Ocean Engineering 118 (2016) 41–57

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Ultimate strength behaviour of steel–concrete–steel sandwich plate under concentrated loads

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ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form
6 February 2016
Accepted 28 March 2016
Available online 7 April 2016

Keywords:
Steel–concrete–steel structure
Sandwich plate structure
Punching shear resistance
Cement composite
Arctic offshore structure
Shear connector
Steel–concrete composite

ABSTRACT

This paper studied ultimate strength behaviour of Steel–Concrete–Steel (SCS) sandwich plate under concentrated loads. Eight square SCS sandwich plates were simply supported and tested to failure under concentrated loads. The investigated parameters included strength of the core material, thickness of the steel skin plate, content of the steel fibre in the core, size of the loading area, and different type of the fibre. Test results showed that SCS sandwich plate exhibited two peak resistances that benefited from the tension membrane action of the top steel skin, which behaved differently from reinforced concrete structures. The influences of different parameters on ultimate strength behaviours of SCS sandwich plate have been analysed and discussed. On the basis of the experimental studies, analysis and discussions, theoretical models were developed to predict the ultimate resistances of the SCS sandwich plate under concentrated loads. The developed models considered the punching shear resistance of the top steel skin plate, modified the resistance contributed by the headed studs, adopting proper critical perimeter for the punching cone, and developing formulae for the second peak resistance. The analytical models were observed predicting well the ultimate resistances of the SCS sandwich plates.

1. Introduction

Steel–Concrete–Steel (SCS) sandwich structure, consisting of two layers of steel plates and a sandwiched concrete core with mechanical headed studs connected to the steel plates [see Fig. 1(a)], is a relatively new type of structure and becomes popular in recent three decades (Yan et al., 2014, 2015). The advantages of the SCS sandwich structure over the traditional reinforced concrete structure are that the external steel skin plates act as the permanent formwork and flexural reinforcement, and offer waterproofing protections; the fabrication of the SCS sandwich structure requires no detailing, bending and fixing of reinforcement; the external steel skin plates increase the spalling resistance to impact and blast loads (Sohel and Liew, 2014). This structural system was originally developed for submerged tube tunnels, and it also shows versatile potential applications in offshore and onshore structures as the nuclear containment [Fig. 1(b)], LNG or oil container [Fig. 1(c)], submerged tube tunnels, defensive structures [Fig. 1(d)], shear walls [Fig. 1(e)], bridge deck [Fig. 1(f)], offshore deck [Fig. 1(g)], ship hulls, undersea oil storage tank [Fig. 1(h)], and caissons. More recently, the SCS sandwich shells and plates were used as the ice-resistant wall in the Arctic offshore structure.

The growing world's demand for oil and gas reawakened the interest in oil and gas exploration in the Arctic region. It is important to provide better structural reinforcement schemes for Arctic offshore structures to withstand the Arctic harsh environmental conditions. The key factor affecting the design of Arctic offshore structures may come from the ice loads. Marshall et al. (2012) and Yan et al. (2016) have developed the Arctic offshore structures with SCS sandwich shell type and plate type of periphery ice-resistant walls as shown in Fig. 2(a) and (b), respectively. These developed Arctic offshore structures aim on the applications in locations with sea water depth of 10–100 m. In these developed gravity based structure (GBS), the ice-resistant wall with slopes failed the impacting ice creatures in flexural bending instead of crushing as that happened in the vertical ice-resistant walls [see experimental observations in Fig. 2(c)], which significantly alleviate

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Abbreviations: COV, coefficient of variation; HSS, headed shear stud connector; LVDT, linear varying displacement transducer; PVA, polyvinyl alcohol; SCS, steel–concrete–steel; SF, steel fibre; ULCC, ultra-lightweight cement composite; YS, Yield strain

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http://dx.doi.org/10.1016/j.oceaneng.2016.03.062
0029-8018/

Nomenclature

A_s	cross section area of the shank of the headed stud connector
E_c	elastic modulus of the ULCC
E_s	Young's modulus of the steel
$K_e = P_e/\delta_e$	elastic stiffness of sandwich shell at working state
P_e	load at the elastic limit in the load deflection curve
P_1, P_2	first and second peak resistance in load-deflection curves of the SCS sandwich plate.
S_a	spacing of the headed stud connectors
T	tensile resistance of the headed stud connectors
V_c, V_s, V_{sp}	punching shear resistance contributed by the concrete core material, shear connectors, and the steel skin plate, respectively.
a	width of the square patch loading
b_0	critical perimeter for the punching shear failure of the ULCC core
f_{ck}, f_t	compressive and tensile strength of the ULCC
f_y, f_u	yield and ultimate strength of the steel skin plate
h_c	height of the ULCC core
h_e	effective height of the cross section and equals $h_c + t_t/2$
h_t	nominal height of the cross section and equals $h_c + t_c + t_t$
t_c, t_t	thickness of the top and bottom steel skin plate in the SCS sandwich plate
u	average test-to-prediction ratio
v_c	punching shear stress of the ULCC
δ_e	deflection corresponding to P_e
σ_y, σ_u	yield and ultimate strength of headed stud connectors
ρ_{SF}	volume fraction of the steel fibre in ULCC

