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Design and behavior of steel–concrete–steel sandwich plates subject to concentrated loads

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ABSTRACT

This paper investigates, experimentally and analytically, the ultimate strength behavior of steel–concrete–steel (SCS) sandwich plates under concentrated loads. The proposed SCS sandwich plate consists of two external steel plates and a sandwiched concrete core. 17 quasi-static were carried out to evaluate their structural performances under concentrated loads. 20 test data in the literature were used to analyze the failure mode and load-transferring mechanisms of the SCS sandwich plate under concentrated loads. The influences of sandwich plates with different plate geometry, diameter of connectors and their spacing, and concrete core strengths were analyzed and discussed. Theoretical models were developed to predict the resistances of the connectors, flexural resistance of the SCS sandwich plate, punching resistances of the concrete core and punching resistance of the top steel plate. Design methods were then developed to predict the maximum resistance of SCS sandwich plate subject to concentrated load based on the minimum the design resistance calculated for each individual components. The accuracy of the design methods were validated against the test results. Finally, the ultimate load resistance of the SCS sandwich plate was compared with the ice-contact pressure in ISO code to check its applicability for use as ice-resisting wall in the arctic region.

1. Introduction

Steel–concrete–steel (SCS) sandwich plate consists of two steel plates connected to a central concrete core by means of mechanical connectors or adhesive materials such as epoxy, etc. SCS sandwich structure exhibits superior structural performance in terms of strength and stiffness as compared to conventional reinforced concrete slab of equivalent thickness. It is also more superior to stiffened steel plate with less steel consumption as it reduces the needs of plate stiffeners and welding. The main advantages of SCS sandwich structure include: (1) the steel plates act as the flexural reinforcement and offer permanent formwork that reduce site labor work and increases construction efficiency, (2) the steel plate can be easily cut to any shape and the connectors can be rapidly installed avoiding the works needed for cutting, bending and tying of the reinforcement bars, and (3) the steel plates are impermeable and act as impact and blast resistant membranes. Previous studies showed that SCS sandwich structures have excellent structural performances in resisting static, impact, and blast loads [1–4]. Potential applications of the SCS sandwich structure include submerged tunnels, building core walls, offshore decks, bridge decks, gravity sea-walls, nuclear containment walls, liquid containment, and protective structures [1–6]. More recently, the SCS sandwich plate structure has been proposed to be used as offshore structural walls to resist contact pressures induced by the continuously movement of the floating ice in the sea as shown in Fig. 1 [7,8].

In the pilot research on SCS sandwich plate structures [9], cohesive materials (e.g., epoxy) were used at the steel-concrete interacting surface to provide the continuous bond. The disadvantage of the cohesive material type of bonding is that its quality is affected by the surface imperfections which may compromise the structural performance of SCS sandwich plate. Mechanical connectors, offering the alternatives to the steel–concrete bond, have been

Abbreviations: COV, coefficient of variation; HSS, headed shear stud connector; LVDT, linear varying displacement transducer; PVA, polyvinyl alcohol; SCS, steel–concrete–steel; SF, steel fiber; ULCC, ultra-lightweight cement composite; YS, yield strain.

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Nomenclature

A_s	cross section area of the shank of the headed stud connector
E_c	elastic modulus of the concrete
E_s	Young's modulus of the steel
P_1, P_2	first and second peak resistance of the SCS sandwich plate under concentrated loads in the $P-\delta$ curves, respectively
$P_{1,test}$, $P_{2,test}$	experimental first and second peak resistance, respectively
$P_{1,a}$, $P_{2,a}$	predicted first and second peak resistance, respectively
$P_{YL,e}, P_{YL}$	elastic and plastic flexural resistance of the SCS sandwich plate, respectively
P_{PS}, P_{PST}	punching shear resistance that correspond to failures of the concrete core and top steel plate, respectively
S	perimeter of the loading area
S_a, S_b	spacing of the connectors in the top and bottom steel plate in SCS sandwich plate, respectively
T	tensile resistance of the connectors
$T_{Br}, T_{pl}, T_{ut}, T_{ps}$	concrete breakout resistance, pullout resistance, ultimate tensile fracture resistance, and punching shear resistance of the steel face plate, respectively
V_c, V_s, V_{sp}	punching shear resistance contributed by the concrete core material, shear connectors, and the steel plate, respectively
V_H	shear resistance of the stud connectors
a	width of the square patch load
b_0	critical perimeter for the punching shear failure of the concrete core
d	diameter of the connectors in SCS sandwich structure
f_{ck}, f_t	compressive and tensile strength of the concrete
f_y, f_u	yield and ultimate strength of the steel plate
h_c	height of the ULCC core
h_e	effective height of the cross section and equals $h_c + t_c + t_t/2$
h_s	height of the connectors used in the SCS sandwich plate
h_t	nominal height of the cross section and equals $h_c + t_c + t_t$
k_t	the composite action ratio of the cross section
n	number of the connectors attached to the steel plate
t_c, t_t	thickness of the top and bottom steel plate in the SCS sandwich plate
u	average test-to-prediction ratio
v_c	punching shear stress of the concrete core
w	unit width of the SCS sandwich plate
x	the position of the neutral axis
δ	deflection of the SCS sandwich plate
σ_c, σ_t	compressive and tensile stress in the steel plate, respectively
σ_y, σ_u	yield and ultimate strength of headed stud connectors
ρ_f	volume fraction of the fibers in the concrete
v	Poisson's ratio of the steel plate

