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Studded bond enhancement for steel-concrete-steel sandwich shells

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ABSTRACT

A double-wall steel-concrete-steel (SCS) composite vault has been proposed for the "Singapore Cone" Arctic offshore structure. The SCS vault performs well under uniform pressure, but can fail prematurely under partial asymmetric loading. These shells will often experience a punching shear failure or flexural steel plate buckling which is exacerbated by the loss of bond between the steel wall and concrete interface. In this study, a construction friendly method using an array of welded mini studs to improve the steel–concrete interfacial bond is proposed and studied. Two workable Type I Portland cement grout mixes are tested as the bulk material: plain, and fiber reinforced. Studded concrete steel interfaces were tested under mode I interface peeling, and mixed mode shear. The small scale tests were also modeled with the nonlinear finite element analysis software ABAQUS, and the numerical results were compared against the laboratory experimental results. After qualitatively matching the computational results with experimental results, a large scale SCS prototype is modeled and designed, with working stresses limited to the elastic range. Mode I peeling ultimate strength of $0.46\sqrt{f_c'}$ was used for the prototype analysis, with mixed mode shearing limited by bulk concrete away from the studded bond surface.

1. Introduction

Double-wall steel-cement-steel (SCS) composite construction has been used in jacket-type fixed offshore platforms since 1947, with the annulus between piling and jacket leg being cemented oil-field style. Tests revealing loss of bond at the cement-steel interface in grouted tubular space frame connections was observed in the 1970s, and incorporated into design codes and nonlinear finite element analysis protocols. Ice-resistant steel and concrete Arctic structures were intensively studied in the 1980s, before an earlier cycle of low oil prices made them uneconomical (Gerwick et al., 1981).

Corder and Kozik's (1989) study of SCS in Arctic drilling and production platforms focused on reducing steel weight. Their ice wall design was validated by linear and nonlinear finite element analyses (Ramnath, 1991), but never built. The platform was a gravity-based, cone-shaped, ice-resistant structure. The exterior was a steel-concrete-steel sandwich configuration, with nearly flat panels. Internal bulkheads behind the ice wall were to transmit the ice loads down to the foundation. Tensile cracking in the concrete core was predicted at ice pressures between 2.40 and 2.75 MPa. However, their study did not consider the effects of debonding, either mode I peeling and mode II shear slippage.

Today, the default design assumption is zero tensile or shear bond along the steel–concrete interface – only contact friction, bearing, and geometric interference (API, 2000, Choo et al., 2012). The most recent design standard for offshore drilling structures in the Arctic (ISO, 2010), describes ice loads reaching 8.4 MPa and higher on small loaded areas ($<1\ m^2$), with lower pressures (but larger total force) on larger areas. The loading is dynamic, but not like impact, as the pressure slowly builds up, then drops suddenly as the ice shatters, with temporary high pressure zones dancing randomly across the face of the structure (Palmer and Croasdale, 2013). Under these conditions, ISO (2010) discourages reliance on bond or contact friction.

National University of Singapore (NUS) investigated the "Singapore Cone", a slightly different offshore drilling structure for the Arctic, (Fig. 1) (Marshall et al., 2010, 2012). Here, the ice wall consists of fluted barrel vaults spanning between the internal bulkheads.

The 32-500-32 mm steel-concrete-steel barrel shells have a total thickness 564 mm, and a span of 5.0 m between radial bulkheads; giving a depth/span ratio of 1:8.9, a thickness/radius ratio of 1:6.3, and a rise/span ratio of 0.2. The axial length between circumferential bulkheads (or stiffening rings) was designed to be 1.4–3 times the span, but testing and analysis at NUS used a shorter length, with no bulkheads (Marshall et al., 2012). Significant curvature provides compressive arching action, rather than just flat panel bending. Steel yield was taken as 355 MPa, and the un-reinforced slurry concrete core set at 30 MPa compressive strength (f_c'). The unstiffened steel shells were sized to resist

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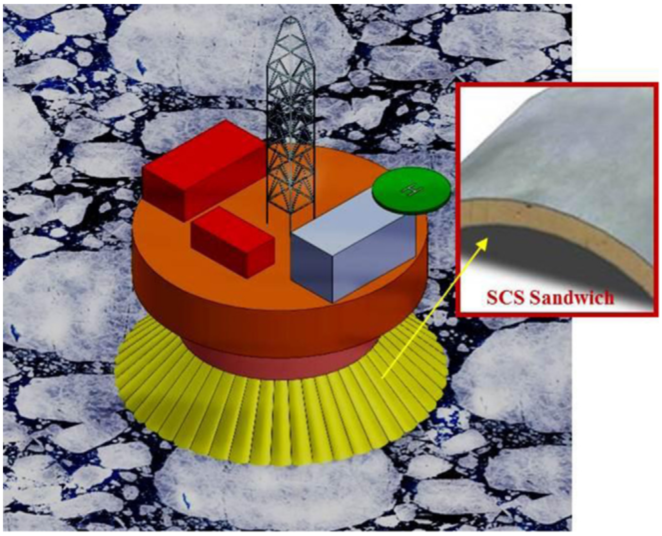

Fig. 1. Singapore Cone (Marshall et al., 2012).

hydrostatic pressure during the concrete pour, and over-sized for the in-place sandwich condition. Principal design concerns in-place are mode I tensile peeling, and Mode II shear slippage at the concrete–steel interface. Inclined fracture in the concrete core (mixed mode due to punching shear) is not influenced by bond improvements, and is the upper limit for shells with perfect bond. Shear reinforcement can further enhance the capacity beyond plain diagonal tension, but complicates fabrication.

