Steel-concrete-steel sandwich composite structures-recent innovations

J.Y. Richard Liew, Jia-Bao Yan, Zhen-Yu Huang

1. Introduction

Steel-concrete-steel (SCS) sandwich composite structures consist of two steel face plates in filled with lightweight cement composite material has been developed. This paper reviews the recent innovations of SCS sandwich structures subject to blast, impact, fatigue, and static loads. Novel J-hook connectors, high strength steel plates and new lightweight cement composite materials have been considered for the development of the SCS sandwich products to improve their strength-to-weight performance. Extensive tests have been conducted to investigate the effectiveness of J-hook connectors to achieve better composite action to resist flexural, shear, impact, blast and fatigue loads. Flat and curved SCS sandwich plates under patch loading are also investigated. The experimental results are essential to understand the structural behaviour of the SCS sandwich structures and to provide data for the development of analytical models for design implementation. Design equations have been proposed to predict the shear and tensile resistances of J-hook connectors and to determine the flexural, shear, impact, blast and fatigue resistances of SCS sandwich beam. The punching shear resistance of sandwich shells and compression resistance of sandwich walls are also investigated. The accuracy of the design equations are validated by the test data and finite element analysis results.

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1. Introduction

Steel-concrete-steel (SCS) sandwich composite structures consist of two steel face plates and a sandwiched concrete core which are bonded together by mechanical connectors to form an integral unit to resist external loads. In the early days, SCS sandwich structures were developed for infrastructures and tunnels to resist loading due to accidental impact and vehicular loading. With the recent investigation on their performance under static impact, fatigue and blast load [1–6], the applications of SCS sandwich structures have been extended to offshore decking, protective structures, oil storage containers and ice-resistant walls [7, 8]. Steel-concrete-steel sandwich structures have also been proposed for structural walls in nuclear facilities [9,10].

Different types of SCS sandwich composite structures have been developed by using different bonding techniques at the steel-concrete interface. Cohesive materials, such as epoxy, were used in the SCS sandwich composite structures [11]. Compared with the mechanical shear connectors, brittle bond failure tended to take place at the steel-concrete interface due to the imperfection of the bonding material which would compromise the structural integrity of the SCS sandwich structure. A double skin structure with overlapped stud connectors to bond the concrete and steel plates was initially proposed for tunnel liner [12]. However, the bond between the steel plates and concrete core depends greatly on the spacing and the lapped length of the connectors. Once the concrete core failed under the action of extreme loads, the steel plates and the concrete core may separate and affect the structural integrity of the sandwich plate. One novel way to improve the structural integrity of SCS sandwich structure is to connect the two steel face plates with straight steel bar connectors using friction welding [13]. However, the installation of the connectors using the friction weld apparatus limits the thickness of SCS sandwich structure within the range of 200 to 700 mm. Angle-section connectors were also proposed for SCS sandwich constructions in Japan [14]. Owing to the shallow embedment of the angle-section connectors, bond failure tended to occur at the service load level unless additional stiffener plates were provided. To develop a slim deck for offshore platforms, J-hook connectors were developed by Liew et al. [1] as shown in Fig. 1(a). Experimental studies showed that SCS sandwich structures with J-hook connectors exhibited excellent performances under impact, blast, and fatigue loadings [2,3]. This type of structure is suitable for applications in shear walls, protective structure, ship hulls of cargo tank, bridge/offshore decks, and ice-resistant wall in Arctic offshore platform as shown in Fig. 1(b–e).

To reduce the self-weight of the SCS sandwich structure, lightweight concrete (LWC) has been proposed by the authors [13]. LWC with different strength to weight ratio offers more choices to design SCS sandwich structures to achieve higher strength-to-weight ratio. LWC with a density of 1450 kg/m³ and compressive strength of 30 MPa has been
Fig. 1. Applications of the SCS sandwich structure.
used by the authors in their earlier work [1,3]. More recently, a new type of ultra-lightweight cement composite (ULCC) material with density ranging from 980 to 1450 kg/m$^3$ and compressive strength up to 60 MPa has been developed [15,16]. The development of lightweight cement composite material has led to further research on sandwich composite structures.

In this paper, recent innovations on SCS sandwich structures are summarized. These innovations include the development of new J-shaped shear connectors.

Fig. 2. Novel shear connectors for SCS sandwich structure (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) U connector-Steel Cable-U connector (UCU); (i) Root connector (RC); (j) Through bolt connectors; (k) Overlapped headed stud connectors; (l) J-hook connectors.

Fig. 3. Stress-strain curves of the normal mild steel (NMS) and high strength steel (HSS) under different temperatures.

Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Material property</th>
<th>ULCC$^{*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Density after de-mould</td>
<td>1450 kg/m$^3$</td>
</tr>
<tr>
<td>2</td>
<td>Compressive strength, cube $f_{cu}$</td>
<td>64.0 MPa</td>
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<tr>
<td>3</td>
<td>Compressive strength cylinder $f_{cu}$</td>
<td>64.6 MPa</td>
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<td>4</td>
<td>Ratio $f_{cu}/f_{ck}$</td>
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<tr>
<td>5</td>
<td>Splitting tensile strength</td>
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<td>6</td>
<td>Flexural strength</td>
<td>6.7 MPa</td>
</tr>
<tr>
<td>7</td>
<td>Static modulus of elasticity</td>
<td>16 GPa</td>
</tr>
<tr>
<td>8</td>
<td>Static Poisson’s ratio</td>
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</tr>
</tbody>
</table>

ULCC$^{*}$ = Ultra Lightweight Cement Composite.
hook connectors and new ultra-lightweight cement composite core materials for SCS sandwich structures. Experimental and numerical investigations were carried out to determine the resistances of the shear connectors, SCS sandwich beams and SCS plates and shells. Their impact, fatigue, blast and static load performance were also studied. Finally, analytical formulae were developed to predict the design resistance of SCS structures under axial compression, bending moment, shear and punching loads.

