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Damage plasticity based numerical analysis on steel–concrete–steel sandwich shells used in the Arctic offshore structure

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ABSTRACT

This paper develops a three-dimensional damage plasticity based finite element model (FEM) to study the ultimate strength of the steel–concrete–steel (SCS) sandwich shell structure under patch loading. The FEM considers complex geometric nonlinearities of hundreds of stud connectors in the structure, complex interaction between the connectors and concrete, and material nonlinearities of steel and concrete used in the structure. In the developed FEM, the concrete core material adopts the concrete damage plasticity model to predict the post-peak softening and residual strength; the stud connectors and steel shells adopt a continuum damage model to phenomenologically describe the damage evolution in the steel material. The reasonable agreement between FE analysis and the quasi-static tests on the SCS sandwich shell structure confirms the accuracy of the FEM in predicting the ultimate shear resistance, load–deflection relationship, cracks in the concrete core, and punching shear failure of the top steel shell. A subsequence parametric study based on the validated FEM investigates the influence of the curvature on the first peak resistance of the SCS sandwich structure. Finally, the paper validates accuracy of an analytical model on the punching shear resistance of the concrete core of the SCS sandwich shell.

1. Introduction

The expanding demand for oil and gas drives the petroleum explorations in the Arctic region where about 13% of the world's undiscovered oil and 30% of the world's undiscovered gas are stored [1,2]. According to the United States Geological Survey (USGS), most of these potential reserves locate in the continental shelves with water depth less than 500 m [1,2]. With these rich potential resources, the Arctic will provide an indispensable resource for oil and gas in the future. However, the harsh environment in the Arctic, especially the moving ice sheets driven by the wind and current, poses critical threats to the oil and gas facilities in this region. Many concepts of offshore structures have recently emerged for the oil and gas explorations in the Arctic [3], e.g., the artificial island, the caisson-retained island, jacket structures, and gravity based conical structures. In these concepts, ice-contact pressure remains the main concern to maintain the integrity of the structure and to protect the drilling and service equipment. Marshall et al. [4,5] proposed a type of gravity-based conical structure with external flower-shape-ice-resistant wall (see Fig. 1). This gravity-based structure, for the water depth of 10–100 m, comprises a cylindrical steel–concrete–steel (SCS) sandwich composite body that extends vertically from the base of the seabed to a narrow conical slope at the sea level. The conical shape SCS sandwich shell system at the sea level would raise the incoming ice sheets along the slope and break them in flexural bending, which will alleviate the ice-contact pressure on the structure. Previous studies [3,6–8] have revealed that the ice-contact pressure does not follow a uniform distribution over the interacting surfaces, and shows some localized high pressure zones (HPZ). The ice-contact pressure at these local HPZs could reach about 35 MPa [3], and lead to local punching shear failure in the ice-resistant walls. Therefore, punching shear resistance of these reinforced concrete or steel–concrete–steel (SCS) sandwich structure has become a primary concern in many previous studies [9–14].

Abbreviations: CDM, continuum damage model; CDPM, concrete damage plasticity model; DPM, damage plasticity model; FE, finite element; FEA, finite element analysis; FEM, finite element model; HSS, headed shear stud connector; ULCC, ultra-lightweight cement composite.

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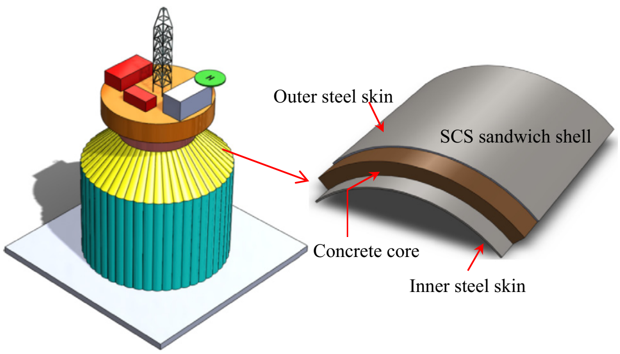
Nomenclature

