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Impact of cement composite filled steel tubes: An experimental, numerical and theoretical treatise

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ABSTRACT

This paper presents a combined experimental, numerical and theoretical study on the transverse impact behavior for ultra lightweight cement composite (ULCC) filled steel pipe structures. The drop weight impact test investigates the impact behavior of the pipe specimens. The numerical simulation using the non-linear finite element software LS-DYNA agrees closely with the experimental data. Meanwhile, this study develops a theoretical method to predict the impact response for cement composite filled pipes. Compared to the experimental results, the theoretical method provides reasonable predictions on the impact force and the global displacement response for the cement composite filled pipe specimens.

1. Introduction

Concrete filled steel tube (CFST) structures have seen wide applications in engineering constructions, including bridges, multistory and high-rise buildings due to their enhanced compressive and flexural capacities, improved ductility and the dispensable temporary formwork compared to the reinforced concrete (RC) structures [1–5]. Researchers have recently started to investigate the behavior of CFST structures subjected to extreme loads such as impact and blast [6–8] due to the increasing interest in understanding the dynamic behavior for CFST structures and the demand to provide practical design guides for CFST constructions in resisting extreme loadings.

Bambach et al. [9] examined the structural behavior of fully clamped square CFST beams under the transverse impact from a flat-headed drop weight. The CFST composite beam consists of a compact or a non-compact square hollow section, classified according to the section slenderness [10], filled by normal weight concrete with an average compressive strength of 88.4 MPa. Compared to square hollow sections, concrete filled non-compact sections demonstrate much higher moment capacity coupled with the significantly decreased lateral deflection but the impact performance for compact sections present little improvement with the filling concrete. Bambach [11] extends the investigation to stainless steel sections filled with normal weight concrete ($f_c = 91.6$ MPa) through the drop weight impact test and the finite element (FE) analysis in ABAQUS. The stainless steel sections exhibit superior energy absorption capacity than that for the mild steel sections.

Qu et al. [12] carried out a numerical study using LS-DYNA to investigate the impact behavior for one end pinned and the other end fixed circular CFST members with a normal weight concrete core ($f_c = 47.5$ MPa). Based on the numerical results, they developed a simplified analytical model to predict the maximum global displacement (w_{max}) for the CFST members at the mid-span. The simplified model ignores the local indentation, the elastic global deformation and the energy losses during the impact and assumes that the two plastic hinges formed in the CFST members dissipated all the impact energy (E_i),

$$w_{max} = \frac{L}{2} \times \theta = \frac{L}{2} \times \frac{E_i}{3M_{ud}} \quad (1)$$

where L refers to the length of the CFST members and θ denotes the rotation angle at the end of the pipe. M_{ud} represents the dynamic plastic moment capacity of the circular CFST section. When calculating the dynamic plastic moment capacity, the model considered the strain rate effect for both the steel and the concrete material by employing the dynamic increase factor (*DIF*) according to Malvar and Ross's model [13] and CEB code [14]. The analytical model predicts accurately the maximum global displacement (w_{max}) for the CFST members under the transverse impact.

Remennikov et al. [15] have studied experimentally and numerically (using LS-DYNA) the impact behavior for square composite pipes. The simply supported composite specimens contain two kinds of filler materials, *i.e.*, the normal weight concrete ($f_c = 41$ MPa) and the rigid polyurethane foam (RPF). The square CFST specimens demonstrate the highest impact resistance and energy absorption capacity, followed by the square RPF-filled specimens and the square hollow sections. Yousuf et al. [6,16] employed the same test instrument as Remennikov's work [15] to investigate the impact performance for concrete filled