2. Novel connectors for steel-concrete-steel sandwich construction

Steel-concrete-steel (SCS) sandwich structures consist of three major components: two external steel face plates, concrete or cement composite core and connectors. Among them, the connectors act essentially on providing longitudinal and transverse shear resistance, and offering pull-out resistance to prevent separation between steel plates and concrete core. SCS sandwich structures with different types of shear connectors have been developed by Yan et al. [6] and Sohel et al. [17] as shown in Fig. 2. 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) U connector-Steel Cable-U connector (UCU), (i) Root connector (RC), (j) Through connectors, (k) Overlapped headed stud connectors, and (l) J-hook connectors.

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’), ‘T’ 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 terms of ease of installation and ability to withstand extreme loads without the loss of structural integrity.

The cable and U-shaped connectors, as shown in Fig. 2(h), require the least steel consumption and they are feasible to install in a thin sandwich panel. Here the cable would be threaded through the U-shaped connectors which were pre-welded to the top and bottom steel plates in an overlapped position. Jacks would then be used to spread the plates into their final position and deform the cables. Concrete is pumped in between the two plates and the cables would resist the tensile separation of the two plates during the casting of the concrete.

Compared with the overlapped headed shear studs that were commonly used in the steel-concrete composite structure, the double J-hook connectors, as shown in Fig. 2(l), have the advantages of fast installation, low cost, and equivalent structural performances. The main advantage of the J-hook over the overlapped headed studs is that the tensile resistance of the overlapped headed studs greatly depends on the confinement of concrete while the double interlocked J-hook connectors could provide certain degree of tensile resistance without the confinement of concrete. This advantage becomes more apparent when significant cracks developed in the concrete core under the action of extreme loads. Therefore, considering these advantages, the J-hook connectors were chosen for further research of SCS sandwich plates under extreme loads.

3. Use of high strength steel and lightweight concrete materials

In steel-concrete-steel sandwich composite structures, the steel and concrete are the main materials that are used to resist tension and compression forces, respectively. Recently, high strength steel (HSS) with yield strength over 700 MPa was available for the steel-concrete composite structure [18–21]. Yan et al. [18,19] studied the mechanical properties of the mild steel and high strength steel under ambient and low temperatures (−60 °C) for the applications of the SCS sandwich structure in the
Arctic region. Fig. 3 compares the engineering stress-strain curves of the normal mild steel and high strength steel under tension. The steel strengths in terms of proof load and ultimate tensile strength increase as the temperature is lower from room temperature of 30 °C to −60 °C although the percentage increase is not very significant (<10%).

Different types of concrete mixtures such as normal weight concrete (NWC), lightweight concrete (LWC), and ultra-lightweight cement composite (ULCC) could be used in the SCS sandwich composite structure. The ULCC was a special type of fiber-reinforced cement composite material with a density of 1450 kg/m³ and 28-day compressive strength of about 60 MPa. Detailed properties and description of such materials was reported [15, 16]. The ULCC has a high specific strength (strength to density ratio) above 40 compared to 25 kPa/(kg/m³) for normal concrete with similar strength. Besides a 40% weight reduction from normal concrete, the ULCC exhibits ultimate tensile and flexural strengths comparable with normal concrete of similar strength. Due to its porous matrix, the ULCC has lower modulus of elasticity which is approximately 50% that of normal weight concrete. Table 1 shows the material properties of the ULCC at 28-day. Basic components of the ULCC were ordinary Portland cement, silica fume, fine aggregate named cenosphere with a diameter of ranging 100 to 300 μm and 6 mm long polyvinyl alcohol (PVA) fiber. Short PVA fibers (0.5% by volume) were used in ULCC to reduce the shrinkage and drying effect. To improve the workability and performance of such material, super plasticiser and shrinkage reducing admixture were added to achieve a desired flow of 210–240 mm. Such high flow was required so that the cement composite can fill the thin void between the two steel plates and flow around the closely spaced shear connectors. Besides the weight saving, the absence of the coarse aggregates leads to a highly workable material suitable for pumping and grouting in construction.

The mechanical properties of the normal weight concrete, lightweight concrete, and ULCC under ambient and Arctic low temperatures have been reported by Yan et al. [7]. These mechanical properties may be used in the analysis of the structural behaviour of the lightweight SCS sandwich structure.

4. Comparisons of SCS sandwich structure with conventional stiffened steel plate structure

A stiffened steel plate (SSP) structure, as shown in Fig. 4(a), was widely used in the offshore deck and ship hulls. Compared with the stiffened steel plate structure, the proposed steel-concrete-steel (SCS) sandwich structure could offer the advantages of (1) elimination of the need of secondary beams as shown in Fig. 4(a) and (b), (2) reduction of welding and thus improvement of work productivity, (3) reduction of steel surface area and thus lowering the cost of corrosion protection, (4) improvement of acoustic and thermal insulation, (5) achieving a simple structural form that includes easy of fabrication, flexible services layout, easy inspection and maintenance, and (6) improvement of the structural performance against impact, blast, and fatigue loads.

