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Numerical analysis on steel-concrete-steel sandwich plates by damage plasticity model: From materials to structures

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HIGHLIGHTS

- Develop numerical model for steel-concrete-steel sandwich plate.
- Introduce damage plasticity model (DPM) for steel and concrete.
- Report tests on steel-concrete-steel sandwich plates.
- Validate numerical model with DPM from material to structural level.
- Recommend numerical analysis procedure with DPM from material to structure.

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ABSTRACT

Steel-concrete-steel (SCS) sandwich type of ice-resistant wall has been developed for arctic offshore structures. This paper develops a three-dimensional damage plasticity based finite element model (FEM) to simulate the ultimate strength behaviour of SCS sandwich structure under concentrated loads. The FEM offered detailed simulations on the complex geometry of hundreds of studs, complex interactions of these connectors with the concrete, and mechanical nonlinearities of the steel and concrete materials. Concrete damage plasticity model was used to simulate the post-peak softening of concrete, and continuum damage model (CDM) was developed to phenomenologically simulate the damage evolution in the steel materials. The key parameters in the CDM were calibrated by the uniaxial tensile tests on the steel coupons. The accuracy of the FE simulation was checked by nine full scale tests. The validations proved that the developed FEM simulate well the ultimate strength behaviours of the SCS sandwich plates under concentrated loads in terms of load-deflection curves, ultimate resistances, and failure modes in the steel plates, studs and concrete core. Through the FE simulations, the failure modes corresponding to different peak resistances were analysed and recognized. Finally, the FE simulation procedures on SCS sandwich plate with CDM and CDPM were recommended.

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1. Introduction

Steel-concrete-steel (SCS) sandwich plate, consisting of two external steel face plates and a sandwiched concrete core using the cohesive material or mechanical shear connectors to bond as an integrity, provided superior ductility over reinforced concrete structure and exhibited higher buckling resistance compared with the stiffened steel plate. This type of structure exhibited versatile advantages over conventional reinforced concrete structures that included saving formwork and site labour force, avoiding the detailing and bending of the reinforcements as occurred in reinforced concrete structure, providing impermeable steel skin plates, and offering impact and blast resistant membranes of the external steel skin. The versatile applications of the SCS sandwich plate include shield tunnel, submerged tunnel, shear walls in building core, bridge and offshore deck, nuclear walls, liquid containment, oil storage, and anti-blast or impact protective structure. More recently, due to the oil and gas explorations in the Arctic region,

Abbreviations: CDM, continuum damage model; CDPM, concrete damage plasticity model; COV, coefficient of variation; FE, finite element; FEA, finite element analysis; FEM, finite element model; HSS, headed shear stud connector.

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Nomenclature

D_c,D_t	compressive and tensile damage ratios of concrete, respectively
D_i	damage ratio of steel at load step i
D_R	damage ratio of steel
E_0	initial elastic modulus of concrete
E_s	elastic modulus of the steel
E_{sh}	elastic modulus of the headed stud
P_1, P_2	first and second peak resistance in the load-deflection curves of the SCS sandwich plate
S_a	spacing of the connectors in the SCS sandwich plate
f_c	compressive stress at the softening region in the stress-strain curve
h_c	thickness of the core material in SCS sandwich plate
h_t	depth of the composite section in SCS sandwich plate
t_c, t_t	thickness of the compressive or tensile steel face plate
$\bar{u}_i^p$	the total equivalent plastic displacement at the i^{th} 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_n^p	uniaxial plastic strain at onset of necking of the steel coupons in stress-strain curves
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^{In},ε_c^{In}	inelastic tensile or compressive strain of the concrete
ε_t^{pl},ε_c^{pl}	true tensile or compressive plastic strain of the concrete
$\bar{\varepsilon}_0^{pl}$,ε_0^{pl}	tri-axial and uniaxial equivalent plastic strain at the onset of damage, respectively
ε_i^{nom}	the nominal strain obtained from the tensile tests at the loading step i
θ	stress triaxiality
σ_i^{nom}	the nominal stress obtained from the tensile tests at the loading step i
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

SCS sandwich plate has been used as the ice-resistant walls in the Arctic offshore structures as shown in Fig. 1 [1–3].

