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Finite element analysis of curved lightweight steel-concrete-steel sandwich panel subjected to lateral loads

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ABSTRACT

A novel flower-shaped conical caisson structure using steel-concrete-steel (SCS) sandwich shell is proposed for Arctic offshore application. This type of cone structure is designed for withstanding high magnitude ice pressure imposed thereon by impinging sheet ice in Arctic region. This study mainly investigates the ultimate strength behaviour of SCS sandwich shell subjected to quasi-static load numerically using commercial finite element (FE) package ABAQUS/Explicit.

The FE results show that the failure mode of SCS sandwich shell is related to significant parameters such as rise-to-span ratio(r/L), span-to-height ratio(L/h_c), loading area and loading position. Under lateral ice loading, several possible failure modes have been observed, which are punching shear failure, flexural failure, separation between steel plate and concrete, snap-through failure and beam-shear failure. The results also show that the proposed SCS system possesses high resistance against ISO ice pressure and the load-displacement behaviour indicates that it can absorb a great deal of energy at failure.

1. INTRODUCTION

The Arctic continental shelf is believed to be the area with the highest unexplored potential for oil and gas as well as to unconventional hydrocarbon recourses such as gas hydrates. World demand for oil is set to increase 37% by 2030, according to the US-based Energy Information Administration's (EIA) annual report (BBC, 2006). And US geological survey shows that 30% of the world's undiscovered gas and 13% undisclosed oil are found in the arctic. The growing demand for oil and gas nowadays have reawakened the interest in oil and gas exploration and development in this area. However, one challenge is that these waters in this area are covered with vast area of ice sheet, moving ice ridges, ice bergs which may induce high contact forces on any stationary offshore structures. Hence, high resistance structure with high ductility is required. Although a great number of arctic structures are proposed and being in operation, they are still incapable of year-round operations in extremely harsh ice environment. Hence, there is a need for new ideas to existing design concepts to

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produce an economical yet feasible solution that allows continual year-round operation in arctic region.

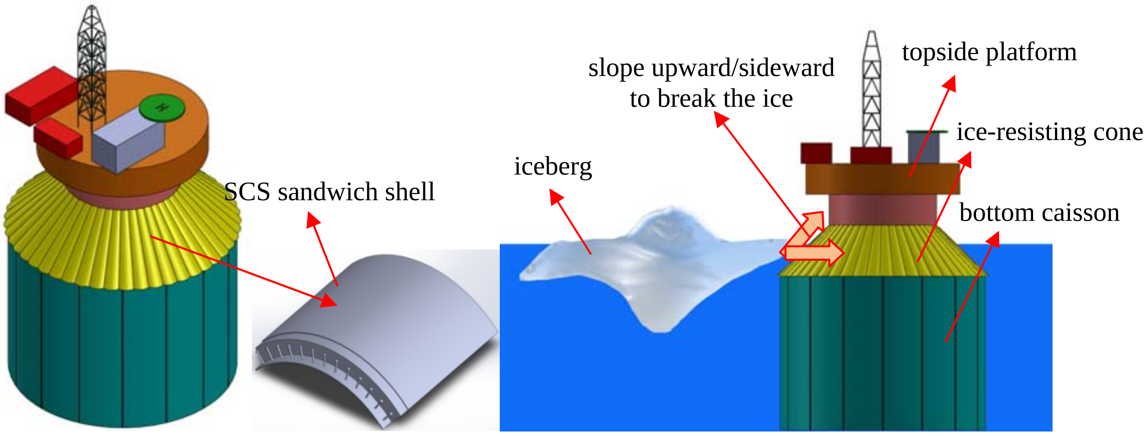
Steel-Concrete-Steel (SCS) sandwich composite structure that takes advantages of both concrete compression and steel tension is accepted in civil and offshore domain due to its excellent cost-strength performance. For decades, extensive researchers have investigated static and dynamic behaviour of steel-composite structure for building and offshore constructions. Solomon et al. (1976) appraised the SCS sandwich structure as a potential structural form to reduce self-weight of roadway slab on composite bridge. Tomlinson et al. (1989) proposed double skin SCS with shear studs for immersed tube tunnel application under Conwy river. In 1990s, Steel Construction Institute (1994 and 1997) issued two design guidelines for the application of SCS sandwich construction. In these applications, the shear transfer between steel skin and concrete relies on the overlapped headed shear studs. Shukry and Goode (1990) carried out the punching tests on SCS sandwich shells for the first time. In order to enhance the composite action of SCS sandwich structure, Liew et al. (2008, 2009) proposed a novel J-hook shear connector and responsive push out and pull out tests showed that the connector possessed high resistance with excellent ductility comparing to normal head shear stud connectors (Yan, 2012). Furthermore, static and impact performance of SCS sandwich beam and plate through experimental test (Liew and Sohel, 2009; Liew et al, 2009; Liew and Sohel, 2010; Sohel and Liew, 2011; Sohel et al., 2012) were evaluated. However, most of the past works were contributed to flat composite beams and panels. Ultimate strength behaviour of curved SCS sandwich panel subjected to global failure is very limited.

In this paper, a novel sandwich caisson system for arctic offshore is proposed. Quasi-static behaviour of curved lightweight SCS sandwich panel subjected to lateral loads are evaluated through the finite element (FE) analysis.