Table 2 illustrates the detailed conceptual comparisons that include steel consumption, overall weight, moment resistance of the cross section, and elastic stiffness between the steel plate structure and SCS sandwich plate. If all the properties for the steel plate structure were taken as unity, i.e., steel consumption, overall weight, moment resistance of the cross section, and elastic stiffness for the steel plate are equal to 1.0, the relative corresponding values for the SCS sandwich plate are given in Table 2. The comparisons show that if the steel consumption in SCS sandwich plate is maintained the same as that of the steel plate structure, i.e., the total thickness of the steel plate is kept the same as t, the SCS sandwich structure with concrete core thickness 15t would significantly increase the moment resistance and elastic flexural stiffness by 12 and 200 times, respectively. Meanwhile, the overall self-weight of the SCS plate is increased by 92% as compared to the steel plate. If the flexural
resistance and stiffness of the steel plate structure are to be maintained, then an equivalent SCS sandwich structure would require a plate thickness of $t/3$ and core thickness of $5/3t$ which reduces the steel consumption by 33% and the overall weight by 56%. The above comparisons confirm the advantages of the SCS sandwich structure over the traditional stiffened steel structure in terms of structural efficiency.

5. Mechanical connectors for SCS sandwich structure

Mechanical connectors play an important role in the structural performance of SCS sandwich structures. The shear and tensile resistances of the connectors needed to be established. Under flexural loading, the shear forces at the steel-concrete interface will be resisted by the connectors which bond the two face plates and the concrete core. When the SCS plate is subjected to transverse shear force, the mechanical connectors could behave as reinforcement bars to bridge the shear cracks in the concrete core, and their tensile resistance will contribute to the transverse shear resistance of the cross section. Moreover, the connectors also provide buckling restraint to the steel face plate under compression. Therefore, the shear and tensile resistances of the mechanical connectors need to be evaluated carefully.

5.1. Shear resistance of connectors

The design shear resistance of the headed shear studs can be calculated by Eurocode 4 [22]:

$$P_h = \min \left( 0.29\alpha d^2 \sqrt{\frac{f_{ck}E_{ck}}{s}}, 0.8\alpha_s \pi d^2/4 \right)/\gamma_v \quad (1a)$$

where $\alpha = 0.2(h_s/d + 1)$ for $3 \leq h_s/d \leq 4$, $\alpha = 1$ for $h_s/d > 4$; $h_s$ denotes the height of the headed shear stud; $f_{ck}$ is the compressive strength of concrete cylinder; $E_{ck}$ denotes elastic Young’s modulus of the concrete; $d$ is the connector diameter; $\gamma_v$ is the partial factor; $\sigma_u$ denotes the ultimate strength of the connector.

For the J-hook connectors, Yan et al. [23] proposed a formulae to calculate shear resistance as the following:

$$P_J = 0.855f_{ck}^{0.265}E_{ck}^{0.469}A_k \left( \frac{h_c}{d} \right)^{0.154}/\gamma_v \leq 0.8\alpha_s A_h/\gamma_v \quad (1b)$$

where $A_k$ is cross sectional area of connector, in mm$^2$; $h_c$ denotes the embedding depth of connector, in mm.

5.2. Tensile resistance of connectors

The tensile resistance for the mechanical connectors is governed by the smallest value of concrete breakout resistance $T_{cb}$, concrete pullout resistance $T_{pl}$, tensile fracture resistance of connector bar $T_s$, and punching shear resistance of the steel plate $T_{ps}$ [5,24].

For an SCS sandwich with overlapped headed shear stud (see Fig. 5), the tensile resistance can be determined by [5,24]

$$T_{ts} = \min \left\{ T_{cb} = 0.333\sqrt{f_{ck}nh_s^2(1 + d/h_s)}/\gamma_v, T_{pl} = 8A_{brg}f_{ck}/\gamma_v, T_s = A_s\sigma_u/\gamma_{M2}, T_{ps} = n_d\left( f_{ys}/\sqrt{3} \right)/\gamma_{M0} \right\} \quad (2)$$

where $h_s$ is height of connector; $A_{brg}$ is the bearing area of the head of stud; $\gamma_{M2}$ is partial factor for cross-section in tension to fracture [25]; $\gamma_{M0}$ is partial factor for resistance of cross-section [25].

For SCS sandwich structure with J-hook connectors, the pullout resistance in Eq. (2) needs to be modified as the following [24]

$$T_{pl} = 1.26f_{ck}e_cd + 0.116f_{ys}d^2 \quad (3)$$

where $e_d$ denotes the distance from the inner shaft of a J-hook to the outer tip of the J-, and $3d < e_d < 4.5d$.