These barrel vaults are very strong against full-span uniform loading but vulnerable to partial-span asymmetric patch loading, which creates large punching shears and shell bending moments that reduce pressure capacity (Marshall et al., 2010). Design pressure demand (at prototype scale) also varies with load patch size, according to ISO, 2010 and API (1995) codes, as shown in Table 1.

Based on impact tests of flat sandwich panels, Liew and Sohel (2009) devised several schemes for tying the steel plates together to prevent separation. These included patented J-hooks, precision match-welded before assembly of the sandwich; overlapping long headed studs; and cross ties welded at both ends by a small robot operating between the plates after assembly. Application of J-hooks to the Singapore Cone improved peak load for the 10% patch case by approximately 50% over the unreinforced sandwich with a plain interface, as the latter partially de-bonded during construction and setup. However, the unreinforced sandwich also exceeded ISO (2010) design requirement. Huang and Liew (2016) tested large scale curved SCS shells embedded with full thickness overlapping welded studs and reported three failure mechanisms: flexural failure, diagonal strut crushing, and shear tension failure. Huang et al. (2015) studied the punching shear resistance of lightweight SCS shells and showed the shells are capable of resisting localized contact and punching loads. However, internal reinforcement schemes can be inconvenient to fabricate in marine hulls with more complex curved shells. Wet concrete cast onto wet epoxy prevented corrosion and created shear bond strengths of 0.34–1.59 MPa, for low water cement ratios (Aboobucker et al., 2009). Timing and access would be tricky for the labyrinthine cast-in-place Singapore Cone application.

Table 1
Ultimate capacity versus code design pressures.

Loading case	Ultimate capacity (MPa)	ISO pressure	API upper bound (MPa)
100%	9.5	1.5 MPa @ 32.3 m^2	9
50% patch	5.25	1.7 MPa @ 8.1 m^2	11
20% patch	8.5–14	6.1 MPa @ 1.3 m^2	14
10% patch	> 14	16.4 MPa @ 0.32 m^2	20

The objectives and scope of this research are to further inform the SCS design process as follows:

1. To develop understanding of a physical enhancement at the concrete-steel interfaces, sufficient to develop useable tension and shear properties, comparable to those of the bulk cement fill, for both plain and fiber-reinforced concrete.
2. To understand the bond strength with mini studs for both plain and fiber reinforced concrete, specifically critical stress for Mode I peel-off and Mode II shear failure.

2. Experimental program

2.1. Concrete mix design and standard tests

In the Arctic, dry concrete would be brought to the offshore installation site, with fresh water and aggregate coming from a nearby river. High fluidity is desired for pumping, and for self-compaction without vibration inside the labyrinthine steel shell (Fig. 1). Two mix designs are studied here: 1) plain concrete (PC), and 2) a fiber reinforced concrete (FRC). The cement content was 1390 kg/m^3 with a water to cement ratio (w/c) of 0.35. Low aggregate volume was used, similar to oil well cementing practice, with well-graded sand/cement and coarse aggregate/cement ratios of 0.15 for each. The FRC mix contains 50 mm steel fibers at a dosage of 5.5% (of cement mass) and 19 mm long mono filament polypropylene fibers at a dosage of 0.5% (of cement mass). The slump of the PC and FRC mixes were 241 mm and 191 mm, respectively.

The two concrete mixes were tested for compressive strength, f'_{c}, using ASTM C39, split-tensile strength, f'_{t}, using ASTM C496, and modulus of rupture, f'_{r}, using ASTM C78. Cylinders with dimensions of 100 mm × 200 mm were used for the compression and split tensile testing, respectively. Prismatic beams with dimensions of 100 mm × 100 mm × 400 mm were used for modulus of rupture testing. Four replicate specimens were cast for each mix and test procedure. Table 2 shows the average (and standard deviation) of the bulk material strengths obtained at 28 days and 145 days, respectively. The bulk material strengths were obtained on the same test day as the composite steel–concrete beams (145 days).

The 145-day compressive and flexural strength properties were approximately 20% greater than the 28-day bulk strengths properties, while splitting strength showed essentially no improvement. The average bulk compression strength of the plain and fiber reinforced concrete at 145 days was used for referencing the composite beam tests.

Table 2
Bulk mechanical properties of the plain and fiber reinforced concrete tested at 28 days and 145 days.

	Plain concrete			Fiber reinforced concrete		
	f'_{c} (MPa)	f'_{t} (MPa)	f'_{r} (MPa)	f'_{c} (MPa)	f'_{t} (MPa)	f'_{r} (MPa)
28-day average	75.1±0.4	3.2±0.6	6.7±0.9	47.9±2.1	4.0±0.1	8.1±1.9
145-day average	97.3±6.7	3.0±0.9	9.1±2.6	72.4±3.4	4.2±0.7	9.3±1.5

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