSTRACT

This study proposes a two-stage approach to predict the lateral load (P) versus the local indentation (δ) relationship for cement composite filled pipe-in-pipe structures. The first stage extends a theoretical shell model used in predicting the P–δ relationship for hollow steel pipes, to the sandwich composite pipes by introducing an equivalent thickness to describe the composite action. This composite action, however, deteriorates at large indentation levels. The indentation resistance in the second stage, therefore, combines the resistance of three individual layers of materials. This approach predicts closely the P–δ relationship measured for the pipe-in-pipe composite specimens under lateral loads.

1. Introduction

Circular hollow sections have seen wide applications in both onshore and offshore infrastructures, including offshore jacket and jackup structures, oil and gas pipelines, etc., due to their low resistance to fluid flow and easy handling in construction, transportation and erection [1]. External interference has become a primary threat and a frequent cause of damage in onshore and offshore pipelines, contributing to more than 50% of recorded failures in Europe and in the United States [2]. The external interference here refers to a wide spectrum of loading conditions, *e.g.*, trawl gears or boards from fishing vessels, heavy objects such as anchors and excavation equipment as well as moving debris. The pipelines installed in the Arctic region also face the risk of mechanical damage caused by the movement of ice floes or icebergs. Concrete filled pipe-in-pipe composite structures have recently emerged as a popular solution to enhance the structural resistance against external loadings [3–5]. These composite structures have seen applications as columns in transmission towers to increase the bending moment capacity and to reduce the weight of the structure [6,7]. Engineering applications of such composite structures in pipelines in a harsh offshore environment requires an improved understanding on the load–indentation relationship for these pipe-in-pipe composite structures.

Previous investigations on the steel hollow pipes have paved a strong foundation in understanding the behavior of pipe-in-pipe composite structures. Thomas et al. [8] investigated experimentally the large deformations of thin-walled steel pipes under transverse loads applied using a wedge-shaped indenter at the mid-span. During the test, the specimens experienced local indentation, global bending and finally collapsed with a large plastic deformation. Their subsequent study [9] concluded that the short pipes ($L < 1.5D$) deformed like a compressed ring and consisted of inextensible hoops bending about generators of the pipe, while the long tubes ($L > 6D$) experienced significant membrane stretching in the longitudinal direction. Fig. 1 illustrates the rings and the generators in a pipe as well as an inextensible ring bending about generators under the lateral indentation.

Wierzbicki and Suh [10] have proposed a simplified ring-generator model to estimate the lateral load (P) versus the local indentation (δ) relationship for steel pipes under combined actions of lateral, axial and bending loads. With the demonstrated close agreement with the experimental data, their theoretical model became widely recognized [11–13] and implemented in engineering guidelines [14]. For steel pipes with free ends, their proposed P–δ relationship [10] follows,

$$\frac{P}{M_o} = 16\sqrt{\frac{\pi}{16}\frac{\delta}{R_o}\frac{D_o}{t_o}} \Rightarrow P = \sigma_y t_o \sqrt{2\pi\delta t_o} \qquad (1)$$

where M_o denotes the plastic moment capacity of a pipe wall strip with a unit width ($\sigma_y t^2/4$) and σ_y refers to the yield strength of steel pipe.

Det Norske Veritas [15] recommends a P–δ relationship for local indentation on the steel pipe supported by a rigid base as follows,