developed and used in SCS sandwich structures [2,10], e.g., headed studs, friction welded connectors in 'Bi-steel structure', angle connectors, J-hook connectors, C-channel connectors, laser welded corrugated strip connectors, bolt connectors, and perfobond connectors as shown in Fig. 2. The mechanical connectors offer localized bonds at discrete points along the member depending on their spac0069ng. The dominant advantage of the mechanical connectors over the cohesive materials is that they can bridge the shear cracks developed in the concrete core and thus provide the transverse shear resistance. Since the experimental studies [7] confirmed the advantages of shear connectors on improving the ultimate load carrying capacities of the SCS sandwich structure, mechanical shear connectors were strongly recommended for the SCS sandwich plate structure. Previous experimental studies [1] on the SCS sandwich beams showed that the shallowly embedded angle connectors could not offer effective steel–concrete bond to resist interfacial shear forces and up-lifting effect compared with J-hook connectors and overlapped headed studs. The experimental studies [1,10] also confirmed that the overlapped headed studs could offer comparable steel–concrete bond with the double J-hook connectors in SCS sandwich structure. In addition, overlapped headed stud connectors show advantages over the double J-hook connectors on easier fabrication and installations. Therefore, in this paper, overlapped headed shear studs were used to develop the SCS sandwich plate structure.

There is a wide range of options to select the core materials for the SCS sandwich plate structure depending on different application purposes. Normal weight concrete (NWC) with a density of about 2500 kg/m^3 and compressive strength from 25 MPa to 60 MPa was used to develop the submerged tunnels, building cores, and bridge deck [6,11–13]. In order to reduce the self-weight of the SCS sandwich structure, lightweight concrete

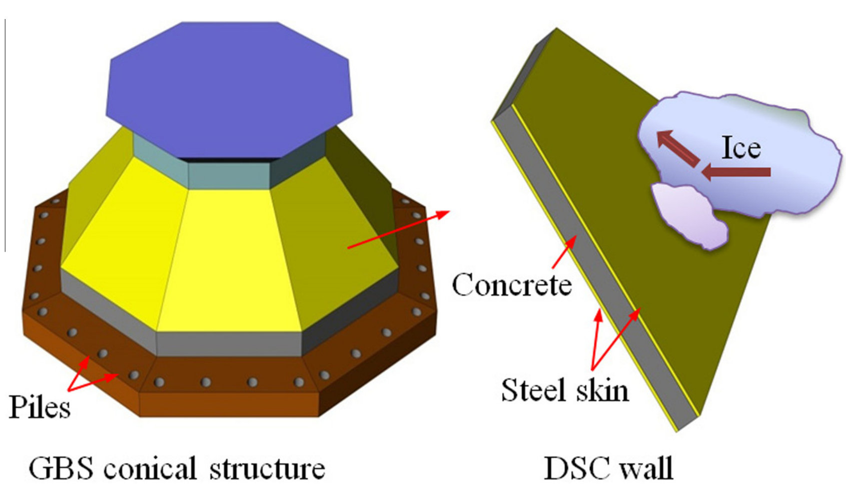

Fig. 1. Application of the SCS sandwich plate in Arctic offshore structure.