The inclined SCS sandwich plate type of ice-resistant wall would raise the impacting ice sheets and fail them in flexural bending that significantly alleviate the ice-contact pressure on the structure. The ice-contact pressure acting on the ice-resistant wall was observed unevenly distributed, and there were some high pressure zones (HPZs) at the ice-structure interacting surface that can be extremely higher than 15 MPa [4,5]. Under these concentrated loads of HPZs, punching shear failure tends to occur to the SCS sandwich plate. Experimental studies on the SCS sandwich plate have been reported by Shanmugam et al. [6], and Sohel and Liew [7]. However, these experimental studies only provide limited information on the SCS sandwich plate, and these tests proved to be costing and time consuming. Finite element (FE) technique becomes increasingly popular and offers alternative approach to analyse the structural behaviour of the SCS sandwich plate. The FE model provided useful method to simulate different components in SCS sandwich plate, the interactions among the steel face plates, concrete core, and connectors, different loading scenarios and boundary conditions, and different materials. Previous FE simulations focused on the push-out tests that were used to obtain the shear strength behaviour of the headed stud connectors [8–11]. However, these developed FE models only consists of several stud

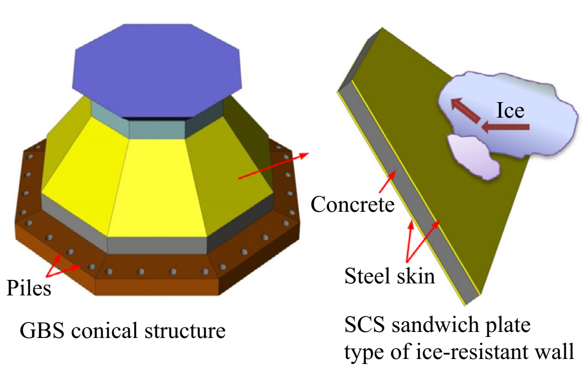

Fig. 1. SCS sandwich plate type of ice-resistant wall in Arctic offshore structure [1].

connectors (usually less than six). FE models for SCS sandwich beams with J-hook connectors or overlapped headed studs have been developed to investigate their ultimate strength behaviour [12,13]. In these developed FE models, the complex geometry of a pair of interlocked J-hook connectors or overlapped headed shear studs were simplified by two cylindrical studs linked by three-dimensional (3D) nonlinear spring elements. Although this simplification significantly increases the computing efficiency, it could not fully simulate the shear-tension interaction strength of the studs that finally results in inaccurate estimations on the ultimate resistance of the structure. In addition, this FE model also could not simulate the punching shear failure of the steel skin that has been observed in the quasi-static tests on SCS sandwich plate [1]. Sohel et al. [14] also applied the same FE model [12,13] to analyse the structural behaviour of SCS sandwich plate subjected to impact force. However, the same limitations existed on simulating the shear-tension interaction of the connectors. Shanmugam et al. [6] developed a simplified FE model for SCS sandwich plate by using the anisotropic materials to simulate the concrete core with inside headed stud connectors. Nonlinear spring elements were used at the steel-concrete interface to simulate the interfacial shear-slip behaviour of the connectors. However, this model also considered the shear resistance and tensile resistance independently, and ignored the shear-tension interaction strength of the connectors in the SCS sandwich structure. Moreover, this developed FE model could not simulate the punching shear failure of the steel materials. All these compromised the accuracy of the FE simulation.

Novel ultra-lightweight cement composite (ULCC) and headed shear studs have been used in the developed SCS sandwich plate structure to increase the specific strength and composite action of the structure [1–3]. This new material and hundreds of the headed studs bring the challenges on the FE modelling of the SCS sandwich plate and complex the interactions between the connectors and concrete core. Moreover, the damage of the connectors and punching shear failure of the top steel skin need to be properly simulated that proved to be essentially related to the ultimate resistances of the SCS sandwich structure [1].

This paper aims to develop a FE model to simulate the ultimate strength behaviour of the SCS sandwich plates with ULCC and headed stud connectors. In this model, hundreds of headed studs

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