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Punching shear resistance of steel–concrete–steel sandwich composite shell structure

Jia-Bao Yan [a,b,*], J.Y. Richard Liew [c], Min-Hong Zhang [c], Zhong-Xian Li [a,b]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] Key Laboratory of Coast Civil Structure Safety of Ministry of Education, Tianjin University, Tianjin 300072, China
[c] Department of Civil and Environmental Engineering, National University of Singapore, E1A-07-03, 1 Engineering Drive 2, Singapore 117576, Singapore

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ABSTRACT

A novel concept of steel–concrete–steel (SCS) sandwich conical structure has been developed for the Arctic offshore platforms. In this structure, punching shear resistance to localized patch loading is the main concern that considers the high pressure zones due to nonuniform distribution of the ice contact pressure. In this paper, quasi-static tests on nine large scale SCS sandwich shell structure were firstly carried out to investigate the ultimate strength behavior of the SCS sandwich shell structure under patch loading. Based on these test results, the influences of different parameters on the ultimate resistance were discussed and analyzed. These studied parameters are composite action, steel shell thickness, spacing of connector, strength of concrete core, and curvature of the sandwich shell. Theoretical models were developed to predict the shear resistance of the SCS sandwich shell structure. The innovations of the developed models include developing formulae to predict the resistances of the connector used in the sandwich shell structure, redefining the critical perimeter to analyze the punching shear resistance of SCS sandwich shell, and modifying the formulae in Eurocode 2 to calculate the punching shear resistance. The accuracy of the developed prediction models were checked and confirmed by nine reported tests and 11 tests in the literature. Finally, design recommendations on the punching shear resistance of the SCS sandwich shell were offered based on the discussions and validations.

1. Introduction

The Arctic continental shelf is believed to be the area with the highest unexplored potential reserves for oil and gas as well as unconventional hydrocarbon resources such as gas hydrates [1]. Though there are huge potential resources of oil and gas, the harsh environment in the Arctic region especially the moving ice sheets challenges the practice of Arctic offshore structures. Generally, ice-resisting wall made of steel or concrete is used around the periphery of the Arctic offshore structures to undertake the ice loads and provide protections to the inside structure and equipment. Steel–concrete–steel (SCS) sandwich composite shell, consisting of two external steel shells with the annulus and sandwiched concrete core, has been proposed as the ice-resistant walls in the Arctic offshore platform that aims to be used in the region with the water depth of 10–100 m [2] (see Fig. 1). This proposed conical SCS sandwich structure with slopes inward 50° to the horizontal waterline lifts up the impacting ice and breaks it in flexural bending rather than crushing that commonly occurred to the vertical ice-resistant walls, which significantly reduced the ice loads [2]. Moreover, the SCS sandwich composite structure permits prefabrication that increases the construction efficiency, shortens construction period, saves formwork and manpower, and provides high resistance to blast and impact loads [3–7]. It is convenient to repair the damaged curved ice-resisting wall after the impact or collisions through cutting the damaged portion, attaching the new plate to the remained portion, and grouting. This developed SCS sandwich shell structure has versatile potential applications as the protective structure to resist the drop weight and collision of the ships, cooling containment in the nuclear power plant, oil container, and submerged tunnels.

The most challenging loads to the Arctic offshore structure may come from the moving ice. For the proposed conical SCS sandwich offshore platform, it will suffer ice-contact pressure during service

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Abbreviations: CM, cement mortar; Cov, coefficient of variation; HPC, high performance concrete; PSC, punching shear failure of concrete; PSS, punching shear failure of steel shell; ULCC, ultra-lightweight cement composite.

[*] Corresponding author at: School of Civil Engineering, Tianjin University, Tianjin 300072, China. Tel.: +86 15222626986; fax: +86 022 27407177.

E-mail address: ceeyanj@163.com (J.-B. Yan).

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Nomenclature

B	width of the curved SCS sandwich shell
L	span of the SCS sandwich shell structure
L_a	length of the punching cone in the arch direction
L_b	length of punching cone in the width direction
P	load applying on the structure
P_1, P_2	first and second peak resistance in the load–deflection curves
P_{rd}	shear resistance of the stud connectors
P_J	shear resistance of the J-hook connectors
R	radius of bottom shell
S	average spacing of the connectors
T	tensile resistance of the shear connectors
U_0	control perimeter for the punching shear resistance of the SCS sandwich shell
V	punching shear resistance of the concrete core
$V_{Rd,c}$	punching shear resistance contributed by the concrete
$V_{Rd,s}$	punching shear resistance contributed by the connector
h_c	thickness of the concrete core in the SCS sandwich shell
h_t	depth of the cross section of the SCS sandwich shell
t	thickness of the steel shell
a	length of the loading plate in arch direction
b	length of the loading plate in width direction of the shell
d	diameter of the connector
f_{ck}	compressive strength of concrete
f_y, f_u	yield and ultimate strength of the steel shell
h_c	height of the concrete core in the SCS sandwich shell
h_{arch}, h_{long}	the height of the control section in arch and longitudinal direction, respectively
t	thickness of the steel shell
δ	deflection of the SCS sandwich shell
u	average ratio
u_A	control perimeter in ACI318
u_E	control perimeter in Eurocode 2
v	average shear stress
v_c	shear strength of concrete
θ_a	angle of the shear failure surface in arch direction
θ_b	angle of the shear failure surface in width direction