5.3. Resistance of connector under combined shear and tension

Yan et al. [26] proposed the following formulae to predict the resistance of the J-hook under combined shear and tension based on calibration with numerical and test results:

(a) If applied shear force $P \leq 0.2P_u$, full tension resistance can be developed:

$$P \leq P_u \quad (4a)$$

![Fig. 7. Scatter of R ratio for different types of sandwich composite beams.](image-url)
(b) If applied tensile force $T \leq 0.2\phi T_u$, full shear resistance can be developed:

$$T \leq T_u$$  \hspace{1cm} (4b)

(c) If $V > 0.2\phi V_u$ and $N > 0.2\phi N_u$, then the following interaction formula may be used:

$$\left(\frac{P}{P_u}\right) + \left(\frac{T}{T_u}\right) \leq 1.2$$  \hspace{1cm} (4c)

where $P$ denotes the design shear force; $P_u$ is the design shear resistance from Eqs. (1a) and (1b); $T$ denotes the design tension force; $T_u$ is the design tension resistance of the connector from Eq. (2).

6. Flexural and shear behaviour

Three- or four-point bending tests on SCS sandwich beams have been carried out to investigate their structural performances under flexural and transverse shear forces by Liew and Sohel [1], and Yan et al. [5, 6]. Finite element analysis offers a useful means to investigate the structural behaviours of the steel-concrete composite structures compared to experimental studies which are often expensive to perform [27–29]. Numerical studies on SCS sandwich beams have been reported by
Based on these experimental and numerical studies, the design equations have been developed to predict the flexural and shear resistance of the SCS sandwich beams that are summarized herein.

6.1. Flexural resistance

Several assumptions were made for the calculation of the flexural resistance of the SCS sandwich composite beams as the following: (1) plane section remains plane; (2) contribution of tensile strength of concrete is ignored; (3) full plastic rectangular stress block can be developed in the concrete.\(^\text{[5,6]}\)

Based on plastic analysis of the cross section, the plastic stress blocks acting on a SCS section are shown in Fig. 6\(^\text{[5]}\).

The compressive strength of the concrete can be calculated as\(^\text{[30]}\)

\[
N_{cc} = \eta f_{ck} x B / \gamma_c \quad (5)
\]

where \(B\) is the width of the beam; \(x\) is the depth of the neutral axis position. \(\lambda = 0.8\) for \(f_{ck} \leq 50\) MPa, \(\lambda = 0.8 - (f_{ck} - 50) / 400\) for \(50 < f_{ck} \leq 90\) MPa; \(\gamma_c\) is the partial factor for concrete.

The maximum force developed in the steel plate is governed by either the yield resistance of the steel plate or the shear resistance of the connectors in the compressive or tension zone of the concrete, i.e.

\[
N_{cs} = \min (n_c P_s f_{ysc} A_{sc} / \gamma_{Mo}) \quad (6)
\]

where \(n_c\) is the number of the shear connectors in the compressive zone; \(P_s\) is the shear resistance of the connectors calculated by Eqs. (1a) and (1b); \(f_{ysc}\) and \(A_{sc}\) are yield strength and area of the steel plate in compression, respectively; \(\gamma_{Mo}\) is the partial factor.

Following the same principle, the tension force in the tension steel plate could also be calculated by

\[
N_{ts} = \min (n_t P_s f_{yst} A_{st} / \gamma_{Mo}) \quad (7)
\]

where \(n_t\) is the number of the shear connectors attached to the tension steel plate; \(f_{yst}\) and \(A_{st}\) are yield strength and area of the steel plate under tension, respectively.

Based on the equilibrium of tension and compression force acting on the section, the depth of compression zone of concrete can be calculated by

\[
N_{cc} + N_{cs} = N_{ts} \quad (8a)
\]

\[
x = \frac{(N_{ts} - N_{cs})}{\eta f_{ck} B x / \gamma_c} \quad (8b)
\]

The plastic moment resistance is obtained by taking moments about the center of the compression steel plate as

\[
M_{rd} = N_{ts} (h_c + t_c/2 + t_t/2) + N_{cc} (\lambda x/2) \quad (9a)
\]

When the top and bottom steel plates are of equal thickness and strength i.e. \(t_c = t_t\), the moment capacity of the section is reached when the neutral axis moves near the lower surface of the compression steel plate.

Fig. 10. (a) Drop weight impact test machine (b) test specimen (inter-locking J-hook connectors).
steel plate (i.e., $x \approx 0$) until the top steel plate is yielded. Therefore, the plastic moment resistance of the sandwich section may be obtained from Eqs. (7)–(9a) as

$$M_{rd} = N_{ts}(h_c + t_c/2 + t_s/2)$$

(9b)

6.2. Transverse shear resistance

Transverse shear resistance of the SCS sandwich composite beam consists of contributions from the concrete core and shear resistance provided by the connectors as shown in Fig. 5 [5,6]:

$$V_{rd} = V_c + V_s$$

(10)

where $V_c$ is the shear resistance of concrete and $V_s$ is the shear resistance provided by mechanical connectors. $V_c$ can be calculated as [30]

$$V_c = \left[ C_{rd}^0 \eta_1 (100\rho_1 f_{ck})^{1/3} \right] Bh_e$$

(11)

where $C_{rd}^0$ equals 0.18/$\gamma_c$ for normal weight concrete and equals 0.15/$\gamma_c$ for lightweight concrete; $k = 1 + \sqrt{200/h_c} \leq 2.0$ and $h_c$ is height of concrete core in mm; $\eta_1 = 0.40 + 0.60u/2200$ is the tensile strength reduction coefficient, and $u$ is density of the lightweight concrete in kg/m$^3$; $\rho_1 = t_c/[h_c + (t_s + t_c)/2] \leq 0.02$; $t_c$ is the thickness of the steel plate under compression; $t_s$ is the thickness of the steel plate under tension; $B$ is the width of the beam; $h_e$ is the effective height of the beam.