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Nomenclature

C	Cowper–Symonds strain rate parameter
C_1, C_2	coefficients in the recommended $P-\delta$ relationship for steel pipes
D_o	external diameter of the steel pipe
E	Young's modulus
E_a	absorbed impact energy
E_d	kinematic energy of the pipe
$E_{g,e}$	elastic global deformation energy of the pipe
$E_{g,p}$	plastic global deformation energy of the pipe
E_g	global deformation energy of the pipe
E_i	total impact energy
E_δ	local indentation energy of the pipe
G	total weight of the pipe
I	moment of inertia
L	length of the pipe
L_o	clear span length of the pipe
L_f	crushing failure length of the cement composite under the indenter in the x–z plane
L_t	total length of the cement composite under the indenter in the x–z plane
L_{xz}	length of the load–resistance area of the cement composite in the x–z plane
L_{yz}	length of the load–resistance area of the cement composite in the y–z plane
M_p	plastic moment capacity of the pipe cross section
M_{ud}	dynamic plastic moment capacity of the pipe section
P	transverse impact force or lateral force
P_c	indentation resistance of the cement composite
P_m	post-peak mean force
$P_{\max}$	maximum impact force
P_o	indentation resistance of the steel pipe
R_c	external radius of the cement composite cylinder in the steel pipe
R_{ci}	failure stress of the cement composite in ith direction
R_o	external radius of the steel pipe
V	rebound velocity
V_f	fiber volume
V_o	initial impact velocity
V_0	initial volume of the cement composite
DIF_c	dynamic increase factor of the cement composite in compression
DIF_s	dynamic increase factor of the steel material
EAC	energy absorption capacity
f_c	compressive strength of the cement composite
$f_{c,d}$	dynamic compressive strength of the cement composite
m_d	mass of the drop weight
m_p	mass of the pipe
n	strain-hardening exponent
p	Cowper–Symonds strain rate parameter
r	radius of the semi-cylindrical indenter head
t	time
t_o	thickness of the steel pipe
w_g	global displacement
$w_{g,e}$	elastic global displacement
$w_{g,p}$	plastic global displacement
$w_{\max}$	maximum global displacement
w_o	global displacement when $P = P_{\max}$
w_t	total deflection at the impact location on the pipe
y	coordinate in the longitudinal direction
α_s	parameters defining the strain-rate dependence
β	disperse angle
γ_s	parameters defining the strain-rate dependence
δ	local indentation
δ_c	critical local indentation
$\delta_{\max}$	maximum local indentation
ε	strain
ε_f	failure strain of the cement composite under the uniaxial compression
ε_{fi}	failure strain of the cement composite in ith direction ($i = x, y, z$)
$\dot{\varepsilon}_d$	dynamic strain rate
$\dot{\varepsilon}_s$	static strain rate
υ	Poisson's ratio
ρ_c	density of the cement composite
σ	stress
σ_u	ultimate stress
σ_y	yield stress
$\sigma_{y,d}$	dynamic yield stress
ω_i	ith angle frequency of the natural vibration for the pipe (i=1, 3, 5, …)

square stainless steel tubes with a normal weight concrete core ($f_c = 25$ MPa). The experimental results reflect the excellent impact resistance and energy absorption capability for CFST specimens with stainless steel sections compared to concrete-filled mild steel tubes.

Deng et al. [17] conducted drop weight impact tests on simply supported circular CFSTs, circular posttensioned concrete-filled steel tubes (PTCFST), and circular steel fiber reinforced concrete-filled steel tube (FRCFST) specimens filled with the normal weight concrete ($f_c < 60$ MPa). The application of pre-stressed strands and steel fibers restrained effectively the cracks in the tension area of the concrete core. The PTCFST and the FRCFST specimens demonstrate superior impact resistance than the regular CFST specimens.

Wang et al. [18] have recently studied experimentally and numerically (using ABAQUS) the dynamic performance of axially preloaded circular CFST specimens under the transverse impact. The circular CFST specimens, filled by the normal weight concrete ($f_c = 48.5$ MPa), has one end fixed and the other end constrained by a roller support. The CFST specimens with high confinement from the steel pipe (usually thick-walled) exhibit high ductility while the CFST specimens with low confinement from the steel pipe (often thin-walled) indicate brittle failures under the transverse impact. Han et al. [7] extended the investigation to the impact behavior of CFST specimens filled with high strength, self-consolidating concrete ($f_c \in [68.3$ MPa, 75.1 MPa$]$) under three boundary conditions, *i.e.*, fixed-fixed support, fixed-pinned support and pinned-pinned support. These CFST specimens demonstrate high capacity and ductility under the impact loads. They have also proposed a simplified model to estimate the dynamic increase factor for the moment capacity calculation based on the calibrated FE study.

The above research works prove the promising and huge potential of the CFST structures in resisting impact loads. With limited studies reported on the impact response of concrete-filled circular hollow sections, this study aims to investigate the impact behavior of ultra lightweight cement composite (ULCC) [19] filled circular hollow sections through a combined experimental, numerical and theoretical study. This paper examines the impact resistance of the cement composite filled specimens using a post-peak mean force (P_m) and an energy absorption capacity (EAC), similar to the