Proceedings of the 23rd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2015
Trondheim, Norway

ARCTIC PLATFORM CONSTRUCTIONS USING STEEL-CONCRETE-STEEL SANDWICH COMPOSITE

Zhenyu Huang, Andrew Palmer, Peter Marshall and J.Y. Richard Liew
Department of Civil and Environmental Engineering, National University of Singapore

ABSTRACT

This research aims to examine the application of Steel-Concrete-Steel sandwich composite structure in Arctic platform construction by examining the feasibility of the composite structure in terms of materials, structural form, fabrication, transportation and field installation. A composite cone is made up of an outer steel cone, a concrete infill, and an inner steel cone, with shear connectors on the inner faces of the steel cones. The construction sequence is to build the steel cones empty of concrete, to launch and tow the structure to site, and then to ballast it to the seabed and fill the cones with concrete. This paper also presents the latest research breakthrough of ultra-lightweight high strength cement composite for marine and offshore application. The use of this new material enables novel Steel–Concrete-Steel sandwich composite structures to be developed with lower self-weight, which will provide an alternative Arctic platform construction. Novel shear connectors have been developed to improve the composite action between the steel face plate and the concrete.

INTRODUCTION

An offshore platform in the Arctic has to be able to withstand the forces imposed by moving ice. 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. How to calculate those forces is the subject of intense controversy, and is outside the scope of this paper: see, for example ISO19906 (2010) and discussion by Løset et al. (2006), Palmer and Croasdale (2012) and Palmer (2011). The designer also has to remember wave forces in the open-water season, and possible instability of the seabed.

Equally importantly, a platform must be able to be constructed efficiently and economically, and to be installed at its final location, if possible without the need to bring to the Arctic expensive equipment that can only be available for a short time, particularly because of the risk that ice formation might prevent its return to the south and trap it in the Arctic.

The great majority of stationary platforms in the south are fabricated from steel, and held to the seabed by long piles. A few are concrete, often selected for reasons that are partly political, and they are held in position by a combination of weight and some lateral resistance provided by a skirt or by short piles. A very few are steel gravity platforms.

This paper advances the argument that the best option is to combine the advantages of steel and of concrete, and construct a composite Steel-Concrete-Steel platform.

MATERIALS

Steel is strong and reasonably cheap, at least if corrosion resistance is not required. It corrodes easily, and had to be protected by a combination of coating and cathode protection. Fracture-resistant steel is used but not manufactured in the Arctic. The technology of welding it together is understood and widely practiced, and can be performed to the Arctic. Another option is fabrication in the south and transport to the Arctic.

Concrete is different. It is ten times less strong than steel, and about two-thirds lighter per unit volume. Any tension or large shear has to be resisted by reinforcement. It does not normally need corrosion protection. It is normally cast in situ, in the position where the structure is to be used. Concrete construction is again very widely applied. It is possible to build concrete structures in the Arctic, and that is often done, with precautions such as mixing the concrete with hot water, and designing the cement so that the heat of hydration prevents the concrete from freezing before it hardens. Freezing is not a problem for below-water parts of the structure. After curing, cold temperatures enhance the strength of concrete.

Sea ice is lighter again, about a ninth the density of steel. It is extremely brittle and not strong, with a fracture toughness one-fifth that of glass, but there is a lot of it. In its natural forms, it has a complex and irregular internal structure (Palmer and Croasdale, 2012) and includes many cracks and other defects, on a range of scales from fractions of a millimetre to metres.

One of the recent achievements in concrete technology is the development of ultra-lightweight cement composite (ULCC) and a floatable structural cement composite (FSCC) for marine and offshore application. The ULCC achieved a high compressive strengths of about 60 MPa and high flexural strength of 8 MPa, and hardening behaviour when subject to bending tests (Wang et al., 2011). FSCC has a unit weight of less than 1000 kg/m^3 and 28-day compressive strength of up to 40 MPa, a major breakthrough in research in cement composite materials. Figure 1 shows a floating sample of FSCC when it is placed in water. It has lower water absorptivity than that of normal weight concrete, which is essential to retain low unit weight in a marine environment. The use of ULCC and FSCC enables novel curved SCS sandwich composite members to be developed with lower self-weight which will benefit the transportation and installation of pre-filled members in the Arctic region.