2. DEVELOPMENT OF SANDWICH CAISSON SYSTEM FOR ARCTIC REGION

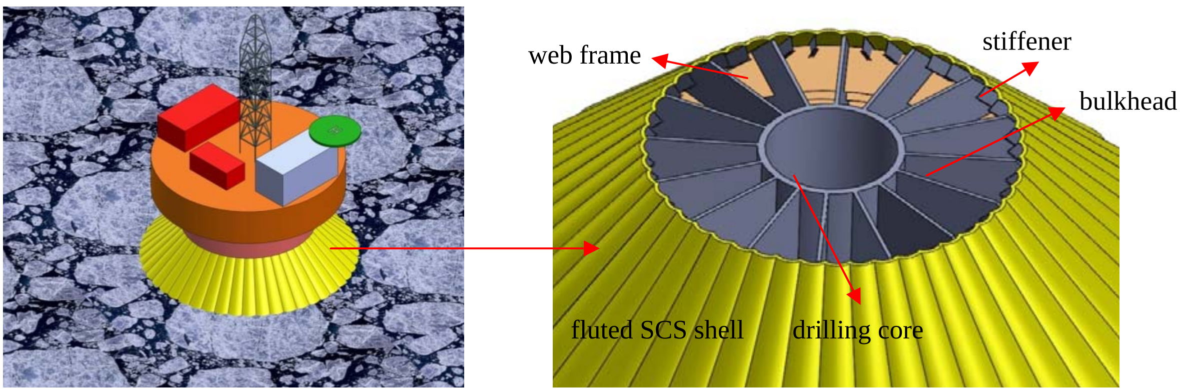
For arctic offshore application, the structures require high impact resistance, high ductility and extended fatigue lifespan in a mostly below sub-zero temperature environment. Using conventional reinforced concrete (RC) structure, besides being heavier to transport it also leads to large amounts of congested reinforcement in order to withstand high magnitude ice force. With seepage of sea water, corrosion of reinforcement would be a dominating factor as that weaken durability of concrete, which may induce high maintenance cost. In addition, erosion and abrasion of hydraulic structures should not be ignored.

In view of these considerations, a novel flower shaped SCS sandwich conical caisson is developed for the arctic region, as shown in Fig.1(a). Curved SCS sandwich structure with slope is adopted as the ice-resisting wall to withstand the ice loading. Because, it is observed that sloping structures would encounter ice impact forces due to that the collided ice sheet would ride up the slope and fail in flexural bending rather than crushing as that occurred to a vertically sided structures, as shown in Fig.1(b). In this way, ice force will be alleviated and most parts of the structure are under compression and possess high resistance due to arch action. The natural geometry also helps to optimize and improve the composite action. Furthermore, modular construction with rapid installation can be achieved, reducing the fabrication cost comparing to RC structures. A possible ice caisson design is illustrated in Fig.2. The typical configurations for such SCS sandwich shell has two 30 mm thick steel plates of 355 MPa yield strength and 500 mm thick concrete core of 30~60 MPa compressive strength. The cylindrical shell segment has 5 m span with 10 m length along axis with rise-to-span ratio of 0.21 based on geometric design.



(a) caisson structure and SCS sandwich shell (b) ice impact on cone shaped caisson

Fig.1 Proposed conical caisson structure with SCS sandwich shell



(a) caisson in ice environment (b) ice-resisting cone connected with drilling core

Fig.2 A possible design of conical caisson structure with SCS sandwich shell

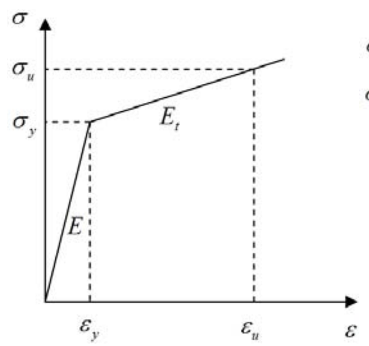
For weight sensitive marine and offshore structures, infill core material should be optimized. Ultra lightweight cementitious composite (ULCC) has been developed by Chia et al. (2011) for the proposed SCS sandwich system. ULCC is a type of fiber-reinforced composite material which is developed with 28-day compressive strength up to 60 MPa and a low density of 1250~1450 kg/m^3. Compared with conventional normal weight concrete (NWC) with similar grade, the ULCC exhibits a high strength-to-density ratio. Besides, around 40% weight reduction from NWC, the ULCC has a comparable tensile and flexural strength with conventional concrete. It has lower modulus of elasticity approximately 50% that of NWC. Basic components of the ULCC are ordinary Portland cement, silica fume and fine aggregate named cenospheres particles with a diameter ranging from 10 to 400μm. Poly vinyl alcohol (PVA) fiber or steel fiber by volume of composite can be used to improve tensile strength. Fresh ULCC is flowable and watery that is feasible for pumping during casting of construction.

3. FLEXURAL FAILURE STUDY BY NUMERICAL METHOD

3.1 FE modeling and material models

A quasi-static analysis was defined using commercial FE package ABAUQS/Explicit solver to study the flexural failure mode of SCS sandwich shell subjected to different lateral ice loads. The concrete core and steel plates were meshed by 8-nodes continuum-brick elements (C3D8R). Contact bond and perfect bond were considered for simulating the interfacial behaviour between concrete and steel plate, respectively. Fix-fix boundary conditions were selected for the sandwich shell.

Mild steel was used for inner and outer skin for sandwich shell, with yield stress 355 MPa, Poisson ratio 0.3 and Young's modulus 198 GPa. It was modeled by Hooke's law of elasticity theory and the J2 flow theory of plasticity associated with von Mises yielding criteria and isotropic hardening law. Therefore, bilinear curves was used for steel material for simulation, as shown in Fig.3.



