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Lightweight steel–concrete–steel sandwich composite shell subject to punching shear

Zhen-Yu Huang [a], Jun-Yan Wang [b,*], J.Y. Richard Liew [a], Peter William Marshall [a]

[a] Department of Civil and Environmental Engineering, National University of Singapore, Blk E1A-07-03, 1 Engineering Drive 2, Singapore 117576, Singapore
[b] Key Laboratory of Advanced Civil Engineering Materials, Tongji University, Ministry of Education, Shanghai 201804, China

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ABSTRACT

The development of Arctic oil and gas fields requires high strength structures that can resist critical loads in extreme environment. A novel conical caisson structure constructed by lightweight steel–concrete–steel (SCS) sandwich shell is proposed for withstanding ice pressure imposed thereon by impinging sheet ice in Arctic region. This paper mainly investigates the ultimate strength behaviour of SCS sandwich shell experimentally and analytically. Two pilot quasi-static tests on the lightweight SCS sandwich composite shells subject to patch loading are carried out. The failure mode of composite shell is punching shear. Tests show that the punching shear resistance depends on the control perimeter of punched concrete frustum and shear connectors. The membrane action of the outer steel plates provides post-hardening strength. On the basis of the experimental failure mechanism, an analytical model is developed to explain the force transfer mechanism and predict the punching shear resistance of SCS sandwich composite shell. The verification of the model shows that the predictions are in good agreement with the test results. It is also shown that the SCS sandwich shell, in accord with the ISO ice load design, is capable of resisting the localised contact and punching loads.

1. Introduction

The Arctic continental shelf is believed to be the area with the highest unexplored potential for oil and gas as well as for unconventional hydrocarbon resources such as gas hydrates. World demand for oil is set to increase 37% by 2030, according to the US-based Energy Information Administration's (EIA) annual report (B.B.C. News, 2006). Moreover, US geological survey showed that 30% of the world's undiscovered gas and 13% undisclosed oil were found in the Arctic. The growing demand for oil and gas today has reawakened the interest in oil and gas exploration and development in this area. However, one challenge is that waters in this area are covered with vast area of ice. An offshore platform in the Arctic has to be able to withstand the forces imposed by moving ice. The ice will sometimes be broken and sometimes continuous, and may include pressure ridges 30 m or thicker. The forces imposed by that ice will be large, 100 MN or more, and can be greater than those generated by waves on platforms in open water. Therefore, high resistance structure with high ductility is required. Although a great number of Arctic structures have been proposed and in operation, year-round operations in extremely harsh ice environment still ask for more capable structures. Hence, it suggests new ideas as alternatives for existing design concepts to produce an economical yet feasible solution that allows continual year-round operation in the Arctic region.

The great majority of stationary platforms in the south Arctic are fabricated from steel, and held to the seabed by long piles. A few are concrete, often selected for reasons that are partly political, and they are held in position by a combination of weight and some lateral resistance provided by a skirt or by short piles. A very few are steel gravity platforms. Some researchers (McLean, 1987; McLean et al., 1990; Sabnis and Shadid, 1992; Ellis and Macgregor, 1993; Birdy et al., 1985) investigated the punching shear behaviour of RC shell subject to local loads. It offers vast information for early design of concrete shell structures.

Thanks to the high performance of steel–concrete composite structures, steel–concrete–steel (SCS) sandwich composite structure that takes advantages of both concrete compression performance and steel tension performance is a good alternative in the civil and offshore domain due to its excellent cost-strength performance (Marshall et al., 2010; Liew and Wang, 2011). The SCS sandwich composite exhibits significant structural and economic advantages over the conventional reinforced concrete structures in terms of higher flexural stiffness and high energy

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* Corresponding author. Tel.: +65 9175 2275; fax: +65 6779 1635.
E-mail address: johnsonong25@gmail.com (J.-Y. Wang).