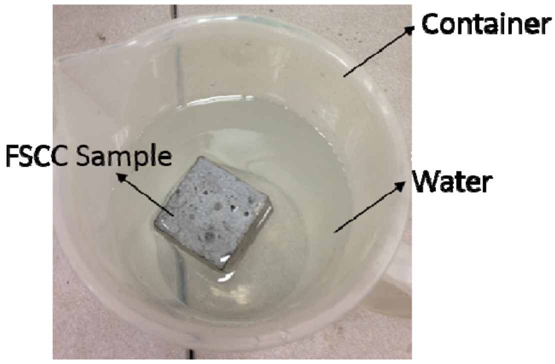


Figure 1. Floatable structural cement composite (FSCC) sample in water

STRUCTURAL FORM

The optimal form of an Arctic structure is much debated. A vertical-sided structure has a simple shape. Wind and current drive ice against the structure, and the ice crushes close to the structure. There are significant scale effects (Dempsey, Palmer and Sodhi, 2001; Palmer and Croasdale, 2012). The broken ice fragments move around the structure and are carried downstream. There are some offshore structures with vertical sides, such as the

Nordstromsgrund lighthouse in the Baltic, which was instrumented and has been the object of much research, though it needs to be kept in mind that the northern Baltic is much less saline than the oceans and that its ice has different properties.

An alternative is a structure with sloping sides, either upward-sloping or downward-sloping, typically at 50° to the horizontal. When the slope is upward, advancing ice is lifted and bent, and it breaks before the slope or on it. This sloping option has been used in several offshore structures, among them the Confederation Bridge in Canada, platforms in the Bohai Sea, and ice barriers in the northern Caspian Sea (Palmer and Croasdale, 2012). Figure 2 is a photograph of an intermediate-scale test. The force to break the ice is smaller than the force the break the same ice in compression crushing, although it needs to be added that there is ongoing controversy about ice forces, and that there is little verification against field measurements on full-scale structures. The ice can be expected to be weaker in bending when the bottom of the ice is in tension, because the bottom is irregular and fissured by brine channels.

Figure 2. Intermediate-scale test on sloping-sided structure in the Esso basin. (Metge, M. and Tucker, J.R., 1990; with permission of Imperial Oil, Calgary)

Downward-breaking pushes the ice downward beneath the water, and again the ice breaks in bending. That option is invariably chosen for ice-breaking ships. An advantage of downward-breaking is that the force needed to push the ice downward in the water is about 125 kg/m^3 (the difference between the unit weights of ice 900 kg/m^3 and water 1025 kg/m^3), whereas upward-breaking has to lift the ice out of the water, against 900 kg/m^3. On the other hand, the fragments formed by upward breaking may be less likely to clear from around the lower parts of the structure, and they may float up under the advancing ice sheet and create a jam: that mechanism is important in river ice jamming (Beltaos, 1995). A further option is to have upward and downward breaking together on the same structure, and cones of that form are a promising alternative for jack-up legs (Tian and Palmer, 2014).

An upward-breaking structure cannot lead the ice to push up the slope indefinitely, because then the ice would impact the topsides and crush at the bottom of the slope. That can be avoided by steepening the slope past the vertical, so that the ice falls back on itself, in the way shown in Figure 2 of Marshall et al. (2012).

STEEL-CONCRETE COMPOSITE STRUCTURES

Composite steel-concrete structures use the best qualities of both materials. They have been known and used for a long time, and there are many books (see, for example, Johnson (1993, 2004)) and codes (Eurocode, 2004). Most of the applications are to slabs and columns, but they can also be three-dimensional shell structures (Huang et al., 2013).

One important issue is that if composite action is to be achieved, in conditions other than pure membrane stress, shear must be transmitted across the interface between the steel and the concrete. For plain steel, the bond strength in tension (peeling) and shear is essentially zero (friction only) as it often disbands during concrete curing. Much attention has been given to the design of shear connectors (Johnson, 2004; Yan et al., 2014).