Considering the thickness of the steel plate, the effective depth of the SCS beam needs to be modified as [5,6]

$$h_e = h_c + t_c E_s/E_c$$

(12)

where $h_c$ is the height of the concrete core; $t_c$ is the thickness of the compression steel face plate; $E_s$ is the elastic Young’s modulus of steel face plate; $E_c$ is the elastic secant modulus of concrete.

The shear resistance provided by the presence of headed stud connectors is calculated by:

$$V_s = n_0 T$$

(13)

where $T = T_{hs}$ is the tensile resistance of a pair of overlapped headed studs embedded in concrete core by Eq. (2).
6.3. Resistance under combined bending moment and shear force

The design equation proposed by Roberts et al. [31] may be used to check the strength of SCS beam section subjected to combined action of bending and shear:

\[
\frac{V}{V_{rd}} + \frac{M}{M_{rd}} \leq R^2 \leq 1
\]  

where \(V_{rd}\) and \(M_{rd}\) are the shear and bending resistances of the beam section, respectively; \(V\) and \(M\) are the shear force and bending moment acted on the beam section; \(R\) is the index of the strength which is used to check the load capacity of the sandwich composite beam.

6.4. Validation

There exist 78 tests on SCS sandwich beams with different types of connectors, which were reported by Yan et al. [5,6], Roberts et al. [31], Oduyemi and Wright [32], Foundoukos [33], and McKinley and Boswell [34], and these were used to check that accuracy of the proposed models. The \(R\) ratios which are computed for the test specimens from Eq. (14) are plotted in Fig. 7. \(R\) greater than one indicates that the predicted strength of the SCS sandwich specimen which were governed by the failure of the connectors are higher than the maximum strength.
obtained from the tests. Fig. 7 shows that the average $R$ ratio for 78 beam tests is 1.29 with a coefficient of variation (COV) of 0.16. The proposed equations give conservative and reasonable predictions on the ultimate strength of the SCS sandwich beam structure.

7. Fatigue behaviour

Dai and Liew [3] performed tests on eight SCS sandwich beams with partial composite connection subjected to fatigue loads. The test specimens consisted of fiber-reinforced lightweight concrete core (density = 1450 kg/m$^3$) sandwiched in between two face plates which were interlocked by J-hook connectors that were capable of providing composite action between the steel plates and the concrete core. Fig. 8 shows the test set-up, loading scheme and failure modes of SCS sandwich beams subjected to fatigue loading.

The failure mode of the test specimens was due to fatigue failure of the steel concrete interface bond which was controlled by the number of shear connectors. The fatigue test results showed that the SCS sandwich beam with J-hook connectors were capable of interlocking the face plates providing composite action between steel and concrete when it was subjected to transverse load fluctuating within an applied load range $\Delta P$, as shown in Fig. 8.

The fatigue life of the SCS sandwich structure was affected by both the fatigue load range $\Delta P$ and maximum applied load $P_{\text{max}}$. Both the maximum applied stress and stress range affected the fatigue behaviour of the SCS sandwich system as reflected by the permanent deformation, hysteretic response, stiffness and energy absorption capacity. Fatigue life reduces when the load range $\Delta P$ or maximum applied load $P_{\text{max}}$ increases.

Based on these experimental observations, a three-parameter fatigue design equation is proposed based on calibration with test data as follow:

$$\log_{10}(N_f) = 5.09 - 4.33 \times \log_{10}\left(\frac{\Delta \tau}{\tau_u}\right) + 3.00 \times \log_{10}\left(1 - \frac{\Delta \tau}{\tau_u}\right)$$ (15)

where $N_f$ is the fatigue life, i.e. the number of cycles to failure; $\Delta \tau$ is the shear stress range; $\tau_u$ is the shear strength of the connector.

Fig. 9 shows the comparison of S-N curves obtained from the proposed equation (Eq. (15)), BS5400, EC4, Bi-steel S-N curve, JSSC and AASHTO approaches. The results show that the fatigue life predicted by the proposed equation is in good agreement with the experimental data.
by Eq. (15) for the J-hook connectors is as good as if not better than those of conventional headed stud connectors predicted by various codes. The fatigue shear strength of mechanical connectors at $1 \times 10^6$ load cycles is in the range of $100 \pm 20$ N/mm². Based on the same shear stress amplitude ($\Delta\tau$) a less conservative fatigue life ($N_f$) may be obtained from the proposed design equation.

The proposed SCS sandwich system with lightweight concrete core and J-hook connectors shows good performance under fatigue loading making it attractive for offshore and marine applications in which slim design and lightweight are of prime concerns.