the ice-contact pressure acting on the structure. Previous studies also revealed that this ice-contact pressure on the structure was not averagely distributed, and there were some high pressure zones (HPZs) on the ice-structure interacting surface (Palmer and Croasdale, 2012). The ice-contact pressure in these HPZs can be extremely higher than 15 MPa that is much larger than that in building floor of about 0.00475 MPa (Ellis and Macgregor, 1993). Therefore, the ultimate resistance of the SCS sandwich ice-resistant wall subjected to the localised patch loads becomes the main concern for the development of this type of structure.

Experimental and analytical studies have been carried out on ultimate strength behaviours of SCS sandwich shell used as ice-resistant wall in the conical Arctic offshore structures (Marshall et al., 2012; Yan et al., 2015; Yan, 2012). This paper continued the research and focused on ultimate strength behaviour of SCS sandwich plate type of ice-resistant wall in the conical Arctic structures. Recently, the ultra-lightweight cement composite (ULCC) has been developed that exhibits high specific strengths of 47 kPa/(kg/m^3), high freeze and thaw resistance, and low water permeability (Liu et al., 2012; Wang et al., 2013). In this paper, the developed SCS sandwich plate adopted this new ULCC as the core material and headed studs as the bonding measures at the steel–concrete interface. The structural behaviours of SCS sandwich beams have been reported by Roberts et al. (1996), Wright et al. (1991), Oduyemi and Wright (1989), and Yan et al. (2015, 2014). The ultimate strength behaviour of SCS sandwich plate with J-hook connectors was experimentally studied by Sohel and Liew (2011). Shanmugam et al. (2002) reported 12 tests on SCS sandwich plate with normal weight concrete. The test data on the SCS sandwich plate is still quite limited especially for the SCS sandwich plate with novel ULCC. Therefore, further experimental studies are necessary to advance the understanding on the ultimate strength behaviour of SCS sandwich plate with ULCC under concentrated loads, which simulates the critical scenario of SCS sandwich wall under lateral ice loads or slab under vertical load transferred from the supporting column in actual construction. These necessary experimental studies further support the development of design protocols in engineering guidelines that are not currently available.

This paper aims to develop the SCS sandwich plate type of ice-resistant wall with ULCC for the Arctic offshore structure used for oil and gas explorations. Their ultimate strength behaviours under concentrated ice loads were studied through eight one fourth large scale quasi-static tests. The parameters studied in the test programme were strength of the core material, thickness of the steel skin plate, volume fraction of the steel fibre in ULCC, area of the patch loading, and different types of the fibre. The test programme reported the failure mode, ultimate strength, and load transferring mechanism, and also discussed the influences of different parameters. An analytical approach was also developed to predict the ultimate resistances of the SCS sandwich plate. Their accuracies were validated by the reported eight-test results. Finally, design recommendations on the SCS sandwich plate were given based on these experimental and analytical studies.

2. Experimental programme

2.1. Details of specimens

Totally, five parameters were involved in the experimental programme, i.e., the strength of the core material, thickness of the steel face plate (i.e., steel content of the section), volume fraction of the steel fibres, loading area, and types of the fibres. This experimental programme comprised eight SCS sandwich plates. Each specimen consists of two external steel skin plates and a sandwiched core between them with overlapped headed stud connectors bonding as integrity [see Fig. 3(a)]. Fig. 3(b) shows the standard fabrication process of the SCS sandwich plates that include welding the headed stud connectors to the top and bottom steel skin plates, preparing the steel skeletons for casting, and casting of the specimen.

All the SCS sandwich plates were designed with the same depth of 100 mm for ULCC core and overall length of 1020 mm (span equals 900 mm). All the specimens adopted Ø13 mm headed studs to bond these three different layers of materials as integrity and work compositely. SF1–3 adopted different strengths of ULCC core, i.e., 45 MPa, 65 MPa, and 85 MPa, respectively. SF1, SF4, and SF5 had external steel skin plate in different thicknesses of 4 mm, 6 mm, and 8 mm, respectively. Different volume fractions of steel fibre in the ULCC core was used to investigate their influences on the ultimate strength behaviour, i.e., 0.5% and 1% for specimen SF1 and SF6, respectively. SF1 and SF7 adopted different square-patch-loading area of 100 × 100 mm^2 and 125 × 125 mm^2, respectively. SF1 used the steel fibres whilst SF8 adopted polyvinyl alcohol (PVA) fibres in the ULCC core. Table 1 gives more details of the tested specimens.