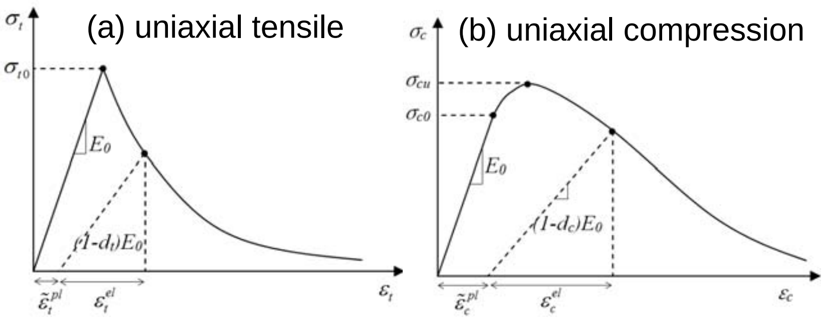


Fig.3 Stress-strain curve of steel   Fig. 4 Stress-strain curves of concrete

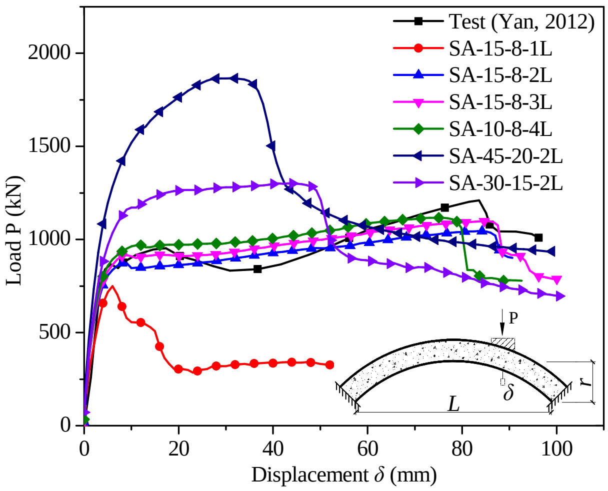
The concrete damage plasticity (CDP) model was used to simulate the mechanical properties of ULCC, which can consider the inelastic behaviour using the concepts of isotropic damaged elasticity in combination with isotropic tensile and compression plasticity. The stress-strain curves for uniaxial tension and compression were needed to define elastic, plastic and damaged behaviours, as shown in Fig.4. The mass density, elastic modulus, poison’s ratio, compression strength and tension strength of ULCC were 1450 kg/m^3, 12 GPa, 0.23, 60 and 6 MPa, respectively. Table.1 tabulates the mechanical properties of ULCC and steel plate.

Table.1 Mechanical properties of ULCC and steel plate

	ULCC	Steel
Mass density ρ (kg/m^3)	1450	7850
Elastic modulus E (GPa)	12	198
Poison's ratio	0.23	0.3
Compression strength f_{ck} (MPa)	60	355
tension strength f_f(MPa)	6	

3.2 Validation against test data

Based on the mesh sensitivity study (Fig.5) and contact property studies (Fig.6), a FE model with the recommended mesh size (15 mm for global mesh, 8 mm for loading region and 3 layer for steel skin) and reasonable parameters for the curved SCS sandwich panel were obtained. Comparison of load-displacement curves indicated good agreement between FE and test results. In test, the failure mode of SCS panel without connectors subjected to eccentric loading was local snap through. Local buckling at free edge was observed. Comparing Figs.7 (a) to (b), it was found that the FE simulation can capture the failure mode. Therefore, the proposed FE model can be used to implement the parametric studies.



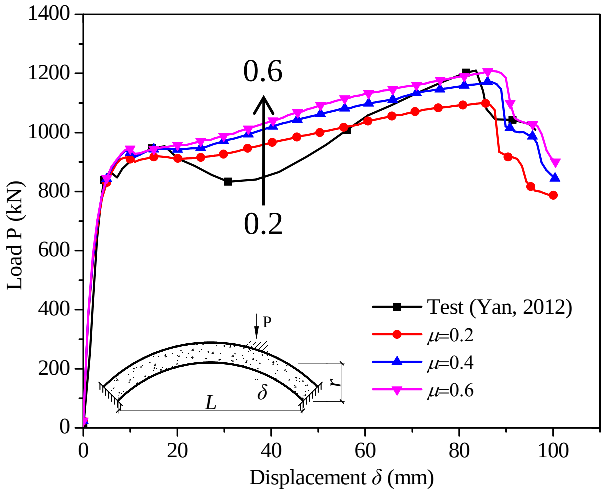
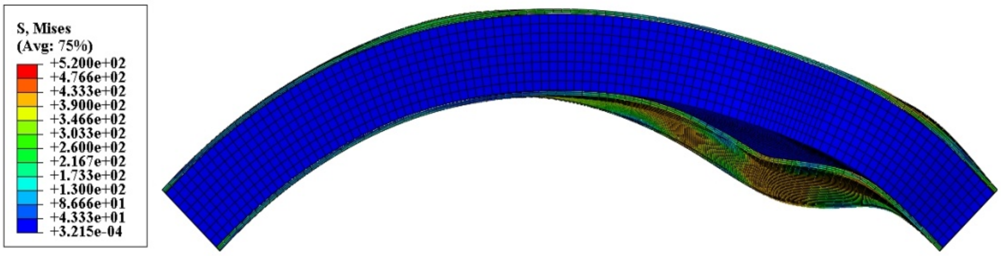


Fig.5 Load-displacement curve on different mesh size
Fig.6 Comparison between test and FE with different friction coefficient



(a) deformed shape of SCS sandwich shell (FE results)

(b) deformed shape of test specimen SA1(Yan, 2012)

Fig.7 Comparison of failure modes

3.3 Parametric study of curved SCS sandwich panel under quasi-static load

In FE model, the material models, element meshes and boundary conditions were chosen as the same as that determined by validation. The primary investigated parameters included rise-to-span ratio (*r/L*), span-to-height ratio (L/h_c), loading position and loading area. Table.2 lists the investigated parameters of SCS sandwich shell.

