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Nonlinear finite element modelling and parametric study of curved steel–concrete–steel double skin composite panels infilled with ultra-lightweight cement composite

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HIGHLIGHTS

- We develop an efficient FE model to investigate the behaviour of composite panel.
- We propose a simplified connector element for shear stud embedded in concrete.
- Flexural failure, shear failure and three-hinge beam mechanism are investigated.
- Good agreement is achieved between the test and FE results.

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ABSTRACT

Curved steel–concrete–steel (SCS) double skin composite structure with shear connectors has been developed and exhibits versatile potential applications in building and offshore constructions. A novel ultra-lightweight cement composite is used as core material and headed shear studs are welded on steel face plate to achieve the composite action. This paper demonstrates a comprehensive 3D nonlinear finite element (FE) analysis of curved double skin composite panels infilled with ultra-lightweight cement composite (ULCC) under patch load. Nonlinear FE analyses are performed using ABAQUS to study the load deflection behaviour up to the maximum load resistance. A constitutive model for ultra-lightweight cement composite is generated from standard test data and assigned to the concrete materials. A simplified connector element incorporated tension–elongation behaviour is proposed for the shear studs in the curved double skin composite panels. The accuracy of the FE model is validated using experimental results from the literature in terms of load displacement curves, failure modes and maximum load resistance. An extensive parametric study is carried out to identify the effect of the rise-to-span ratio, span-to-thickness ratio, concrete compressive strength and steel yield strength and loading type on the ultimate resistance.

1. Introduction

A fixed offshore platform located in the Arctic region has to be designed to resist the forces imposed by moving ice floating in the sea [1]. The ice will sometimes be broken and sometimes continuous, and may include pressure ridges of 30 m or thicker. The forces imposed by the floating ice on the platform can be as high as 100 MN or more, and are usually greater than those generated by waves in open water. The determination of "correct" design forces induced by ice is a subject of intense controversy, and is outside the scope of this paper, for example ISO19906 [2] and discussions by Løset et al. [3], Palmer and Croasdale [4]. Such extremely harsh environment in Arctic region requires structures with high resistance and high ductility which could operate for year-round.

Steel–concrete–steel (SCS) double skin composite panels are structural elements that comprise two external steel plates infilled with a concrete core. The composite action between the steel plates and concrete core is achieved by using mechanical connectors or adhesive materials [5–7]. The shear connectors resist the longitudinal slip and prevent tensile separation between the steel plate and concrete core through mechanical interaction. The SCS double skin structure provides superior structural performance in terms of resistance against impact, blast and projectile penetration [6,8–10]. The external steel plates serve as a permanent formwork during concreting, promoting construction efficiency, which could

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Nomenclature

d	stud diameter	r	rise of the curved SCS double skin beam
d_c, d_t	compression and tension damage parameters	s	shear stud spacing
$D_{c,norm}$, $D_{t,norm}$	normalised compressive damage variable (d_c); normalised tensile damage variable (d_t)	t_s	thickness of steel plate
E_c, E_s	Young's modulus of concrete and steel, respectively	κ	viscosity parameter
f_{ck}	compressive strength of concrete cylinder	ν	Poisson's ratio
f_y	yield strength of steel	ε_s, ε_c	tensile strain of steel plate; compressive strain of concrete
f_u	ultimate strength of steel	$\tilde{\varepsilon}^{in}_{c,norm}$	normalised compressive inelastic strain
h_c	thickness of concrete core	ε_{cu}, ε_{cm}	ultimate strain corresponding to the ultimate stress and maximum compressive strain, respectively
h_s	height of shear stud	$w_{t,norm}$, w_u	normalised cracking displacement; maximum cracking displacement
k_s	shear stiffness	δ	mid-span displacement
L	clear span of curved SCS double skin beam		
P_{max}	maximum load		
p	maximum contact pressure		

reduce the site handling cost comparing to conventional reinforced concrete construction. The waterproof feature inherently provided by external steel plates reduces surface area that needs expensive corrosive protection and makes it easy for inspection and maintenance. As a result, with a lightweight core, the SCS double skin composite system is suitable for offshore applications, including submerged tunnels, gravity seawalls, deck structures and nuclear power station walls that require resistance against extreme loads [9–11].

