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Experimental behavior of cement filled pipe-in-pipe composite structures under transverse impact

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ABSTRACT

This paper investigates the transverse impact performance for ultra lightweight cement composite (ULCC) filled pipe-in-pipe composite structures through drop weight impact tests and numerical simulations in LS-DYNA. Compared to steel hollow pipes, the sandwich composite pipes demonstrate superior impact performance with higher impact resistance, smaller global deformation and local indentation. The outer pipe and its thickness determine directly the impact resistance and the global bending deformation of the composite pipe. The ULCC layer restricts effectively the development of the local indentation. The presence of the inner pipe enhances the confinement to the ULCC material. The numerical simulation predicts closely the impact response for pipe-in-pipe composite specimens during the drop weight impact test.

1. Introduction

External impacts have become a primary threat and a frequent cause for the damages incurred in submarine oil and gas pipelines. This drives the need to advance the understanding on the impact behavior for pipe structures [1] and the demand to investigate practical approaches to strengthen such hollow pipes. Concrete filled pipe-in-pipe composite structures have recently emerged as a popular solution to enhance the structural resistance against external loadings due to the steel-concrete-steel composite action [2–4]. Engineering applications of such structures as pipelines in a harsh offshore environment requires an improved understanding on the impact behavior for the pipe-in-pipe composite structures, including the steel-concrete-steel composite action under impact loads as well as the effect of each component (the outer pipe, the inner pipe and the concrete layer) in resisting the external impacts.

Previous investigations on the hollow steel pipes have paved a strong foundation in understanding the lateral impact behavior of concrete filled pipe-in-pipe structures. Thomas et al. [5] investigated experimentally the large deformations of simply supported steel pipes subjected to static indentation at the mid-span. During the test, the specimens experienced local indentation, global bending and finally collapsed with a large plastic deformation. They also carried out dynamic tests by dropping a wedge-shaped indenter onto hollow pipes. To sustain the same amount of final deflection, hollow pipes dissipated more external energies under the dynamic load than those under the static load. Jones et al. [6] conducted a large number of lateral impact tests on fully clamped steel pipes. Based on the abundant test data, they proposed an empirical equation to predict the impact response for hollow steel pipes [7]. Their subsequent studies investigated experimentally and theoretically the structural performance of steel pipes subjected to impacts at different positions with various internal pressure levels [8–10]. Zeinoddini et al. [11] first introduced an axial compressive load to the hollow steel pipes under the transverse impact. Their test results indicated that the axial load had a significant effect on the damage level of the steel pipes, subjected to the transverse impact. The higher the axial compressive load level was applied, the larger permanent deformation for the steel pipe would occur. They verified their test results by using the non-linear finite element program ABAQUS [12] and extended the numerical study to investigate the transverse impact performance of pipelines supported on flexible seabed [1]. Al-Thairy and Wang [13] developed FE models in ABAQUS/Explicit to simulate the transverse impact behavior and failure modes for axially compressed steel tubes. Many researchers have also used the explicit code in the non-linear FE program LS-DYNA to investigate the lateral impact performance of hollow steel pipes [14,15]. The aforementioned studies indicate that thin-walled steel pipes demonstrate limited structural strength under lateral impacts, coupled with large global deformation and local indentation.