Table.2 Investigated parameters of SCS sandwich shell

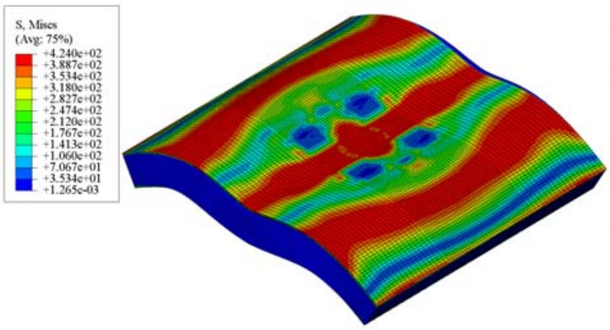
Parameters	Specification	Parameters	Specification
rise/span ratio (*r/L*)	0.13	loading position	4-patch loading
	0.21		strip pressure
	0.5		half-span strip pressure
span/height ratio (L/h_c)	5	loading area	1%
	10		6%
	15.6		100%

Effect of rise-to-span ratio (*r/L*) Rise-to-span ratio affects the stiffness, failure mode and ultimate strength of SCS sandwich shell. The SCS sandwich shells were applied with 4-patch loading at the mid-span. It can be observed from the deformed shape of the shells that the three SCS sandwich shells have a large concave which indicates that they fail in flexural mode, as shown in Figs.8 (a)-(c). The load-displacement curves with different rise-to-span ratio for partial and full composite are shown in Figs.9~10, respectively. Some findings can be summarized:

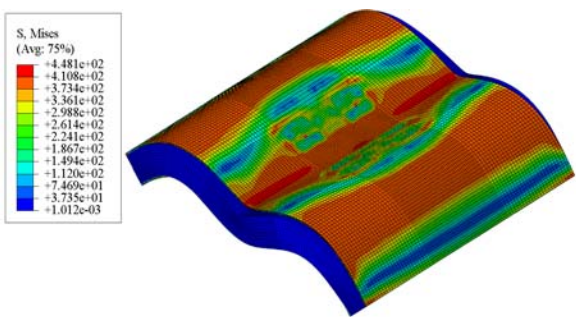
(1) For partial composite, there are two types of load displacement curves can be observed. The first type exhibited two peak values among which the second peak value is smaller than the first peak value (curves of *r/L*=0.13 and 0.21) while the second type curve exhibites a larger second peak value (curve of *r/L*=0.5). The two curves shows the sandwich shell possesses a ductile manner carrying load with large deformation.

(2) For full composite, only one type of load-displacement curve is observed which is similar to the first type curve for partial composite. The first peak strength and ultimate strength of full composite are larger than that of partial composite, as can be seen in Fig.11.

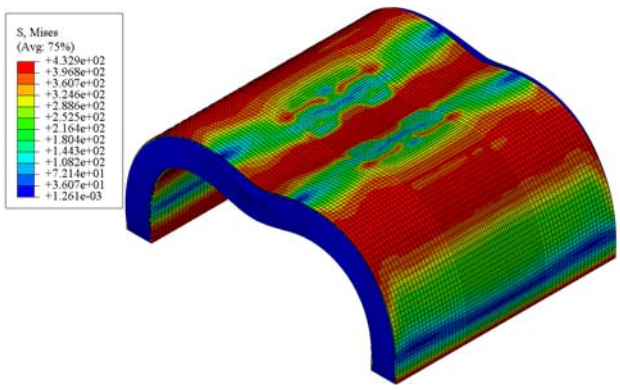
(3) SCS sandwich shell with *r/L*=0.21 is recommended for design application, which possesses a higher ultimate strength with ductile manner compared to that of another two specimens.



