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Experimental and analytical studies of curved steel–concrete–steel sandwich panels under patch loads

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The paper proposes a novel curved steel–concrete–steel (SCS) sandwich panel for Arctic offshore platform to resist the ice loads due to ice floes in Arctic region. The SCS sandwich panel consists of two curved steel plates infilled with a type of novel ultra-lightweight cement composite (ULCC) with a compressive strength of 60 MPa and a density less than 1400 kg/m^3. Headed shear studs working in pairs with overlapped lengths are used to achieve composite action between the core material and steel face plates. This paper investigates the performance of curved SCS sandwich composite panel experimentally and analytically. Ten quasi-static tests on the curved sandwich composite panels subjected to patch loads are carried out to explore their failure modes, ultimate strength and load–defection behaviour. The main failure modes of the tests are identified as flexural failure, diagonal concrete strut crushing and shear tension failure. Based on the failure mechanism, a unified deep beam model is constructed to estimate the shear resistance of flat and curved SCS sandwich panels by considering equilibrium status, material yielding criteria and boundary conditions. The validations show that the modified model can provide close and conservative estimations on shear resistance for SCS sandwich composite panel.

1. Introduction

Steel–concrete–steel (SCS) sandwich composite structures are structural elements composed of two external steel plates and connected to a concrete core. The workability and performance of SCS sandwich structures depends greatly on steel–concrete interfacial behaviour which concerns most researchers. The common measures to achieve the composite action between steel and concrete are to weld shear connectors using mechanical interlocking effect or to glue two contact areas using cohesive materials [1–3]. The SCS sandwich composite exhibits significant structural and economic advantages over the conventional reinforced concrete (RC) structures in terms of higher flexural stiffness and higher energy absorption capacity to withstand extreme environmental and accidental loads. The external steel plates may serve as a permanent formwork during concreting, promoting construction efficiency and reducing the site handling costs and time. 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, its high structural performance enables its potential application to extend nuclear installations [4], ice-resisting wall for Arctic offshore [5], ship hulls, tunnels, military shelters [6] and shear wall in buildings. The offshore structures installed in the Arctic region face the risk of mechanical damage caused by the movement of ice floes or ice bergs. Using conventional RC structure for offshore construction results in transport difficulties due to its weight and also leads to large amounts of congested reinforcement subjected to high magnitude ice load in Arctic region [7]. Corrosion of reinforcement caused by seepage of sea water is another dominating factor as it weakens durability of concrete and results in high maintenance costs. Therefore, SCS sandwich composite structures infilled with high performance grout have recently emerged as popular solution to enhance the structural performance against extreme loadings [8].

For decades, extensive researchers explored the structural behaviour of sandwich structures. Static and impact performance of SCS sandwich beams and panels were evaluated experimentally, numerically and theoretically [1–3,6,9–16]. Solomon et al. [9] appraised the SCS sandwich structure as a potential structural form to reduce self-weight of roadway slab on composite bridge. Robert et al. [1] and Xie et al. [2,11] presented an experimental investigation on static behaviour of Bi-steel sandwich beams where some effective resistance prediction models were proposed. Four primary failure modes were observed which were plate yielding, bar shear, bar tension and concrete shear. The study of failure modes was valuable to enhance the understanding of the static performance of SCS sandwich structure. Despite exhibiting high resistance behaviour and fast-construction efficiency, the Bi-steel structure is limited within a range of 200–700 mm thick with plate thicknesses range from 5 mm to 20 mm due to the limitations of the welding machine. Thus the Bi-Steel panel cannot be applied for very slim deck with thickness less than 200 mm. In recent lightweight applications, more alternative

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Nomenclature

a_s	depth of concrete strut
A_c	cross-sectional area of concrete core
A_s	cross-sectional area of steel face plate
A_{se}	cross-sectional area of shear connector
A_v	punching area of steel face plate
d	diameter of shear connector
E_s	modulus of elasticity of structural steel
E_c	modulus of elasticity of concrete
f_{ce}	effective strength of concrete strut
f_y	yield strength of steel
f_u	tensile strength of steel
f_{ut}	tensile strength of shear stud
f_{ck}	cylinder compressive strength of concrete
f_{st}	splitting tensile strength of concrete
h_c	thickness of concrete core
M_{pl}	plastic bending moment resistance
N_t	minimum tensile force of top steel plate
N_c	minimum compressive force of top steel plate
P_{test}	applied test load
P_{stu}	shear resistance of shear connector within a SCS sandwich structure
R	internal radius of the arch
s	connector spacing
t_s	thickness of steel face plate
W	width of sandwich wall section
V_C	shear resistance contribution by concrete in RC beam
V_s	shear resistance contribution by shear studs in RC beam
φ	inclined angle between CDC and horizontal axis
V_{C_1}	force components of top concrete (vertical)
C_1	force components of top concrete (horizontal)
V_{s_2}	shear force of bottom plate
C_2	force components of diagonal compression (horizontal)
V_{C_2}	force components diagonal compression (vertical)
β	central angle corresponding to the inflection point and loading point
β_s	a factor to account for the effect of cracking and confining reinforcement on the effective compressive strength of the concrete in a strut
e_h	distance from the inner shaft of a stud (bolt) to the outer tip of the stud (bolt)
ρ_w	density of ULCC
λ	shear span ratio
T_1, T_2	tensile force in bottom plate
μ_{sc}	friction coefficient between steel and concrete
n_p, n_{cp}'	number of shear connectors
$X_{s,i}, X_{s,i+1}$	a distance from the ith shear connector to the loading point
α_i, α_{i+1}	angle between the ith stud axis and vertical axis
V_{R_1}, V_{R_2}	shear resistance of free body part I and part II
ν_c, ν_s	Poisson's ratio of concrete and structural steel
P_s, $P_{s,i}$, $P_{s,i+1}$	tensile resistance of shear connector within an SCS sandwich structure
h_s	height of shear stud
L	clear span of curved SCS sandwich beam
$L_{\lim}$	limit yielding length of bottom steel plate
r	rise of curved SCS sandwich beam