Bond improvement without shear connectors extending throughout the concrete thickness has also been studied (Aboobucker et al., 2009; Marshall et al., 2010; 2014). Surface bond strength can be increased to a useful fraction of the bulk strength of the concrete, e.g. with mini-studs (Thang, 2014).

Johnson (2004) points out that…

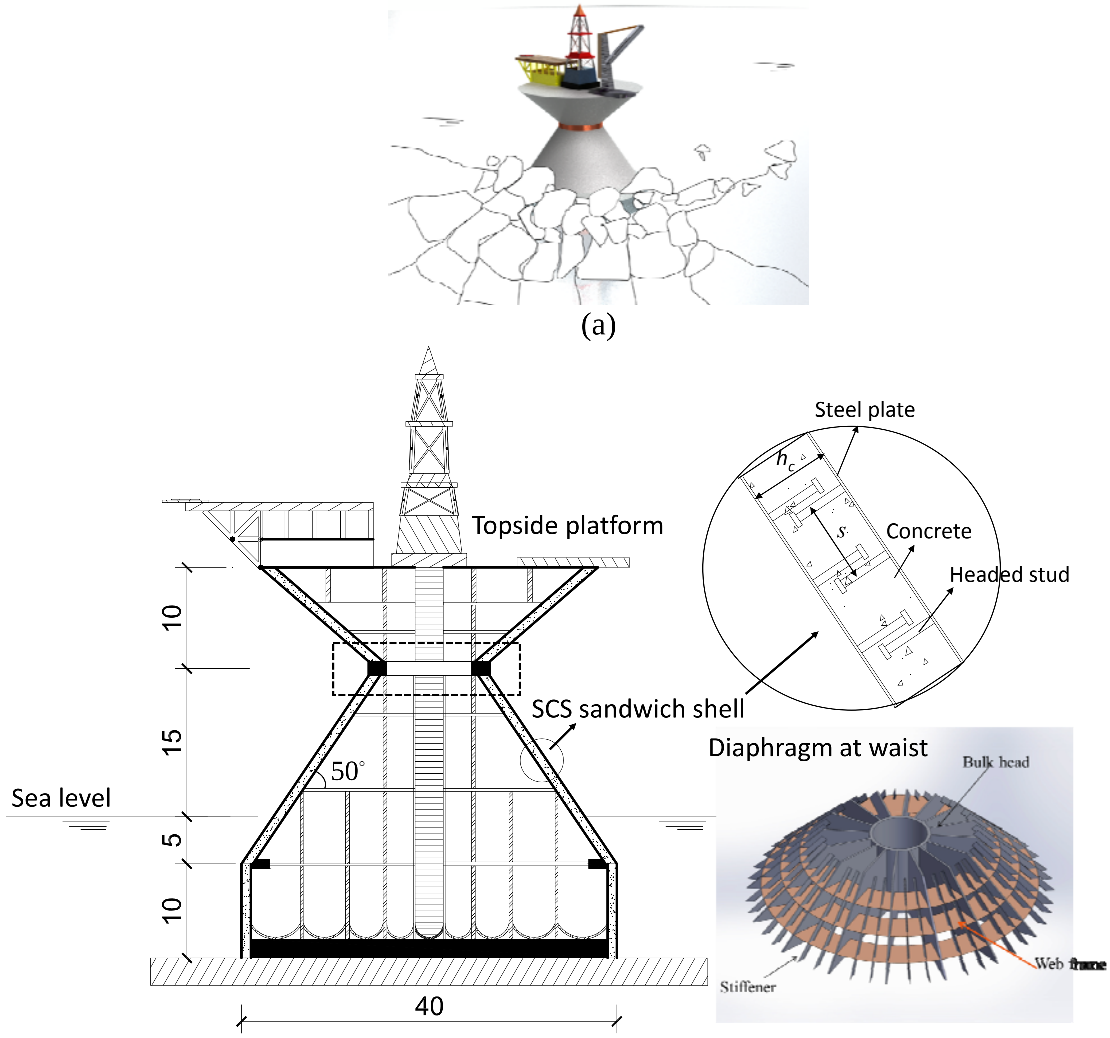
> 'No income is received from money invested in the construction of a multi-storey building …until the building is occupied. …. The construction time is strongly influenced by the time taken to construct a typical floor of the building, and here structural steel has an advantage over in-situ concrete. Even more time can be saved if the floor slabs are cast on permanent steel formwork that acts first as a working platform, and then as bottom reinforcement for the slab'

…which highlights the possibility of using steel both as formwork and as reinforcement. That concept has been considered for shell roofs (Teng et al., 2005).