in the Arctic region. However, it is recognized that this ice-contact pressure is not uniformly distributed at the ice-structure interacting surface and there are some localized high-pressure zones [8–10]. Including the localized ice pressure, the accidental collision of the ship or drop weight from the above structure also produce localized loading to the structure.

Under the localized patch loading, punching shear resistance becomes the major concern for the design of SCS sandwich composite shell structure. The theoretical and experimental studies on the punching shear resistance of SCS sandwich shells are still limited. Shukry and Goode [11] reported 19 static tests on SCS sandwich shells under point loads to study their punching shear resistances. However, these tested specimens are 1/8 scaled with section of 25 mm in depth that ignored the size effect on the strength of the normal weight concrete. Moreover, these specimens did not take bonding measures at the steel–concrete interface and showed low composite action. Birdy et al. [12] experimentally studied punching shear resistance of slabs and shells that were used for Arctic reinforced concrete platforms. Mclean et al. [13] also reported the tests on punching shear strength of lightweight reinforced concrete slabs and shells. Based on the tests on reinforced concrete shells, Sabnis and Shadid [14] developed empirical formulae to predict the punching shear resistance of the reinforced concrete shells. In these reported tests, the punching shear resistances were the main concern that considers the localized ice-contact pressure. However, these reported tests [12–14] were carried out for the reinforced concrete shells rather than SCS sandwich shell structures, and the developed formulae are empirical and validations are still needed to check their applicability to the SCS sandwich shell structure. Nevertheless, there are limited design guidelines that can be followed to predict the punching shear resistance of the SCS sandwich shell structures. Most of the design codes, e.g., Eurocode 4 [15] and ACI 318 [16], are mainly developed for reinforced concrete slabs based on reinforced concrete slab tests.

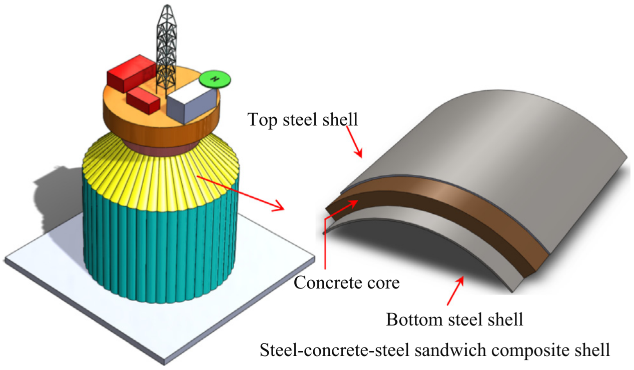

Fig. 1. Conical Arctic offshore platform.

In this study nine large scale SCS sandwich composite shells were firstly tested to investigate their structural behaviors under patch loading. The investigated parameters that influence the punching shear resistance of the SCS sandwich shells are composite action of the shell, steel content of the shell section (i.e., thickness of steel shell), strength of concrete core, spacing of the connectors, and curvature of the shell. New analytical models on estimating the punching shear resistance of SCS sandwich composite shell were developed by modifying the Eurocode 2 provision [17]. These modifications include rebuilding the calculation approach on the resistances of the connectors, redefining the critical perimeter for the SCS sandwich shell, and modifying the effective thickness of the shell structure. Accuracy of the developed theoretical models was checked through validations against the nine tests reported in this study and eleven tests by Shukry and Goode [11]. Moreover, the predictions by the developed theoretical models were also compared with predictions by ACI 318 [16], Eurocode 2 [17], and the model developed by Sabnis and Shadid [14]. Through the validations and comparisons, the accuracy of these models were compared and discussed. Finally, the design recommendations were given based on these validations and discussions.

2. Experimental program

This was a two-stage experimental program. Firstly, two SCS sandwich composite shells were prepared to study the influence of composite action on the punching shear resistance of the structure. The second stage experimental program investigated the influences of different parameters on the punching shear resistance of SCS sandwich shell.