sandwich constructions have been proposed such as adhesively bonded steel corrugated core sandwich [17,18], laser-welded trapezoidal corrugated-core sandwich panels [19] and corrugated sandwich coupons system manufactured using glass (both long fibre and woven fabric) and carbon (woven fabric) fibres [20,21]. The use of these sandwich structures, on the basis of preliminary information obtained from the experimental tests, can lead to a weight reduction of the ship structures, providing an adequate structural strength under operating conditions. However, they may not be applicable for Arctic platform constructions which have to withstand the forces imposed by moving ice in Arctic. The ice will sometimes be broken and sometimes continuous, and may include pressure ridges 30 m or more thick. The forces imposed by that ice will be large, 100 MN or more, and can be greater than those generated by waves on platforms in open water [8].

Latest research development was based on the tests of nine curved SCS sandwich panels subjected to local ice load [5]. It is found that ACI 318 [22] under-predicts the punching shear resistance while Eurocode 2 [23] over-predicts the resistance of curved SCS sandwich panels subjected to punching shear. A modified model is thus proposed to predict the shear resistance. However, the model is regressed based on the limited test data, so it needs to be verified. Huang et al. [24] recently applied the ULCC to develop an SCS sandwich shell and wall for the structures requiring protection against larger impact and blast loads. Leng et al. [25] recently investigated the failure mechanism and shear resistance of flat SCS sandwich deep beams. On the basis of observed shear failure mode and test results, an analytical method is proposed to predict the shear resistance of SCS deep beams. This lower bound approach offers close predictions for shear resistance of SCS deep beams. The theory considers the equilibrium and boundary condition of each element and do not have limitations on the type of mechanical connectors.

Based on the above-mentioned research, most of the past works are limited to flat SCS sandwich composite beams and slabs with simply supported boundary conditions. Research work done on fixed-end supported curved SCS sandwich panels infilled with ultra-lightweight cement composite material subjected to patch load are rather limited [5, 26]. The failure mode of curved SCS sandwich structure could be shear failure of concrete core, flexural failure or punching shear which is quite different from that of flat ones. The force transfer mechanism and load–deflection behaviour could be affected by the arch action effect. As shear becomes rather critical in thick SCS sandwich members used in offshore structures, it is important to examine the force transfer mechanism of curved SCS sandwich members. This is helpful to enhance the understanding of the development of ultimate strength of sandwich structure as well as provide valuable information for practical design.

This paper aims to examine the shear behaviour of curved SCS sandwich panel infilled with ULCC. Quasi-static tests on one flat and nine curved sandwich panels subjected to patch load are carried out. Based on a combined experimental and analytical investigation, this paper proposes a unified deep beam model based on Leng's model [25,26] to estimate the shear resistance of curved SCS sandwich panels. The analytical results are validated against the measured test results so that the theoretical model can be used to evaluate the performance of curved sandwich panels subjected to shear failure.

2. Experimental programme

2.1. Specimen preparation

The experimental programme includes one flat and nine curved SCS sandwich panel, with a clear span $L = 1250$ mm and a width $W = 300$ mm but with different span-to-thickness ratio (L/h_c), steel contribution ratio ($A_s f_y / A_c f_c$), rise-to-span ratio and plate slenderness ratio (s/t_s) as listed in Table 1. Fig. 1 illustrates the fabrication procedure of curved sandwich panels. It can be fabricated from segments formed from a flat plate by inextensional bending. Shear connectors are welded to each flat plate after roll forming but before it is assembled to make a panel, which facilitates the use of automatic welding. Next, the space between the two steel face plates is filled with ultra-lightweight cement composite grout. Panel assembly was finished in workshop conditions.