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Nomenclature

A_N	projected area of cone surface to the free concrete surface
A_{se}	cross-sectional area of shear stud
A_v	punching shear area of steel plate
α_i	angle between stud axis and horizontal axis
C_c	0.15 for LWC, 0.18 for NWC
d_s	diameter of shear stud
E_s	Young's modulus of steel
E_c	Young's modulus of concrete
f_{ut}	ultimate strength of headed shear stud
f_u	ultimate strength of steel plate
F_c	concrete breakout resistance
F_u	stud tension failure resistance
F_p	plate punching shear resistance
F_t	tension resistance of shear stud embedded in concrete which equals to the minimum value among F_c, F_u and F_p
$\overline{h}_c$	effective height of concrete core
h_c	height of concrete core
h_{ef}	embedded height of shear stud
k_f	0.29 is used for synthetic fibres
k_c	$1+\sqrt{200/\overline{h}_c} \leq 2.0$
n	ratio of E_s/E_c
n_{cp}	amount of the shear studs linking the shear cracks
η_1	$0.4+0.6\rho/2200 \leq 1.0$
P_1	first peak load
P_2	second peak load
γ_c	partial safety factor for concrete
s	stud spacing
t_s	thickness of plate
$\tau_{f,FRC}$	$4.23V_f$, V_f is the percentage of fibre volume faction
u_1	control perimeter of punching concrete
U	control perimeter of punching plate
V	total punching shear resistance
$v_{lRd,c}$	punching shear resistance per unit area of a lightweight concrete slab
$v_{lRd,cs}$	punching shear resistance per unit area of concrete with shear reinforcement
ρ	density of concrete (kg/m^3)

absorption capacity to withstand extreme environmental and accidental loads. The external steel plates may serve as a permanent formwork during concreting, promoting construction efficiency and reducing the site handling costs and time. The waterproof feature inherently provided by external steel plates reduces surface area that needs expensive corrosive protection and makes it easy for inspection and maintenance. As a result, SCS sandwich composite structures can be adopted as heavy duty and protective layers such as ship hulls, ice-resisting walls, tunnels and nuclear power station walls that require resistance against extreme loads.

At 1980s, researchers and applications of steel–concrete–steel composite structures were hot topics as the economic growth at that time drove a high demand of new ideas of structural application. Researches on development of composite ice-resisting wall structures for Arctic offshore drilling/production structures were examined by scholars at University of Alberta, contributing much fundamental information to design and application (Kennedy Stephen, 1987; O'Flynn, 1987; Zimmerman, 1993). For decades, many researchers have investigated static and dynamic behaviour of steel–composite structure for building and offshore constructions. Solomon et al. (1976) appraised the SCS sandwich structure as a potential structural form to reduce self-weight of the roadway slab on composite bridge. Tomlinson et al. (1990) proposed double skin SCS with shear studs for immersed tube tunnel application under Conwy River. In 1990s, Steel Construction Institute (1994, 1997) issued two design guidelines on the application of SCS sandwich construction. In these applications, the shear transfer between steel skin and concrete relies on the overlapped headed shear studs. Shukry and Goode (1990) carried out the punching tests on circular composite shells for the first time.

In order to enhance the composite action of SCS sandwich structure, Liew and Sohel (2009) proposed a novel J-hook shear connector and responsive push-out and pull-out tests showed that the connector possessed high resistance with feasible fabrication comparing to normal headed shear stud connectors (Yan et al., 2014a, 2014b). Later, a couple of novel shear connectors have been proposed by Sohel et al. (2012) for the SCS composite structures to enhance the interfacial bond between the face plate and the internal core. Furthermore, static and impact performances of SCS sandwich beam and plate were evaluated experimentally (Liew et al., 2009; Liew and Sohel, 2010; Sohel and Liew, 2011). Recent tests also showed that the SCS sandwich structure exhibited superior impact performance (Sohel and Liew, 2014). Finite element analysis using ABAQUS has been conducted, with well-agree the experimental results (Huang et al., 2013a, 2013b, 2015).

Most of the previous studies focused on the flexural or shear behaviour of flat composite beams and panels. However, very limited works have been done on SCS sandwich shells under larger patch loads and impact loads. SCS sandwich shell is a new form of structure, which may have a single or double curvature. Compared to the flat panel, it has advantages such as longer span between web frames and simpler internal structure. Non-hydrostatic loading creates shell bending and inter-layer shear stresses, which depend on the concrete-to-steel bond. This is a bigger issue than that for flat panel, which must develop shell bending and bond shear for all cases. The researches on ultimate strength behaviour of SCS sandwich shells is scarce. As the force transfer mechanism and failure modes become rather critical in thick SCS sandwich shell members, experimental and analytical researches become essential.

This paper first proposes a concept of conical structure with external SCS sandwich shells filled with ultra-lightweight cement composite for Arctic platform structures. Quasi-static tests are then carried out on two SCS sandwich shells under patch loading. On the basic of the experimental results in this paper and those from the published literature, a modified Eurocode 2 model is developed to explain the force transfer mechanism and shear resisting mechanism and to predict the punching shear resistance of SCS sandwich shells.

2. Development of sandwich caisson system for Arctic region

2.1. Structural form

For Arctic offshore application, the structures are constantly subject to high pressure loading from huge mass of moving ice driven by wind and sea currents, which may cause catastrophic damage to the structure. The design and feasibility of Arctic offshore structure is often dominated by ice environment.