Past research on flat SCS double skin composite structures have paved a better understanding of structural behaviour of concrete filled double skin structures. In recent years, SCS double skin composite beams or slabs have demonstrated advanced behaviours under both static and dynamic external loadings [12–15]. However, a comprehensive review of the published literature reveals that the majority of the research work has been experimentally based and focused on verifying the effectiveness of the theoretical investigations. Although physical testing provides valuable information on the overall performance of SCS double skin composite beams and slabs and the local behaviour of constituent materials, high costs associated with the fabrication of large-scale specimens often limits the evaluation of the parameters that affect the structural behaviour of the SCS double skin composite beams and slabs.

The numerical analysis using finite element method (FEM) is becoming increasingly popular and efficient which can provide a cost-effective tool for carrying out numerical studies on steel–concrete composite structures [16–18]. The FEM allows the direct modelling of wide range of factors, such as material models, boundary conditions, local and global imperfections and various combinations of geometric and loading conditions. The nonlinear behaviour of steel, concrete and reinforced bar or shear connectors can be taken into consideration by incorporating appropriate constitutive laws and iterative procedures [19–22]. FEM can reproduce a thorough structural response under different load scenarios such as displacement, stress, strain and concrete crack development history, etc. Output are available on each node and element of the FE model. It is useful for providing an in-depth understanding of the structural behaviour of the steel–concrete composite structures. Nonetheless, only a very limited amount of research is available on the numerical modelling of such SCS double skin structures using the FE method [16,22]. The available predictions showed that they were still in poor agreement with test results. The lack of in-depth FE studies may be partially due to the challenging nature of modelling the interface between different constituent materials including concrete, steel plate and shear studs and their interactions. Ultra lightweight cement composite used in this paper is a new material, whether the material laws for normal concrete is applicable for it is still in question. Especially, the damage mode between them are different.

This paper presents a three-dimensional nonlinear FE model for curved SCS double skin composite beams using the explicit code in ABAQUS [23]. This model takes into appropriated account of the material nonlinearity, interaction between concrete and steel and shear connectors. Several numerical examples are presented which show that the FE model is capable of accurate modelling of the curved SCS double skin composite panel infilled with ULCC in terms of the overall load–deflection response, failure modes and damage degrees. The validated FE model is then adopted to perform the parametric studies to investigate the effect of the rise-to-span ratio, span-to-thickness ratio, plate thickness, stud spacing and loading type on the predicted shear resistance of curved SCS double skin panel filled ultra-lightweight cement composite.

2. Summary of the experimental work

The FE model reported in this paper is validated using the experimental work carried out by Shukry and Goode [24], Marshall et al. [11] and Yan [25]. They carried out the punching tests on circular composite shells with and without shear connectors. Table 1 lists the geometric and material properties for concrete, steel and shear studs used for composite shell specimens. Three loading conditions are considered which are: concentrated spherical indentor loading (A1–A3), concentrated square area loading (B5–B6 and SB4) and eccentric square area loading (SB4). The double skin shells are filled with fine aggregate concrete as core material. The shells are fixed on two rigid stiffeners and tested until failure, as shown in Fig. 1(a) and (b). The failure modes and load–deflection curves are obtained from the tests.

Latest research development was based on the tests of curved SCS double skin beams subject to patch loads by Huang et al. [26]. Totally ten SCS double skin beams were tested: one flat and nine curved SCS double skin beam filled with ultra-lightweight cement composite. Headed shear studs were welded at inner steel face plates to improve the composite action between steel and concrete. The beams were 1250 mm long and 300 mm wide with fixed-end boundary conditions. Each beam was loaded laterally by the 1000 kN actuator in displacement controlled mode. The test parameters for beam specimens were the rise-to-span ratio (r/L), steel contribution ratio (A_sf_y/A_cf_c), connector spacing (s), and concrete core thickness (h_c). The cross-section details of the specimens can be found in Table 2. Fig. 2 depicts the details of tested curved SCS double skin beams.

3. Finite element model

In order to properly simulate the structural behaviour of curved SCS double skin structures, a three-dimensional FE model incorporating nonlinear behaviour of material was developed. The constitutive models and element types were carefully selected to model the experimental behaviour of the tested beams. The following