DESIGN CONCEPT OF ARCTIC PLATFORM

Bringing these ideas together suggests the structure illustrated schematically in Figure 3. A composite cone is made up of an outer steel cone, a concrete infill, and an inner steel cone, with shear connectors on the inner faces. The concept is to build the steel structure empty of concrete, to launch and tow the structure to site, and then to ballast it to the seabed and fill the shell with heavy-weight concrete. Additional concrete or sand would increase the weight further. (The dimension are of course exploratory, and this is far from an optimised detailed design. The steel-concrete-steel composite shell is composed of an outer and an inner steel shell, each made from 25.4 mm (1 inch) plate, with a 0.942 m space later filled with concrete. The bottom and horizontal floor diaphragm at the waist can be either stiffened plate or pre-cast composite. Allowing an additional 100% for stiffeners and shear connectors, the weight empty of concrete up to the level of the base of the topsides is 3200 tonnes. In that state, the structure is not too heavy to be moved and launched. With that weight and otherwise empty, it would float with a draft of 2.5 m, but it would almost certainly need additional ballast to be stable. If required, ballasting the bottom cylindrical section to 1 m depth with 2500 kg/m^3 sand would double the draft and cut the KG dimension in half, while preserving the robust water plane.

The concept was proposed in an earlier paper (Marshall et al., 2012), which included the results of tests on steel-concrete-steel cylindrical barrel vaults under concentrated loads. The research has now been extended by further tests on segments of cylindrical shells. The scheme is indicated in Figure 4 below. There are two curved steel plates, to which are attached overlapping steel stud shear connects. The space between the plates is filled with concrete. The test shells carried end plates, which rest on foundations that prevent outward movement. The tests explored the effect of changing the ratio between the span *L* and the rise *r*, and of changing the stud spacing and the compressive strength of the concrete. Table 1 lists the parameters. In most of the tests the load was applied through a pad at the top of the arch, but in a few the load was eccentric.



(a)

(b)

Figure 3. Schematic of Arctic platform (dimensions in m).

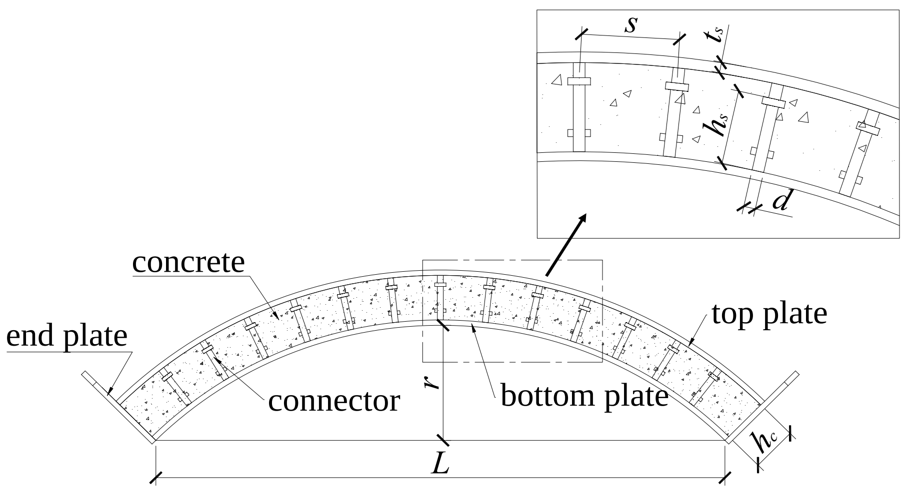


Figure 4. Typical test specimen for curved SCS sandwich panel.

Table 1. Test parameters.