(a) *r/L*=0.13



(b) *r/L*=0.21



(c) *r/L*=0.5

Fig.8 Deformed shape of specimen with varying rise-to-span ratio

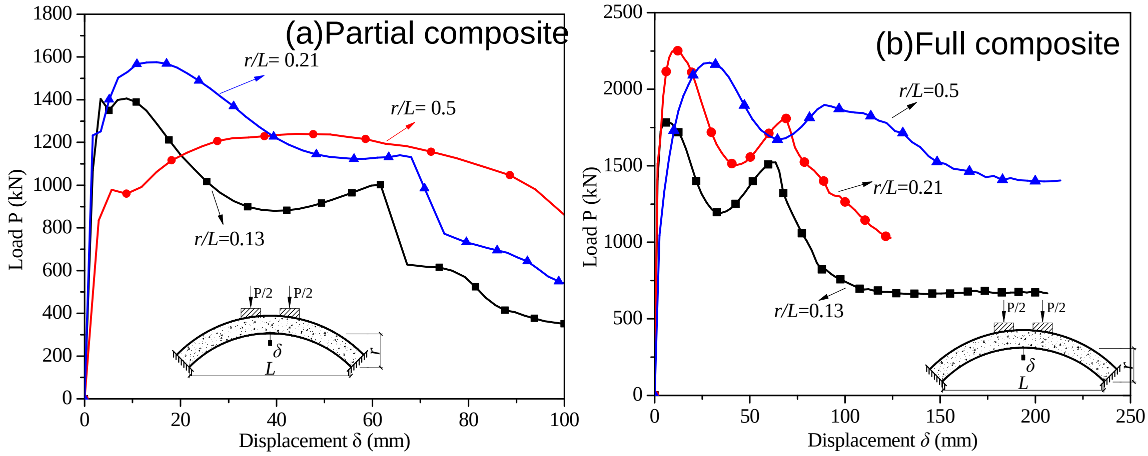


Fig.9 Load-displacement curves with varying *r/L* ratio

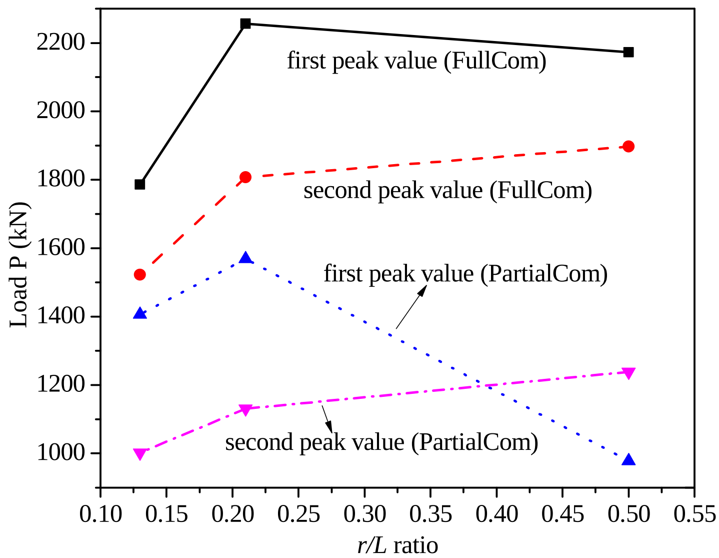


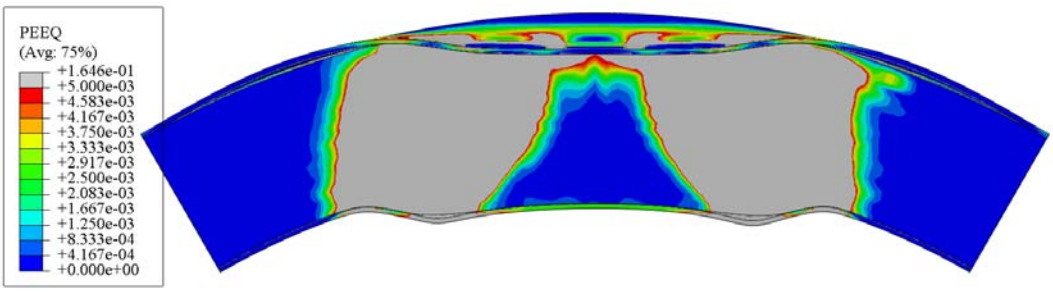
Fig.10 Effect of rise-to-span ratio on strength

<u>Effect of span-to-height ratio (L/h_c)</u> Different span-to-height ratio also leads to different failure modes. With fixed *r/L* ratio of 0.13, three varying concrete height h_c (i.e. 80, 125 and 250 mm represented the span-to-height ratio of 15.6, 10 and 5, respectively) were chosen. Deformed shapes with varying L/h_c ratio are illustrated in Fig.11, which shows that sandwich shell with smaller L/h_c ratio would fail in beam shear (i.e. specimen with L/h_c=5) while for larger L/h_c ratio, flexural failure is dominant. The comparison of load-displacement curves for partial and full composite are shown in Fig.12. The curves of load capacity corresponding to L/h_c ratios were shown in Fig.13. Several conclusions are listed as following:

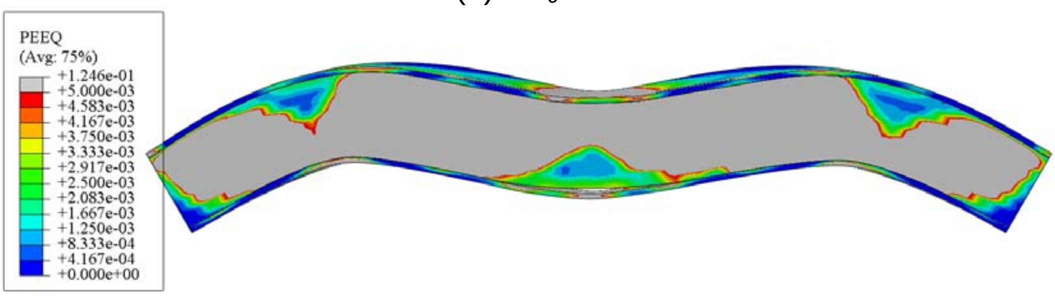
(1) SCS sandwich shell with small L/h_c ratio (such as L/h_c=5) fails in beam shear, the load-displacement behaviour shows a brittle manner with sudden shear through the concrete core, compared to that with larger L/h_c ratios.

(2) For both partial and full composite SCS sandwich shell with L/h_c of 15.6 and 10, ductile load-displacement curves are observed which exhibited two peak load values. Principle for the first peak load is that the shell fails in flexural mode. Flexural deflection is dominant. The bottom steel plate starts to yield firstly at this point. The bottom part of concrete core is subjected to tension while the top part of concrete core is under compression. At this point, the structure achieves the first peak resistance. After that, though the bottom plate yields and the concrete is crushed, the structure still can carry the load due to the membrane tension from the top outer steel plate. However, the second peak load cannot exceed the first peak load value at final stage. The entire structure behaves a global, flexural and ductile failure mode.