B	width of the curved SCS sandwich shell
$C_R = L/R$	curvature ratio
D_i	the calculated damage ratio at the ith step of the steel in stress–strain curve
D_c	compressive damage ratio of concrete
D_R	damage ratio of steel
D_t	tensile damage ratio of concrete
E_0	initial elastic modulus of concrete
E_s	elastic modulus of the steel
$K_e = P_e/\delta_e$	elastic stiffness of sandwich shell at working state
L	clear span of the SCS sandwich shell
P_e	load carrying capacity of the curved SCS sandwich structure under service loading state
P_u	shear resistance of SCS sandwich shell
P_1, P_2	first and second peak resistance in the load–deflection curves of the SCS sandwich shell, and they correspond to punching shear failure of the concrete core and steel shell, respectively.
R	radius of the curved steel face plate
V	shear resistance of the SCS sandwich shell
S_b	spacing of the connectors along the arch direction in the inner shell
S_t	spacing of the connectors along the arch direction in the outer shell
SW	self-weight of the SCS sandwich shell specimen
W	width of the SCS sandwich specimen
$V_{Rd,c}$	shear resistance of the concrete core
$V_{Rd,s}$	shear resistance by the overlapped headed shear studs
V_{sf}	shear resistance contributed by the steel face plate
f_c	compressive stress at the softening region in the stress–strain curve
f_y, f_u	yield and ultimate strength of the steel shell, respectively
h_c	thickness of the core material in SCS sandwich shell
h_t	depth of the composite section in SCS sandwich shell
r_i, r_o	high rise of the inner and outer shell as shown in Fig. 4
t_c, t_t	thickness of the compressive or tensile steel face plate
$\bar{u}_i^p$	the total equivalent plastic displacement at the ith step
$\bar{u}_F^p$	the total equivalent plastic displacement at fracture
δ_f	central deflection of the shell
ε_F^{pl}	uniaxial plastic strain at fracture
ε_R^{pl}	uniaxial plastic strain at the onset of fracture
$\bar{\varepsilon}_F^{pl}$	equivalent plastic strain at fracture
ε_d^p	uniaxial plastic strain at onset of necking of the steel coupons in stress–strain curves
ε_i	the calculated elastic strain at the ith step
ε_i^{pl}	the calculated uniaxial plastic strain at the ith step
ε_t^{el}, ε_c^{el}	true elastic tensile or compressive strain of the concrete
ε_{0t}^{el}, ε_{0c}^{el}	elastic tensile or compressive strain of the concrete
ε_t^{ln}, ε_c^{ln}	inelastic tensile or compressive strain of the concrete
ε_t^{pl}, ε_c^{pl}	true tensile or compressive plastic strain of the concrete
θ	stress triaxiality
σ_t, σ_c	uniaxial tensile or compressive stress of concrete
σ_{cu}	uniaxial ultimate compressive stress of concrete
σ_{t0}	uniaxial ultimate tensile stress of concrete
δ_f	uniaxial ultimate tensile stress of concrete
υ	Poisson's ratio

Yan et al. [15] have reported seven tests on the punching shear resistance of the SCS sandwich shell structure which covers only limited geometric variations. The punching shear resistance of the SCS sandwich composite shell structure requires further understanding supported by a comprehensive parametric investigation.

In SCS sandwich structures, shear connectors lead to enhanced composite action, provide transverse shear resistance, and prevent local buckling of the steel face plates [16–20]. Previous researchers have developed different shear connectors to enhance the composite action in the steel–concrete composite structures, e.g., headed shear studs, angles, C-Channel, and double J-hook connectors [16–18]. The mechanical shear connectors, i.e., headed shear studs and J-hook connectors, have helped to improve the bond between the steel and concrete surfaces and to increase the punching shear resistance in the SCS sandwich shell structures [15,21]. The shear connectors proved to be efficient on improving the punching shear resistance of the SCS sandwich shell structure [21]. However, the presence of such connectors introduces highly complex mechanical interactions among different materials and creates significant challenges for a detailed finite element analysis on these structures, especially in predicting the sequential failure mechanisms in different materials.



SCS sandwich shell structure in Arctic offshore structures

Fig. 1. Applications of the SCS sandwich shell structure.

The finite element analysis provides a convenient tool to simulate the push-out tests on the headed shear stud connectors and investigate their ultimate shear resistances used in the steel–concrete composite structure [22–27]. These FE models often include a very detailed 3-D finite element mesh for each headed stud used in the structure. However, the exponentially escalating computational cost frequently limits the number of headed studs to be fewer than six in a single analysis. To overcome the high computational cost, Foundoukos and Chapman [28] have implemented a simplified 2-D FE model for the 'Bi-steel' type of SCS sandwich composite beam structure [28]. However, this 2-D FE model has limitations in describing the 3-D structural behavior of the connectors in the structure. Yan et al. [29] have replaced the local 3-D mesh for the shear connectors by the nonlinear spring element which reduces significantly the computational demand. However, this model relies heavily on the experimentally calibrated spring properties and neglects the interaction between the connectors and their adjacent concrete material. Shanmugam et al. [30] developed the FE model using the anisotropic material to simulate the concrete core with embedded shear stud connectors. This FE model captures the phenomenological global structural behavior of the SCS sandwich plate structure, and does not simulate the physical