International Journal of Impact Engineering 97 (2016) 10–28

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Blast resistance of metallic tube-core sandwich panels

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ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form 26 May 2016
Accepted 3 June 2016
Available online 7 June 2016

Keywords:
Tube-core sandwich panel
Anti-blast structure
Blast mitigation
Experimental research

ABSTRACT

A tube-core sandwich panel was designed to serve as anti-blast panel of blast resistant walls. Steel tubes are non-expensive and strong for anti-blast walls, and can be easily connected with face sheets through welding. Static three-point bending experiments, close-in explosion experiments and contact explosion experiments were performed to explore its anti-blast ability. The tough interface and shear-resistant tube-core endow the panel with high bending rigidity. In close-in explosion, the front face mitigates the shock wave corrugations through corrugated plastic deformation and the panel is rigid enough to resist the shock wave. In contact explosion, the panel attenuates the shock wave through tube-crushing and skin-tearing. Appropriate thicknesses of the front face and the tube wall promote energy absorption. The experiments indicate that spaced tube-core panel is the better choice for close-in explosions while connected tube-core panel has advantages under contact explosions.

1. Introduction

To resist accidental explosions and terrorist attacks, stainless steel profiled blast barriers [1–6], concrete walls [7], temporary soil-filled walls [8–10], water containers [11–15] and aqueous foam barriers [16] have been developed. Recent research efforts led to the development of lightweight wall panels for the construction of rapidly erected blast-resistant structures [17]. These panels are constructed from solid sawn softwood lumber studs and 9.5 mm thick CDX plywood sheathing, both coated with glass fiber reinforcement to provide enhanced strength and ductility. Su et al. [18] proposed a novel blast wave mitigation device, consisting of a piston-cylinder assembly. A shock wave is induced inside the device when it is subject to a blast wave. The shock wave propagates inside the device and is reflected repeatedly. The peak pressure of the blast wave can be reduced by as much as 98%, or even higher. Chen and Hao [19,20] developed a new multi-arch double-layered blast-resistance door panel to resist explosion. Effectiveness of blast wall barriers is usually predicted by theoretical analysis, experiments, numerical simulations or using neural networks [21]. Recently, flexural membranes have been used to construct anti-blast structures [22,23] to resist explosion generated from small charges or remote blast wave, such as flexible military tents.

Metallic tubes have been applied as energy absorbers to resist explosions [24–27]. Transverse blast loading of hollow beams with square cross-sections have been studied through experiments, simulations and analyses [28–34]. Karagiozova et al. [35] discussed blast response of a circular metallic hollow beam analytically.

In close-in explosion, duration of the blast keeps at the level of millisecond (ms). Li et al. [36,37] studied blast responses under contact explosions through experiments and numerical simulations. It was pointed out that the duration of the contact explosion would be within several hundred microseconds (μs) [36,37].

In this paper, to get a non-expensive and easily-made blast-resistant structure, sandwich panels with steel tube-core were designed. Anti-blast behaviors of these panels under close-in and contact explosions were explored by experiments and numerical simulations.

2. Tube-core sandwich panels

Tube-core sandwich panels have two steel face sheets and steel tube-core. The face sheets are made of Q235B steel 4.5 mm thick. The tube-core is made up of uniformly-spaced thin-walled 20# steel tubes, as shown in Fig. 1. The material properties are listed in Table 1. Three-tube-core sandwich panels have three tubes in the core, while four-tube-core sandwich panels have four tubes and five-tube-core sandwich panels have five tubes. The diameter of the tube is 89 mm and the wall is 5 mm thick. All tubes were welded with the face sheets. Two 4.5 mm thick side walls were welded with the face sheets. Each filled weld is 35 mm long and uniformly-distributed along the panel with 100 mm spacing. All sandwich panels are 100 mm thick, 455 mm wide and 1200 mm long.