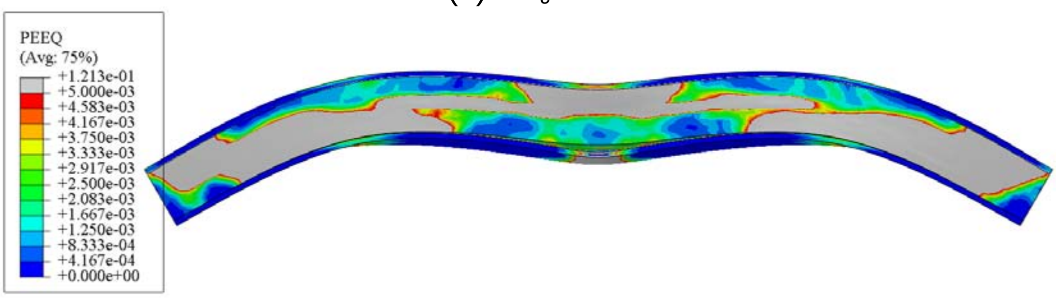
(3) For partial and full composite sandwich shell, the first peak strength and ultimate strength reduce as L/h_c ratio increases.



(a) L/h_c=5



(b) L/h_c=10



(c) L/h_c=15.6

Fig.11 Deformed shapes and PEEQ distribution of specimen with varying L/h_c ratio

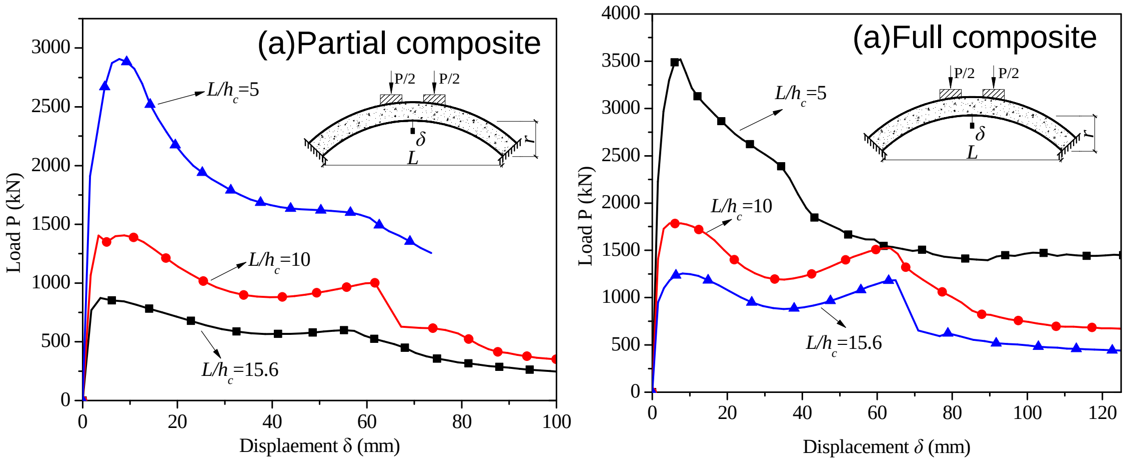


Fig.12 Load-displacement curves with varying L/h_c ratio

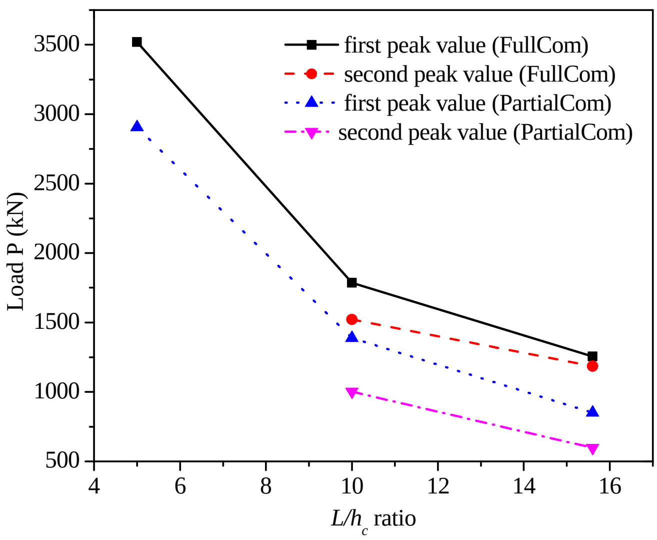
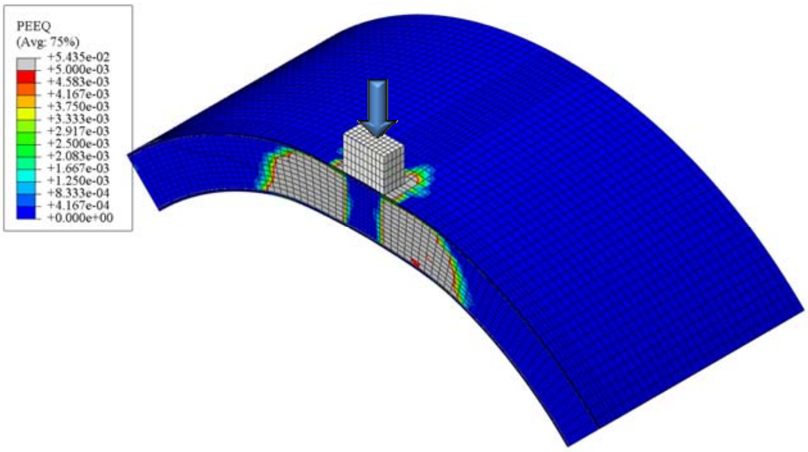


