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Punching shear behavior of steel–concrete–steel sandwich composite plate under patch loads

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ABSTRACT

This paper studied the structural behaviors of steel–concrete–steel sandwich composite plates under patch loads. Ten SCS sandwich plates, adopting an ultra-lightweight cement composite (ULCC) and overlapped headed studs as the bonding measures at the steel–concrete interface, were simply supported and subjected to patch loads till failure. The investigated parameters included spacing of the connectors, strength of the ULCC core, thickness of the steel skin, volume fraction of the fiber, and depth of the cross section. Test results estimated the size of the punching cone and showed that load-defection behaviors of the SCS sandwich plate contained five stages. The influences of the different parameters have been discussed and analyzed. Analytical models have been developed to predict the ultimate resistances of the SCS sandwich plate under patch loads through modifying the code equations. These innovations and modifications included developing models to predict the tensile resistance of the connectors, incorporating the contribution of the top steel skin on the punching shear resistance, consideration of the tensile resistance of the connectors on the second peak resistance of the structure, and adopting a proper critical perimeter. The validations of the predictions against the test results showed that the code provisions overestimated ultimate resistances of the SCS sandwich plates and the developed analytical models offered reasonably good agreements. Design recommendations were finally given based on these validations and discussions.

1. Introduction

According to the U.S. Geological Survey (USGS) in 2008, the Arctic region has the reserves of about 13% of the world's undiscovered oil and 30% of the world's undiscovered gas [1]. However, the Arctic explorations of oil and gas are still in the early stages due to the harsh environments with floating ice features. Many concepts of structural systems have been developed for the oil and gas explorations in the Arctic [2], e.g., an artificial island, jacket structures, a caisson-retained island, and gravity based structures. Marshall et al. [3] have proposed a type of gravity-based conical structure with an external flower-shaped ice-resistant wall as shown in Fig. 1(a). This gravity-based structure focused on applications in the Arctic ocean with water depths of 10–100 m. However, the curved SCS sandwich ice-resistant wall brings difficulties for fabrication and installation [4–5]. To overcome these disadvantages, the authors have proposed another alternative concept of an octagon-shaped gravity based conical structure with a sloped steel–concrete–steel (SCS) sandwich plate type of ice-resistant wall as shown in Fig. 1(b). The peripheral SCS sandwich plates were designed to resist the ice-contact pressure produced by the multiyear ice. This SCS sandwich plate consists of a layer of concrete sandwiched by two external layers of steel with overlapped headed studs to bond them working with integrity. The SCS sandwich plate can not only be applied as an ice-resistant wall, but has also been used as a shear wall in high-rise buildings [6–7], submerged tunnels, caissons, nuclear wall structures, bridge and offshore decks, protective structures and liquid containment [8–11].

An arctic offshore structure has to resist the ice-contact pressure produced by floating ice features [12]. This ice-contact pressure can be up to 2.5 MPa on a large interacting area and more than 15 MPa on a localized interacting area [12–15]. This load is much larger than that in a typical building floor structure of about 0.00475 MPa [15]. Therefore, such extremely high loads in the Arctic region require the developed SCS sandwich plate structure with high resistance and high ductility that permits year-round operation. Previous studies showed that the SCS sandwich plate exhibited superior structural performances against static, blast, and impact loads [8–9,16–18]. In this paper, the SCS sandwich plate type of ice-resistant wall was developed for the

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Abbreviations: COV, Coefficient of variation; SCS, Steel–concrete–steel; LVDT, Linear variable displacement transducer; PVA, Polyvinyl alcohol.

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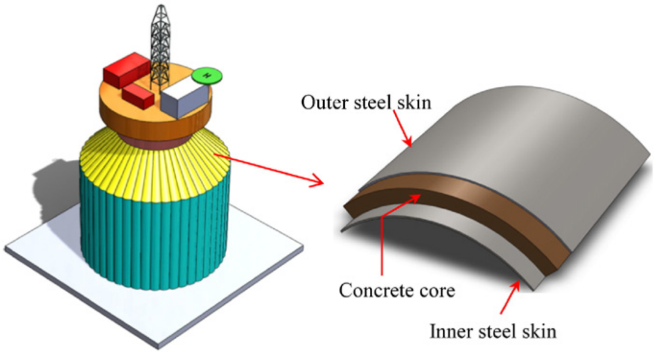
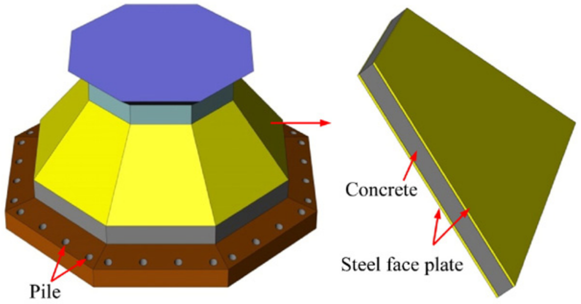
Nomenclature