8. Impact behaviour

The impact behaviour of the non-composite and full-composite SCS sandwich beams has been studied experimentally by Liew et al. [4] and Remennikov et al. [35]. Sohel and Liew [36] investigated the impact behaviour by carrying out 8 tests on SCS sandwich plates measuring $1200 \times 1200$ mm² (width x length) with varying parameters including different core thicknesses (80 and 100 mm) and face plate thicknesses (4, 6 and 8 mm). Special lightweight concrete of density 1450 kg/m³ and interlocking J-hook connectors have been developed for this purpose. The impact tests were conducted by an instrumented drop-weight impact test machine as shown in Fig. 10. A photodiode system, comprising two laser emitters and two photodiodes, was used to capture the incident velocity of the projectile. Both the projectile and the specimen were instrumented in order to capture the impact force and the response of the specimen. Local punching is the dominant failure mode due to low velocity impact by a large mass on the SCS sandwich plate (see Fig. 11a). When the projectile struck the slab, very high stress was developed at the point of impact. The high impact stress would cause local indentation on the face plate and crush the concrete core below the impact (see Fig. 11b). The impact stress waves travelled from the impact point to the edge supports and induced shear cracks in the concrete core. The slab gained momentum as the projectile travelled downward causing downward displacements which further induced more damage in the concrete core due to the formation of flexural cracks. The bottom steel plate experienced impact shock wave from the top and tended to move downward and separated from concrete core as shown in Fig. 12. The separation of the bottom plate could be prevented by the interlocking J-hook connectors which connected both the top and bottom steel plates. An addition of 1% steel fibres in the concrete core showed some beneficial effects in reducing the cracks and spalling of concrete core, which helped to reduce the overall deflection of the slab due to impact.

An elastic-plastic model was proposed to predict the force-indentation relationship of SCS sandwich slab subject to central impact force. Using the proposed force-indentation relations, an energy balance model was adopted to analyse the global behaviour and energy absorption capacity of SCS sandwich slabs. For a given impact energy and slab configuration, the central deflection of the SCS sandwich slab can be determined with reasonable accuracy using this energy balance model. The maximum central deflection is an important index for evaluating the damage levels of the SCS sandwich slabs subject to impact load provided the failure was not due to the projectile punching through the top plate.

9. Sandwich panels subject to blast load

An experimental programme was carried out to investigate the resistance of SCS sandwich panels subjected to blast loads. A total of six specimens were fabricated for three blast tests. Two specimens were tested in each blast load. The configuration and notations of the
specimens are illustrated in Fig. 13. Each specimen had a length of 1200 mm and width of 495 mm. The stiffened plate specimen SP was constructed as a cellular steel structure with 3 mm internal plate stiffeners welded to the 4 mm face plates. The core thicknesses of the steel-concrete-steel (SCS) sandwich specimens were 70 mm and the face plate thickness was 4 mm, 10 mm double J-hook connectors were used to connect the face plates to the internal concrete core.

Three different structural grade concrete materials were employed as the sandwich core: normal strength concrete (NSC), lightweight aggregate concrete (LWAC) and ultra-high strength concrete (HSC). As shown in Fig. 14, five 20 kg TNT (100 kg in total) military crater charges were arranged in an annular pattern and were placed at a standoff distance of 5 m from the specimens. The same arrangement and position of the charges were maintained in all the three blasts.

After the blast, the cellular stiffened plate panel (SP) experienced very large permanent deformation (>100 mm). The sandwich specimen (SCS), which was subjected to the same blast load, sustained relatively less deflection. The maximum permanent mid-span deformation was 27 mm. Considering the two specimens which were designed as the same face plate thickness, same stiffness, and same static flexural capacity, the difference is mainly attributed to the concrete core that added mass and rigidity of the structural system. This demonstrated the effectiveness of SCS sandwich composite compared with the stiffened plate panel in terms of maintaining structural integrity and residual capacity.

Numerical analyses were carried out using LS-DYNA for sandwich panels subjected to blast load. Only the effect of concrete core material was studied, which included the strength of concrete and mass of concrete core. These SCS panels were subjected to large impulsive load of 100 kg TNT detonated at 5 m. The general deformed shape at their respective peak displacements together with the history of the mid-span displacement of 3 panels with different types of concrete filled materials: high strength concrete (HSC), normal weight concrete (NWC)
and lightweight aggregate concrete (LWAC), are shown in Fig. 15. The SCS panel with HSC infill core deflected the least while the panel with LWAC core exhibited the largest deflection. The analyses showed that the density of the core material and the mass of the structural system play a major role in the blast performance of a sandwich panel.

Numerical studies were conducted on blast performance of flat and curved SCS sandwich panels subjected to large impulsive load 1000 kg TNT at 10 m. Fig. 16 shows the structural responses of flat and curved SCS sandwich panels. By comparison of the failure mode and mid-span displacement versus time histories, it was found that the flat panel experiences large flexural deformation (>80 mm) compared to the curved panel (<10 mm) in which compressive arch action played an essential role on improving the structural stiffness and deformation capacity. It is because the rise-to-span ratio of curved panel not only changes the load transfer path but also transforms the failure from flexural mode to compressive dominated mode. In this way, curved sandwich panel would be more efficient to resist the blast load, which can offer a better alternative for the design of protective structures.

10. Curved sandwich structure

The expanding demand for oil and gas drives the petroleum explorations in the Arctic region where large proportion of the world’s undiscovered oil and gas are stored [37]. Curved sandwich composite structure, consisting of two external steel curved shells with the annulus and sandwiched concrete core (see Fig. 1) has been proposed as the ice-resistant walls in the Arctic offshore platform which aims to be used in the region with the water depth of 10 to 100 m [38]. The curved sandwich structure uses the arching effect to resist lateral load and capable of spanning longer between supports.

10.1. Curved sandwich beams

The ultimate strength behaviour of the curved SCS sandwich beams has been experimentally and numerically investigated by Yan et al. [39-43]. Fig. 17 shows the details of these tested curved SCS sandwich beams. The test results showed that all these curved SCS sandwich beams failed in shear tension mode as shown in Fig. 18. Design equations have been developed to predict the transverse shear resistance of the curved SCS sandwich beam [38].