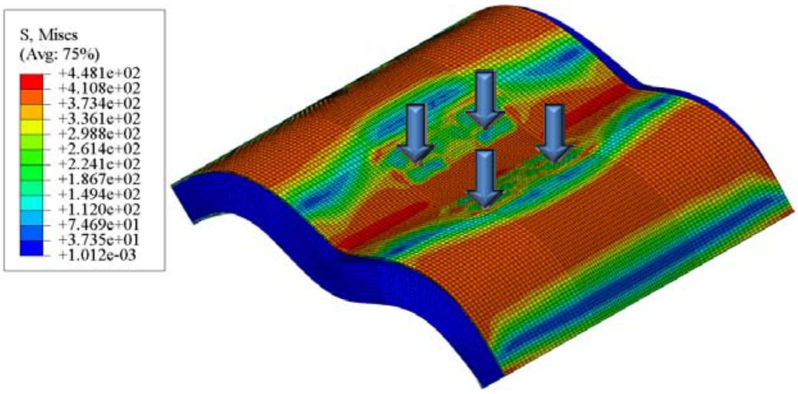
Fig.13 Effect of span-to-height ratio on strength

Effect of loading area Smaller loaded area leads to premature punching failure while larger loaded area makes flexural failure occur prior to punching shear which is brittle. The effect of three varying loaded area (1%, 6%, and 100% loading area) were investigated in this section. Fig.14 shows the deformed shape of specimen with varying loading area. It is found that:

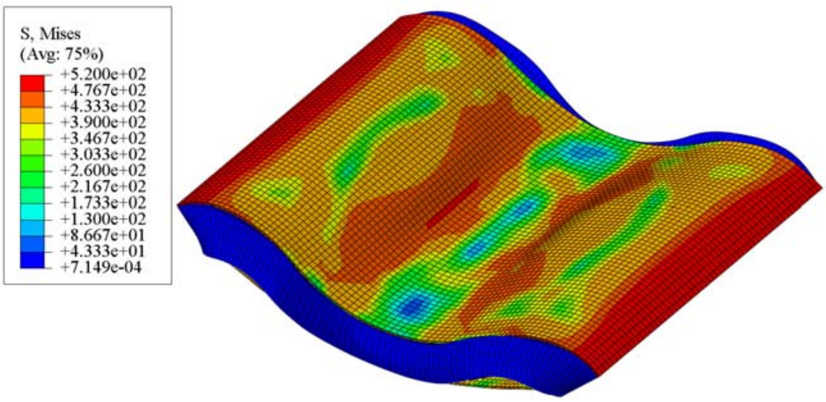
(1) For the case with 1% loading area, typical punching failure is observed. The stress distribution is concentrated around the loading area. There is no yielding of the bottom steel plate at any stage of loading. Failure is by punching of the concrete around the periphery of loading plate. So the strength is mainly controlled by the crushing concrete.



(a) 1% loading area



(b) 4 patch loading



(c) 100% loading area

Fig.14 Deformed shapes of specimen with varying loading area

(2) For the cases with 6% and 100% loading area, large global deformation is observed and flexural failure mode is identified. As can be seen in Fig.15, the ultimate strength of the SCS sandwich shell under 4-patch loads and full-span uniform pressure was about 17.5 and 9.6 MPa, respectively. The SCS sandwich shell fails in a symptomatic way

that exhibits ductile manner. Although the flexural strength is much lower than the punching failure strength, it would permit large deformation and redistribution of ice pressure to the supports. In this way, much impact energy would be absorbed by the structure.

(3) Load pressure curve by FEM and ISO design load curve is plotted in Fig.15 which shows that failure strength of SCS sandwich shell satisfies strength requirement.

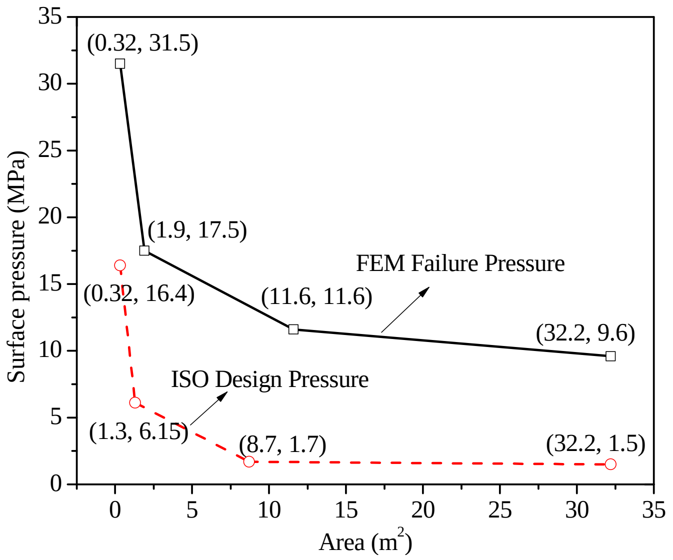
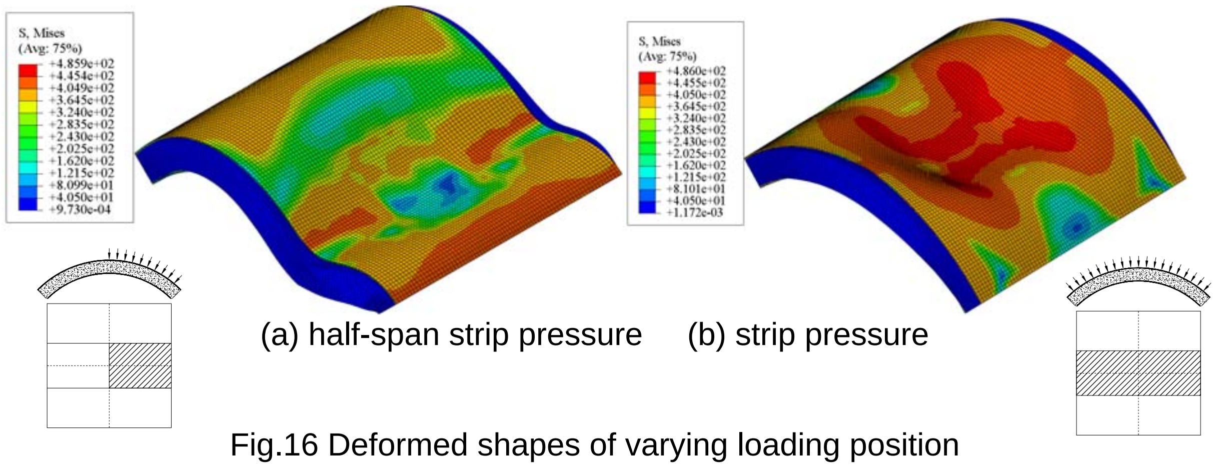