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Nomenclature

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
E_a	absorbed impact energy
E_g	impact energy dissipated by the global deformation
E_i	total impact energy
E_l	impact energy dissipated by the local indentation
E_{sa}	specific energy absorbing capacity
G	total weight of the pipe specimen
H	drop height
L	length of the pipe
P	impact force
P_m	post-peak mean force
P_{max}	maximum impact force
R_o	external radius of the outer pipe in the pipe-in-pipe composite structure or external radius of the hollow steel pipe
V_f	volume of the PVA fiber in the cement composite core
V_i	velocity of the indenter tip
V_o	initial impact velocity
V_p	passing velocity
V_t	velocity of the impact point on the pipe
W	mass per unit length of the pipe
b_1	compressive damage scaling parameter
f_c	compressive strength of the cement composite
g	gravitational acceleration
m	total mass of the structure
m_d	mass of the drop weight
r	radius of the semi-cylindrical indenter head
t	time
t_c	thickness of the cement composite layer
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_1	time instant when the global displacement reaches the maximum value
t_2	time instant when the impact force decreases to zero
w	global displacement
w_i	displacement of the indenter tip
w_{max}	maximum global displacement
w_o	global displacement when $P = P_{max}$
w_r	residual bottom surface deformation
w_t	total deflection at the impact location on the pipe
$w_{t,max}$	maximum displacement of the impact location on the pipe
y	coordinate in the longitudinal direction of the pipe
Δ_{l-p}	distance from the lower laser light to the top surface of the specimen
δ	local indentation
δ_a	total pipe deformation after the impact
δ_{max}	maximum local indentation
υ	Poisson's ratio
ρ	density of the cement composite
σ_u	ultimate stress
σ_y	yield stress

Some engineers, therefore, utilize the reinforced concrete coating outside the steel pipes to enhance the structural impact resistance. Palmer et al. [16] carried out some full-scale transverse impact tests on concrete coated pipes. They employed a steel cage outside the pipe to reinforce the concrete coating. The experimental data demonstrated that the bending deformations and the plastic strains for the pipes decreased apparently due to the protection from the concrete coating. However, the concrete coating crushed severely around the impact location and exposed the steel reinforcement to the open air, which often happened for real damage pipelines [17]. Moreover, the normal weight concrete increases the total mass of pipelines and needs temporary formwork during curing, which creates additional challenges in transportation, construction and maintenance of the pipelines.

In recent years, researchers have started to investigate the lateral impact performance of steel-concrete composite structures [18,19]. Liew et al. [20] carried out experimental and analytical studies on the transverse impact performance of steel-concrete-steel (SCS) sandwich beams with lightweight concrete core. Bambach et al. [21] examined the lateral impact response for square hollow pipes and concrete-filled square pipes by low-velocity drop weight impact tests. Remennikov et al. [22] tested the impact performance of concrete-filled square hollow sections and developed FE models by LS-DYNA to simulate the impact process. Wang et al. [23] explored the structural behavior of concrete-filled circular hollow sections under the combination of axial compression and lateral impact. The various types of steel-concrete composite structures summarized above demonstrate high structural strength and energy absorption capacity under the lateral impact loadings.

This study investigates the lateral impact performance of the pipe-in-pipe composite system consisting of two steel pipes with infilled ultra lightweight cement composite (ULCC) in-between the two pipes (see Fig. 1). The composite pipe, also known as the double-skin composite tube, originates from the steel-concrete-steel (SCS) sandwich panels and concrete-filled pipes (CFP) developed in recent years [2]. Most of the previous research works on the concrete-filled pipe-in-pipe member have focused on the axial compression performance due to its wide applications as columns in civil engineering constructions [24–27]. A number of researchers have examined numerically the ultimate capacity of sandwich composite pipes under an external pressure [28,29]. Uenaka and Kitoh [30] carried out a three-point bending test to

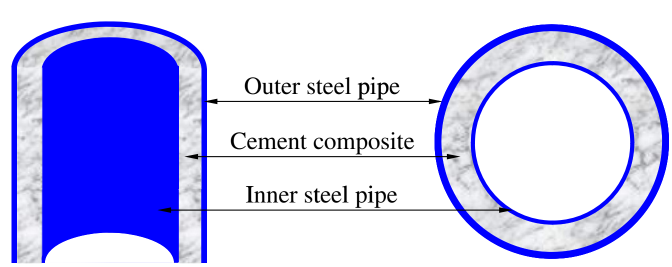

Fig. 1. The cement composite filled pipe-in-pipe structure.