The shear resistance of the curved SCS sandwich beam, \( V_{CB} \) can be determined by [38]

\[
V_{CB} = V_c + V_{sf} + V_s
\]

where \( V_c \) denotes shear resistance of the concrete core; \( V_{sf} \) denotes shear resistance of the steel face plate; \( V_s \) denotes shear resistance of the headed studs.

The shear resistance of the concrete core can be determined as

\[
V_c = v_c B H_{ce}
\]

where \( v_c = u_{rd,c}/\gamma_c k (100 f_{ck})^{1/3} + k_1 \sigma_{cp} f_{ck} \) in MPa; \( u_{rd,c} = 0.18 \) for normal weight concrete; \( k_1 = 0.15 \) for lightweight concrete; \( k = 1 + \sqrt{200/h_c} \leq 2.0, h_c \) in mm; \( \rho = \sqrt{\rho_x \rho_y} \leq 0.02 \), \( \rho_x, \rho_y \) relate to bonded tension steel in x- and y- directions respectively; \( \sigma_{cp} = (\sigma_{cx} + \sigma_{cy})/2 \), \( \sigma_{cx}, \sigma_{cy} \) are the normal concrete stresses in the critical section in x- and y-direction (in MPa, positive in compression); \( B \) denotes width of the beam.
As shown in Fig. 19, owing to the rise of the arch, the actual depth of the curved SCS sandwich beam that was used to determine the shear resistance needs to be modified as the following [38]

\[ H_{\text{ce}} = (R + t_t + 2h_c) - \sqrt{(R + t_t + h_c)^2 - (b/2)^2} + (R + t_t)(1 - \cos \alpha) \] (18)

where, \(b\) is the width of the loading area; \(L_a\) denotes the length between two main shear cracks in the beam, and equals \(2R\sin \alpha\) as shown in Fig. 19; \(\alpha\) is the angle offset from the centreline to the bottom tip of the shear crack as shown in Fig. 19, which can be calculated as the following

\[ \alpha = \cos^{-1} \left( \frac{R + b\tan \theta/2 + h_c}{R} \cos \theta \right) \] (19)

The tests and previous studies [5,6,38] show that the steel face plates have significant influence on the shear resistances of the SCS sandwich structure. Therefore, the shear resistance contributed by the top steel plate can be obtained by using the equivalent depth of the concrete structure as the following

\[ V_{sf} = \min \left( V_c t_t E_s / E_{ck} \frac{f_{ys}}{\sqrt{3} B_t} \right) \] (20)

where, \(0 \leq \cos^{-1} \left( \frac{R + b\tan \theta/2 + h_c}{R} \cos \theta \right) \leq 90^\circ\).

\(V_c\) is the shear resistance of core material calculated by Eq. (21); \(t_t\) is the thickness of steel face plate; \(E_s\) is the elastic modulus of steel face plate; \(h_c\) is the depth of concrete core.

Fig. 23. Comparison of predictions with test results.

Fig. 24. Fabrication of SCS sandwich wall.
shown in Fig. 19. The tensile resistance of the tensile failure of the top steel shell, respectively.

V_{d,s} = \sum_{i=1}^{n} T_{hs}^i \sin \beta_{hi}^i \quad (21)

where \( n \) denotes number of the pairs of the overlapped connectors that the shear cracks cross in the section of the beam; \( i \) = \( i \)th connector; \( T_{hs}^i \) is the tensile resistance of the \( i \)th connector; \( \beta_{hi}^i \) is the inclination angle of the \( i \)th pair of overlapped shear connector to the horizontal surface as shown in Fig. 19.

The numerical and experimental study [38,39,43] showed that the shear resistance of the SCS sandwich beam was influenced by the rise-to-span ratio, span-to-height ratio, steel contribution ratio and support restraint conditions. Therefore, these parameters need to be controlled during the construction to achieve the desired outcome.

10.2. Concentrated load acting on sandwich shells

Nine quasi-static tests on large scale curved SCS sandwich shells under concentrated loading that considered the localized ice-contact pressure were reported by Yan et al. [42,44] and two punching tests on SCS sandwich shell subjected to large patch loads were also conducted [8]. Corresponding design equations have also been developed to predict the punching shear resistance of the SCS sandwich composite shells [7,8,42,44]. Figs. 20 and 21 show the test set-up and failure modes of curved SCS sandwich panel subjected to punching load. The test results showed that introducing the J-hook type of mechanical shear connectors, adopting higher curvature for the curved SCS sandwich structure, and using higher flexural reinforcing content and higher strength concrete core would increase the punching shear resistance of the SCS sandwich shell structure. As shown in Fig. 22, the SCS sandwich shell structure exhibits two peak resistances \( P_1 \) and \( P_2 \), which correspond to the punching shear failure of the concrete core and the punch through failure of the top steel shell, respectively.

Analytical models have also been developed to predict the punching resistance based on these two failure modes as follows [42,44]

\[ P_1 = 0.75 V_{\text{Rd,c}} + V_{\text{Rd,s}} \quad (22) \]

where \( V_{\text{Rd,c}} \) is the design punching shear resistance of the core material; \( V_{\text{Rd,s}} \) denotes the design punching shear resistance by the connectors or shear reinforcement.