Specimen	t_s (mm)	h_c (mm)	L (mm)	W (mm)	L/h_c ratio	r/L	s/t_s	$d \times h_s @ s$ (mm)	f_{ck} (MPa)	f_y (MPa)
FSB-01	4	100	1450	300	14.5	0 (flat)	25	13×75@110	58.3	304
CSB-02	4	180	1179	300	6.55	0.21	25	13×150@110	58.3	304
CSB-03	4	100	1250	300	12.5	0.21	25	13×75@110	58.3	304
CSB-04	8	100	1250	300	12.5	0.21	12.5	13×75@110	41.0	304
CSB-05	12	100	1250	300	12.5	0.21	8.33	13×75@110	58.3	304
CSB-06	4	80	1250	300	15.6	0.21	25	13×50@110	57.4	304
CSB-07	4	100	1250	300	12.5	0.21	50	13×75@220	57.4	304
CSB-08	4	100	1250	300	12.5	0.5	25	13×75@110	57.4	304
CSB-09	4	100	1250	300	12.5	0.21	25	13x75@110	57.4	304
CSB-10	4	100	1250	300	12.5	0.21	25	13×75@110	57.4	304

"FSB" refers to the flat sandwich beam specimen; "CSB" denotes the curved sandwich beam specimen; t_s= steel plate thickness; h_c =thickness of concrete core; L=clear span of sandwich beam; W= width of sandwich beam; s= stud spacing; d= diameter of headed shear stud; h_s =height of headed shear stud; f_{ck} = compressive strength of cylinder; f_y=yield strength of steel.

Figure 5 plots the applied force against the displacement under the point at which the load is applied, for r/L (rise/span) ratios of 0.5, 0.21 and 0 (flat); r/L 0.5 is a semi-circular arch. It can be seen that the arch effect is substantial, but it needs to be remembered that these arches are quite narrow and that a complete ring would not be constrained by supports.

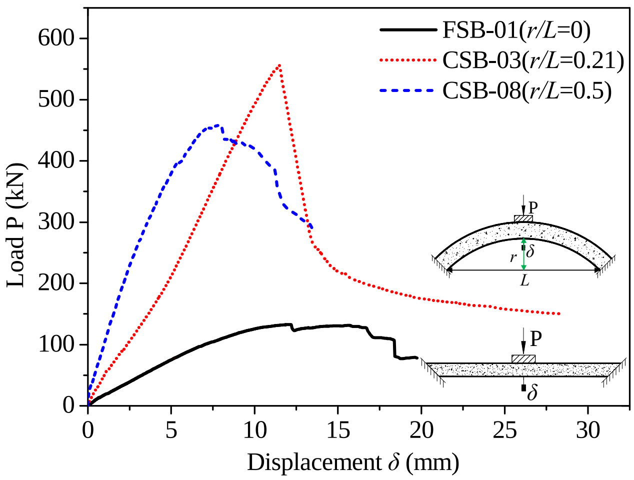


Figure 5. Measured force/displacement relationship.

Finite-element analysis using ABAQUS has been conducted, and results agree well with the experiments (Huang et al., 2013; 2014), as shown in Figure 6.

The results demonstrate the strength of a steel-concrete-steel sandwich composite panel, but the structural response of a complete three-dimensional composite cone still needs to be analysed. Properties of steel, concrete, and bond interface, for which ABAQUS match the tests could be used for further analysis and design (Thang, 2014).

Table 2. Test results

Specimen	Steel contribution ratio (A_sf_y/A_cf_c)	Plate slenderness (s/t)	Initial Stiffness (N/mm)	Loading type	Failure load (kN)	Failure mode
FSB-01	0.41	27.5	14122	Central patch load	133	Flexural
CSB-02	0.23	27.5	294974		1101	Shear-compression
CSB-03	0.41	27.5	47645		556	
CSB-04	0.81	13.8	51218		452	Shear-tension
CSB-05	1.22	9.2	57022		800	
CSB-06	0.51	27.5	29691		239	
CSB-07	0.41	55.0	31793		310	
CSB-08	0.41	27.5	76181		458	
CSB-09	0.41	27.5	18983	Central point load	218	
CSB-10	0.41	27.5	41797	Asymmetric patch load	416	