A_N	The projected area of the cone surface to the plane of the sandwich plate
D	Diameter of the head of the stud connectors
E_{ck}	Initial elastic modulus of concrete
E_s	Elastic modulus of the steel
$K_e = P_e/\delta_e$	Elastic stiffness of SCS sandwich plate
L_a	The perimeter of the square loading area
P_e	Elastic limit resistance of the SCS sandwich plate under service loading state
P_1, P_2	First and second peak resistance of the SCS sandwich plates under patch loads, respectively
$P_{1,A}$, $P_{1,E}$	Predicted first peak resistance of the SCS sandwich plates by Narayanan's model and Eurocode 2
S_a	Spacing of the shear connectors used in the SCS sandwich plate
T	Tensile resistance of the stud connectors used in the SCS sandwich plate
V_c	Punching shear resistance contributed by the concrete core in the SCS sandwich plate
$V_{c,A}$	Predicted punching shear resistance of the concrete core by ACI318-11
$V_{c,E}$	Predicted punching shear resistance of the concrete core by Eurocode 2
V_p	Predicted first peak resistance by the developed analytical model
V_{ps}	Punching shear resistance of the top steel skin
V_s	Punching shear resistance contributed by the stud connectors in the SCS sandwich plate
V_{sk}	Punching shear resistance contributed by the top steel skin
a	width of the square patch loading
b_0	Critical perimeter for the punching cone
d_c	Diameter of the stud connector
f_{ck}	Compressive strength of the ULCC
f_t	Tensile strength of the ULCC
f_y, f_u	Yield and ultimate strength of the steel skin
h_c	Thickness of the concrete core in the SCS sandwich plate
h_e	The depth of the slab, and $h_e = h_c + (t_t + t_c)/2$
h_s	The effective height of the connector
$m = E_s/E_{ck}$	Denotes the modular ratio
u	Average test-to-prediction ratio
t	Thickness of the steel skin plate
t_c, t_t	Thickness of the top and bottom steel skin plate, respectively
v_c	Punching shear stress of concrete
δ_e	Central deflection of the SCS sandwich plate under load P_e
κ	Reduction factor that accounts for the failure of the punching cone and equals 0.5
σ_y, σ_u	Yield and ultimate strength of the stud connectors
ξ_f	The volume fraction of PVA fiber

octagon-shaped gravity based structure. In order to enhance the composite action and increase the load carrying capacity of the structure [5,8], headed studs were used in the SCS sandwich plate. A newly developed ultra-lightweight cement composite, exhibiting excellent strength to weight ratio was adopted as the core material in the development of the SCS sandwich plate.



(a) Conical gravity based SCS sandwich structure



(b) Octagon-shaped gravity based SCS sandwich structure

Fig. 1. Gravity based Arctic offshore structure.

Previous studies mainly focused on SCS sandwich beams [4,8–9,19], columns [20], walls [6–7], and shells [3–4]. However, the structural behaviors of SCS sandwich plates were different from those of beams, walls, and shells. Sohel and Liew [21] reported eight static tests on SCS sandwich plates with double J-hook connectors and low strength lightweight concrete. Shanmugam et al. [22] carried out 12 tests on SCS sandwich slabs with normal weight concrete. These limited tests revealed that the SCS sandwich slabs behaved differently from the reinforced concrete slabs. Previous limited tests were carried out on either the SCS sandwich slabs with a J-hook connector or normal weight concrete. For the developed SCS sandwich plates with a novel ultra-lightweight cement composite, information is still limited and large scale tests on this type of structure are still required to better understand their structural performances. Moreover, the analytical models in the previous reports [21–22] all adopted the yield-line method which assumes the plastic hinge fully developed in the plates that diagonally linked the patch load to the corner of the plate. However, the resistance by the yield-line method is an upper bound that may overestimate the load carrying capacity of the structure since the punching shear failure may occur to the structure. Proper analytical models need to be developed to predict the resistances of the SCS sandwich plate that correspond to different failure modes of the structure. All these will finally contribute to the design of SCS sandwich plates under patch loads that simulate the ice load acting on the Arctic offshore structure.

The present paper investigates the structural behavior of SCS sandwich plates with overlapped headed studs and an ultra-lightweight cement composite core with a density of about 1450 kg/m^3 through large scale tests. A test program consisting of 10 specimens is carried out to evaluate their structural performances under centrally applied localized loading. This experimental program investigates the influences of different geometric and material parameters on the punching shear behavior of the SCS sandwich plates that includes spacing of the connectors in the structure, strength of the ULCC core material, thickness of the steel skin plate, volume fraction of the PVA fiber, and depth of the section. The ultimate resistances, failure modes, load-deflection behaviors, strain development in the steel skin plate, and load-transfer mechanism are obtained and analyzed. Analytical models are also developed to predict the ultimate resistances of the SCS