Tubes in three-tube-core and four-tube core panels have periodic spacing, and these panels are called spaced tube-core sandwich

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http://dx.doi.org/10.1016/j.ijimpeng.2016.06.001
0734-743X/

Nomenclature

A	area of the face sheet
E_p	energy dissipation during face corrugation
h	beam height
I	blast impulse
I_z	second moment of area of the cross-section
L	span of the beam
M_p	plastic bending moment of the plastic hinge
n	number of the tube
P_f	yield load of the tube-core sandwich panel
P_u	ultimate load of the tube-core sandwich panel
r	radius of the tube
t	skin thickness
t_b	wall thickness of the tube
v_1	velocity of the face sheet in phase I
v_2	velocity in phase III
$w_c(x, y)$	corrugation
W_{nx}	ratio of $I_z/(h/2)$
(x, y)	coordinates
b	width of the tube-core panel
Δb	spacing between neighboring tubes
Δc	maximum deflection of the corrugation
Δc_3	corrugation depth of three-tube core panel
Δc_n	corrugation depth of panel with n tubes in the core
Δd	spacing between neighboring tubes
$\sum \theta_p$	total angle of the plastic hinges for each corrugation
σ_f	yield strength of the face sheet
σ_p	plastic stress
σ_u	ultimate tensile strength
ζ	defined by $\frac{2n\pi r t_b}{tb}$
ρ_f	material density of the face

panel. Tubes in the five-tube-core connect with each other and the spacing is zero. These panels are called connected tube-core sandwich panels. Spacing determines the periodic span of the skin, Δb, given by

$$\Delta b = 2r + \Delta d = \frac{b-2r}{n-1} \quad (1)$$

where Δd is the spacing between neighboring tubes and $\Delta d = \frac{b-2nr}{n-1}$, n is the number of the tube; r is the radius of the tube and b is the width of the tube-core panel. As an important constant, skin span greatly affects the dynamic plastic deformation mode of the tube-core panel.

Table 1
Material properties.

Material	Density (kg/m^3)	Young's modulus (MPa)	Yield strength (MPa)	Tensile strength (MPa)
Steel 20# (tube)	7.85×10^3	2.1×10^5	315	490
Steel Q235B (skin)	7.85×10^3	2.1×10^5	285	420

3. Static bending behaviors

3.1. Three-point bending experiments

Three-point bending experiments were carried out on a 4000 kN mechanical testing system. The span of the beam is 1100 mm with a cantilever of 50 mm at each end.

As shown in Fig. 2, the panel exhibits excellent plastic deformation ability. After yielding, the load keeps constant, forming a deformation plateau accompanied with continuously increasing deflection. There is a plastic hinge at the center of the beam. Failures of the welds cause the side walls to partly detach from the front face sheet. The ultimate load varies from 325.5 kN, 374.9 kN to 433.9 kN, as listed in Table 2.

3.2. Analyses

The yield load of the tube-core sandwich panel, P_f, is calculated by

$$P_f = 4\sigma_f W_{nx}/L \quad (2)$$

and the ultimate load of the tube-core sandwich panel, P_u, is calculated by

$$P_u = 4\sigma_u W_{nx}/L \quad (3)$$

with $W_{nx} = \frac{2I_z}{h}$, where σ_f is the yield strength of the face sheet and σ_u is the ultimate tensile strength. L is the span of the beam and h is the beam height. I_z is the second moment of area of the cross-section. For three-tube-core panel $I_z = 11.6 \times 10^6\ mm^4$. For four-tube-core panel $I_z = 12.24 \times 10^6\ mm^4$. For five-tube-core panel $I_z = 12.88 \times 10^6\ mm^4$. Contribution of the core is neglected. Equation (3) consistently predicts the ultimate load, as listed in Table 2. In static bending, the welded steel tube core is strong enough to guarantee the panels fail at face sheet yield.

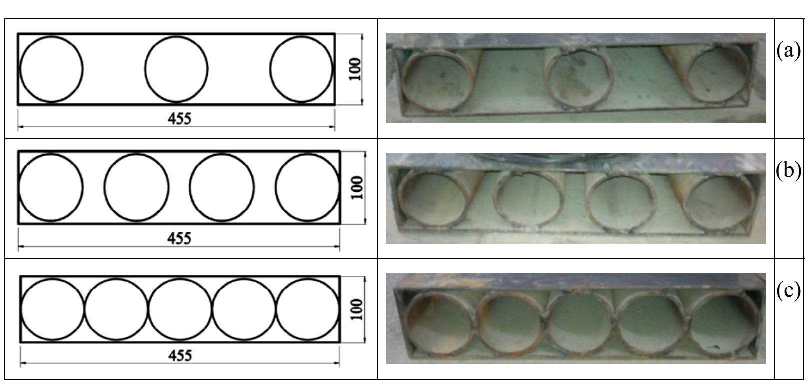

Fig. 1. Cross section of (a) three-tube-core sandwich panel, (b) four-tube-core sandwich panel and (c) five-tube-core sandwich panel (Unit: mm).