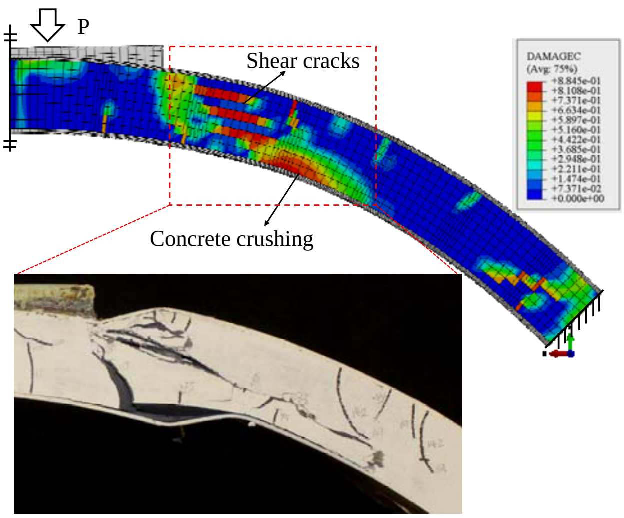


Figure 6. Failure mode comparison between test and FE analysis. (Huang et al., 2013; 2014)

FABRICATION AND TOW

Steel fabrication is best carried out in the south, where costs are much less, well-found construction yards are already available, and competition between yards can reduce cost. Fabrication can continue all year round in locations such as Seattle, Vancouver, Pusan, Vladivostok and Sapporo for later deployment in the western North American Arctic. Even Singapore has been considered, where heavy lift fast transport would be used.

The concept is to fabricate the platform in the south empty of concrete, but with the steel cones complete (including the shear connectors). The platform is then light enough to float, and can be launched and ballasted so that it floats upright. It will then wet be towed to the Arctic, at the time of year when there is no sea ice close to shore (August and September) and the likelihood of severe storms is least. If the platform is destined for shallow water, as the first applications almost certainly will be, its ballasted draft upright will be small enough for it to traverse the Bering Strait (30 m) and through one of the passes between the Aleutian Islands. If its draft is too great for that option, it can if necessary be ballasted so that it floats on its side, like a SPAR, and uprighted later. Navigation will be made easier by increased use of the Northern Sea Route as a result of climate change. There are precedents for towing circular vessels like the drilling vessel *Kulluk*, and there is no inherent difficulty.

A cone has straight generators, and therefore its surface is developable and has zero Gaussian curvature. It can be fabricated from segments formed from a flat plate by inextensional bending. Structurally, it might be preferable to use a surface with positive Gaussian curvature, as is done for domes and parts of the bows of ship, but in this instance it would complicate fabrication.

Shear connectors can be welded to each flat plate after roll forming but before it is assembled to make a panel of the cone, which facilitates the use of automatic welding. That applies whether the connectors are simple studs or J-hooks (Liew and Sohel, 2009). In the case of J-hooks, the hooks on the inner cones can be interlaced with those on the outer cone if one set are L-hooks rather than J-hooks.

Novel shear connectors have been proposed by Sohel et al. (2012) for the Steel–Concrete–Steel composite structures to enhance the interfacial bond between the face plate and the internal core as shown in Figure 7. These new types of connectors are (a) Angle-Steel bar-Angle (ASA); (b) Angle-T channel(AT); (c) Angle-Steel hoop-Angle (AHA); (d) Angle-C channel-Angle (ACA); (e) U connector-Steel bar-U connector (USU); (f) Angle-I beam-Angle (AIA); (g) Angle–Angle (AA); (h) Root connector (RC); (i) U connector-Steel Cable-U connector (UCU).