Fig.15 Load pressure versus ISO design load



(a) half-span strip pressure (b) strip pressure

Fig.16 Deformed shapes of varying loading position

<u>Effect of loading position</u> Ice load can be from any direction toward the structure. Different loading positions of quasi-static load in FE models, i.e. over length and half length of strip pressure applied on the circumferential direction of the shell were

considered. Fig.16 shows the deformed shapes of the SCS sandwich shell subjected to varying loading position. Comparison of load pressure-displacement curves are shown in Fig.17. The findings are concluded as follows:

(1) Generally, the failure load pressure decreases as the loading area increases;
(2) Failure pressure is sensitive to loading eccentricity. It is shown that the failure pressure was around 4 MPa for sandwich shell subjected to half-span strip pressure loading while it is around 10 MPa for shell subjected to full-span uniform pressure loading.

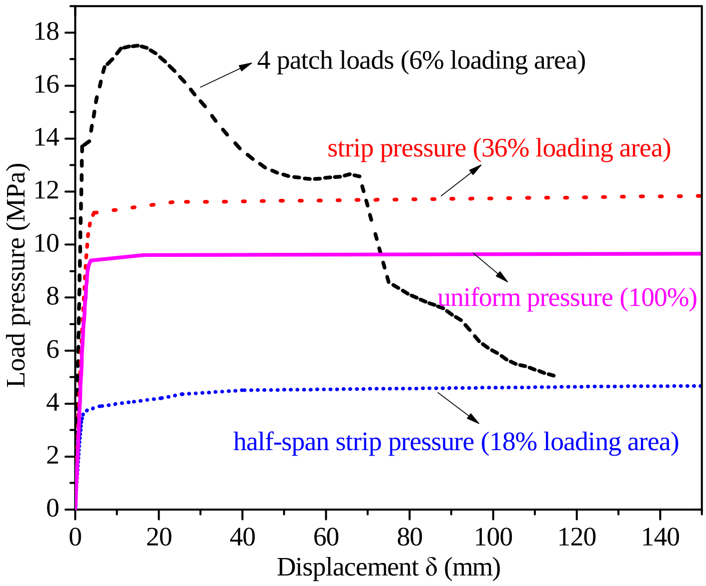


Fig.17 Load pressure-displacement curves of different loading position

4. CONCLUSIONS

This paper presents the background, advantages and challenges of curved SCS sandwich panel as an ice-resisting wall panel used for arctic offshore structures. A novel conical SCS sandwich caisson structure has been proposed based on the concept of curved lightweight sandwich.

A three dimensional finite element model was developed to predict the response of the SCS sandwich shell under lateral loading. The FE model was validated against experimental measurements which showed that the developed FE model is reliable and acceptable. Using this validated model, parametric FE analyses were conducted to investigate their influences on the ultimate strength and failure modes of the SCS sandwich shell structures. The primary investigated parameters included rise-to-span ratio, span-to-height ratio, loading area and loading position. From the results, the key findings are concluded as following:

(1) The rise/span ratio affects the ultimate strength of the specimen. For both partial and full composite shell without connectors, it was found that r/L=0.21 possessed higher strength than that with the other r/L ratios.

(2) The span-to-height ratio affects the failure mode of the specimen. For smaller L/h_c ratio, the sandwich shell fails in beam-shear while for larger L/h_c ratio, flexural failure mode is observed. Ductile flexural failure mode not only gives high carrying capacity but offers large deformation. The beam-shear failure mode behaves a more brittle manner with small deformation although exhibiting a higher peak strength.

(3) Loading area and loading position affects the failure mode and failure strength. Under small loading area, premature punching shear is observed while flexural failure is visualized under larger loading area. As the loading area increases, the failure pressure decreases. Furthermore, failure load is very sensitive to eccentricity of the loading.

(4) Compared to ISO design load, the proposed SCS sandwich shell possesses satisfied strength under different ice loading scenarios.

However, it is of great interests to do more flexural tests on SCS sandwich shells subjected to larger loading area in the future.

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