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Nomenclature

A_c	cross section area of the cement composite
A_{si}	cross section area of the inner pipe
A_{so}	cross section area of the outer pipe
C_1, C_2	coefficients in the recommended P–δ relationship for hollow steel pipes
D_i	external diameter of the inner pipe in the pipe-in-pipe composite structure
D_o	external diameter of the outer pipe in the pipe-in-pipe composite structure or external diameter of the hollow steel pipe
E	Young's modulus
$\dot{E}_{crush}$	rate of the crushing energy for rings
$\dot{E}_{ext}$	rate of the external work
$\dot{E}_{gen}$	rate of the extensional energy for generators
$\dot{E}_{gen,s}$	rate of the extensional energy for a single generator
$\dot{E}_{int}$	rate of the internal work
L	length of the pipe
L_{xz}	length of the loading area in x–z plane
L_{yz}	length of the loading area in y–z plane
M	bending moment
M_o	plastic moment capacity of the pipe wall with a unit width
N	axial force
N_o	axial capacity of the pipe wall with a unit width
P	lateral load
P_c	transient crushing force
P_i	indentation resistance of the inner pipe
P_m	indentation resistance of the cement composite
P_o	indentation resistance of the outer pipe
R_i	external radius of the inner pipe in the pipe-in-pipe composite structure
R_o	external radius of the outer pipe in the pipe-in-pipe composite structure or external radius of the hollow steel pipe
R_1	radius of the bottom arc in a deformed ring
R_2	radius of the upper arc in a deformed ring
S	continuous deformation field
V_1, V_2	tangential velocities of a deformed ring
c_1, c_2	coefficients defined in DNV [15]
f_c	compressive strength of the cement composite
f_{ck}	characteristic compressive strength of the cement composite
n	strain-hardening exponent
r	radius of the indenter head
s_1	length of the bottom arc in a deformed ring
s_2	length of the upper arc in a deformed ring
s_3	half-length of the flat segment in a deformed ring
t_c	thickness of the cement composite layer
t_{gen}	equivalent thickness for the generator model in the pipe-in-pipe composite structure
t_i	thickness of the inner pipe in the pipe-in-pipe composite structure
t_o	thickness of the outer pipe in the pipe-in-pipe composite structure or thickness of the hollow steel pipe
t_{ring}	equivalent thickness for the ring model in the pipe-in-pipe composite structure
$\dot{v}$	rate of the axial displacement
$\dot{v}_o$	rate of the axial displacement at $y = \xi$
w	vertical displacement
w_c	deflection of the pipe
$\dot{w}_c$	deflection rate of the pipe
w_α	deflection at an angle position α
$\dot{w}_\alpha$	deflection rate at an angle position α
y	coordinate in the longitudinal direction
z	vertical distance between the material point and the central axis for a ring
$\dot{\Omega}$	rate of the relative rotation on both sides of a hinge
α	angle position
β	disperse angle
δ	local indentation
$\dot{\delta}$	rate of the local indentation
ε	strain
ζ	confinement factor
$\dot{\theta}$	rate of the rotation
$\dot{\theta}_o$	rate of the rotation at $y = \xi$
$\dot{\kappa}_{xx}$	rate of the circumferential curvature for the ring
υ	Poisson's ratio
ξ	half-length of the indentation zone
σ	stress
σ_o	average flow stress
σ_e	effective stress
σ_u	ultimate stress
σ_y	yield stress
τ_y	yield shear stress
ϕ	angle
χ	hollow ratio of the pipe-in-pipe composite structure

$$P = \frac{1}{4}\sigma_y t_o^2 \left(\frac{D_o}{t_o}\right)^{0.5} k c_1 \left(\frac{\delta}{D_o}\right)^{c_2} \tag{2}$$

where c_1 and c_2 define the geometric dependent coefficients [15]. The constant k (often <1.0) depends on the axial load level, and takes a fixed value of 1.0 in this study due to the zero axial load for the specimens considered.

Ong and Lu [16] conducted a series of experimental studies to estimate the collapse load and the energy absorption capability for hollow pipes (with three different end conditions) subjected to transverse loads applied from a wedge-shaped indenter. The proposed empirical equation, derived based on their test data, for pipes lying on a hard surface with both ends free follows,

$$P = 0.7\sigma_y t_o^2 \left(\frac{D_o}{t_o}\right)^{0.5} \left(\frac{\delta}{t_o}\right)^{0.57} \tag{3}$$

Gresnigt et al. [17] have recently developed an analytical model for the P–δ relationship of steel hollow pipes subjected to an internal pressure based on a calibrated finite element (FE) study. Their analytical model consists of three stages: the initial elastic stage, the subsequent plastic stage and the membrane stretching stage. Khedmati and Nazari [18] examined the P–δ relationships for preloaded steel tubes with three different boundary conditions based on a numerical investigation. Firouzsalari and Showkati [19] compared the existing P–δ formulas with the experimental data and concluded that an appropriate universal expression has not yet evolved for pipes with various geometries at different indentation levels. The aforementioned studies indicate that thin-walled pipes demonstrate limited indentation resistance under lateral loads, coupled with a large local deformation.

Hou et al. [20,21] have recently investigated experimentally and numerically the behavior of concrete-filled circular steel tubes subjected to local load. They adopted a deformation limit, *i.e.*, 3% of the tubular member diameter [22], to determine the ultimate strength of the concrete-filled steel tubular members in trusses, bridges and tower structures. This deformation limit applies specifically to hollow section tubular joints under axial brace loads. For traditional pipelines, the European Pipeline Research Group (EPRG) [23]