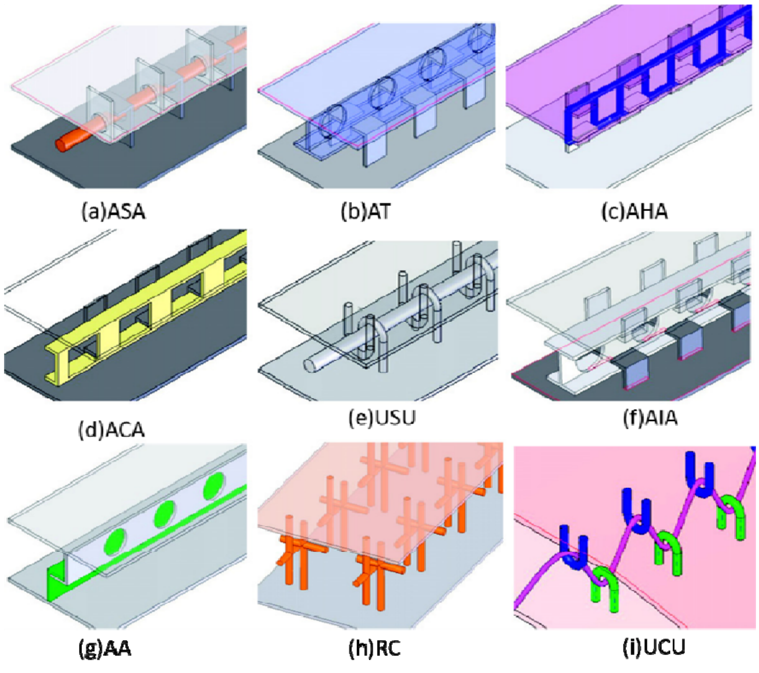


Figure 7. Proposed mechanical connectors used in steel-concrete-steel sandwich panel.

The angle connectors or the 'U' shape connectors are welded to the exterior steel plates to provide interface slipping resistance. The inserted steel bar (used in 'ASA' and 'USU'), steel hoops (used in 'AHA'), C channel (used in 'ACA'), 'I' beam (used in 'AIA') and the steel cables (used in 'UCU'), all serve the same function which is to link the two face steel plates preventing them from tensile separation and to provide bond enhancement between the concrete core and face plates. These connectors have their own merits in term of ease of installation and ability to withstand extreme loads without loss of structural integrity.

The cable and U-shaped connectors, as shown in Figure 7(i), require the least steel consumption and they are feasible to install in a slim sandwich panel. Here the cable would be threaded through the hoops, using a stinger traveling along a straight-line generator, with the U-shaped connectors temporarily in an overlapped position. Remote-controlled jacks would then be used to spread the plates into their final position and deform the cables. By preventing further separation, the cables would resist hydrostatic pressure during the concrete pour, and would enable diagonal compression in the concrete after curing.

INSTALLATION

Once arrived on location, the platform can be ballasted down until it lands on the seabed, and then given enough additional weight to stabilise it against currents and waves. Filling the space between the outer and inner shells with concrete gives the platform enough weight to stabilise the platform against ice forces.

CONCLUSION

A steel-concrete-steel platform can be constructed by fabricating two concentric steel shells, cylindrical at the bottom and conical towards the top. The shells are constructed onshore in the south, where they benefit from lower costs, existing construction yards, and the ability to construct all year round. The platform is buoyant, and can be towed to site. Once arrived, it can be ballasted down until it grounds on the seabed, and the space between the two shells is then filled with ultra-lightweight high strength cement composite grout. This will benefit the transportation and installation of pre-filled structures in the Arctic region. Novel connectors have been proposed to improve the composite action between the steel face plate and the cement grout. These development works are necessary to form a robust and safe structure which is strong enough to resist ice forces.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support by the Maritime and Port Authority of Singapore (MPA), American Bureau of Shipping (ABS) and National University of Singapore (NUS) under project grant R-302-501-002-490. The recent work in Texas was funded by Moonshine Hill Proprietary.

REFERENCES

Aboobucker M.A.M., Wang T.Y., Liew J.Y.R., 2009. ‘An experimental investigation on shear bond strength between steel and fresh cast concrete using epoxy’. *The IES Journal Part A, Civil & Structural Engineering*, Singapore.

Beltaos, S., 1995. *River Ice jams*. Water Resources Publications.

Dempsey, J.P., Palmer, A.C. and Sodhi, D.S., 2001. ‘High pressure zone formation during compressive ice failure’, *Engineering Fracture Mechanics*, vol.68, pp.1961-1974.

Eurocode 4: Design of composite steel and concrete structures, EN1994-1-1.

Huang Z.Y., Liew, J.Y.R., Yan J.B. and Wang J.Y., 2013. ‘Finite element analysis of curved lightweight steel-concrete-steel sandwich panel subjected to lateral loads’, *Proceeding of Advances in Structural Engineering and Mechanics* (ASEM13), Steel and Composite Structures (ICSCS13), pp.2583-2597, Jeju, Korea.

Huang Z.Y., Liew, J.Y.R., Yan J.B. and Wang J.Y., 2014. ‘Static behaviour of curved ultra-lightweight steel-concrete-steel sandwich system subjected to lateral loads’, *The 7th European conference on steel and composite structures*, September 10-12, 2014, Napoli, Ital.
Johnson, R.P., 2004. *Composite structures of steel and concrete*. Blackwell Scientific.
Johnson, R.P. and Anderson, D., 1993. *Designers’ Handbook to Eurocode 4*. Thomas Telford.
Liew, J.Y.R. and Lee, S.C., 2012. ‘Advances in steel concrete composite and hybrid structures’, *Proceedings of the 10th International Conference*. Research Publishing.
Liew, J.Y.R. and Sohel, K.M.A., 2009. ‘Lightweight steel–concrete–steel sandwich system with J-hook connectors’. *Engineering Structures*; vol.31, no.5, pp.1166–78.
Løset, S, Shkhinek, K.N, Gudmestad, O.T. and Høyland, K.V., 2006. *Actions from ice of Arctic offshore and coastal structures*. Lan’, Moscow.
Marshall P.W., Palmer A.C., Liew J.Y.R., and Thein M.K.W., 2010. ‘Bond enhancement for sandwich shell ice wall’, *International Conference and Exhibition on Performance of Ships and Structures in Ice*, ICETECH 2010, Anchorage Alaska.
Marshall, P., Sohel, K., Liew, R.J., Yan, M., Palmer, A.C. and Choo, Y.S., 2012. ‘Development of SCS composite shell for Arctic caissons’, *Proceedings, Arctic Technology Conference*, Houston, paper OTC23818.
Marshall P., Thang V., Brake N., and Corder P., 2014. ‘Bond enhancement in curved sandwich shells’, *International Conference and Exhibition on Performance of Ships and Structures in Ice*, ICETECH 2014, Banff, Canada.
Metge, M. and Tucker, J.R., 1990. *Multifaceted cone tests: Year two: 1989-1990*. Esso Resources Report ERCL.RS.90.11. Part of Joint Industry/Government Project.
Palmer, A.C. and Croasdale, K.R., 2012. *Arctic offshore engineering*. World Scientific.
Raamnath M, 1991. *Nonlinear finite element analysis of the composite ice wall*. MS Thesis, Lamar University, Texas.
Sohel, K.M.A. Liew, J.Y.R, Yan J.B., Zhang, M.H., Chia, KS., 2012. ‘Behaviour of Steel–Concrete–Steel sandwich structures with lightweight cement composite and novel shear connectors’, *Composite Structures*, vol.94, no.12, pp.3500-3509.
Teng, J.G., Wong, H.T. Wang, Z.C. and Dong, S.L., 2005. ‘Steel-concrete composite shell roofs: structural concept and feasibility’. *Advances in Structural Engineering*, vol.8, no.3, pp.287-308.
Tian, H. and Palmer, A.C., 2013. ‘Reducing the ice forces on jack-up legs’, *Proceedings, 22nd IAHR International Symposium on Ice*, Singapore.
Vul Thang, 2014. *Studded Bond Enhancement for S-C-S Sandwich Shells*. MS Thesis, Lamar University, Texas.
Wang J.Y., Chia, K.S., Liew J.Y.R. and Zhang M.H., 2013. ‘Flexural performance of fiber-reinforced ultra lightweight cement composite with low fiber content’, *Cement and Concrete Composites*, vol.43, pp.39-47.
Yan, J.B., Liew, J.Y.R., Sohel, K.M.A. and Zhang, M.H., 2014. ‘Push-out tests on J-hook connectors in steel-concrete-steel sandwich structure’. *Materials and Structures*, vol.47, no.10, pp.1693-1714.