Punching shear resistance contributed by the core material can be determined as [42,44],

\[ V_{\text{Rd,c}} = 2(V_{\text{arch}} + V_{\text{long}}) \quad (23a) \]

\[ V_{\text{arch}} = \left[ C_{\text{arch}} k_{\eta} (100 f_{\text{ck}}) \right] \frac{1}{3} L_{\text{arch}} h_{\text{arch}} \quad (23b) \]

\[ V_{\text{long}} = \left[ C_{\text{long}} k_{\eta} (100 f_{\text{ck}}) \right] \frac{1}{3} L_{\text{long}} h_{\text{long}} \quad (23c) \]

where \( C_{\text{arch}}, k_{\eta}, \) and \( p_{\eta} \) are specified in Section 6.2 under Eq. (11).

\[ h_{\text{arch}} = h_{c} + t_{s} E_{s} / E_{c} \quad (24a) \]

\[ h_{\text{long}} = (R + t_{s} + 2 h_{c}) - \sqrt{(R + t_{s} + h_{c})^{2} - (a/2)^{2} + (R + t_{s}) \\ \\ \times (1 - \cos \alpha) + t_{s} E_{s} / E_{c} \quad (24b) \]

where \( R \) denotes the radius of the shell; \( t_{s} \) is the thickness of the steel shell; \( h_{c} \) is the thickness of concrete core; \( a \) denotes the loading area; \( E_{s} \) and \( E_{c} \) are the Young’s modulus of steel and concrete, respectively.

The punching shear resistance contributed by the shear connectors can be calculated as [42,44]

\[ V_{\text{Rd,s}} = n T f_{\text{Rd,s}} \sin \alpha \quad (25) \]

where \( T \) is tensile strength of the connectors, calculated by Eq. (2); \( n \) is the quantity of overlapped connectors within the critical perimeter; \( h_{c} \) is the thickness of the shell section; \( S \) is the average spacing of the connectors; \( \alpha \) is the inclination angle of the shear stud.
Fig. 26. Failure mode of SCS sandwich wall subjected to compression load applied at an eccentricity, e.

(a) e=0 mm; (b) e=20 mm.

(c) e=40 mm; (d) e=70 mm.

Fig. 27. N-M interaction diagram of SCS sandwich section.
The punching shear resistance of the steel shell can be determined as
\[ P_2 = \sigma_{st} t_s U_p / \sqrt{3} \]  
(26)
where \( U_p \) is the perimeter of the patch loading area; \( t_s \) is the thickness of the steel shell.

The predictions by the developed analytical models are compared with the tests results in Fig. 23. It shows that the developed analytical model significantly improved the accuracy compared with the other available design guidelines.

11. Sandwich wall subject to compression

Steel-concrete-steel (SCS) sandwich wall infilled with ultra-lightweight cement composite has been developed and proposed for applications in offshore and building constructions. A new form of J-hook connector is introduced to connect the external plates to improve the composite action between the steel face plates and cement composite core to form an integrated unit which is capable of resisting extreme loads, as shown in Fig. 24. This research experimentally investigates the structural behaviour of SCS sandwich composite wall based on a series of combined compression and uniaxial bending tests on short SCS sandwich composite wall with interlocking J-hook connectors [40,45]. Fig. 25 shows the test set-up for SCS sandwich wall subjected to compression and uniaxial bending. From the tests, it is found that the SCS sandwich wall exhibits good structural behaviour with a bending failure mode as achieving to a very small value given \( N = 0 \) (pure bending). In compression failure range (from point A to point B), this is done by assuming the compressive strain of extreme concrete fiber as achieving to \( \varepsilon_{c,\text{ult}} \) which is the ultimate concrete compression strain. In tension failure range (from point B to point C), this is done by assuming the tensile strain of extreme steel fiber as achieving to \( \varepsilon_{s} = f_{ys} / E \), which is the yield strain of steel.

The axial force and the bending moment equilibrium equations at the failure moment are displayed as follows.

(1) Pure compression: Point A

By considering the buckling effect of steel face plate, the compression resistance of SCS sandwich wall is calculated by
\[ N_A = N_{pl,Rk} = 0.85A_f f_{ck} + \phi_s A_f f_{ys} \]  
(27)
where \( \phi_s = 0.898R^{-0.771} \) (R ≥ 0.85) [45], \( A_f \) is cross-sectional area of concrete; \( f_{ck} \) is compressive strength of concrete; \( A_f \) is cross-sectional area of steel plate; \( f_{ys} \) is yield strength of steel; \( R \) is the width-thickness ratio, defined as \( R = \frac{h_c}{b} \sqrt{\frac{E_t}{E_c}} \geq 0.85 \).

(2) Compression failure: branch AB

\[ N_u = f_{ck} b h_c + f_{ys} A_h - \sigma_{st} A_{lb} \]  
(28)
\[ N_u e = f_{ck} b h_c \left( h_c - \frac{x_c}{2} + \frac{t_s}{2} \right) + f_{ys} A_h \left( h_c + t_b \right) \]  
(29)
where, \( e = e_0 + \frac{t_s}{2} + \frac{t_b}{2} \) is the width of section; \( f_{ys} A_h \) is the compression force by steel plate in compression side, \( \sigma_{st} A_{lb} \) is the compression force or tension force by steel plate in tension side.

(3) Tension failure: branch BC

Similarly, the force equilibrium is expressed by
\[ N_u = 0.5 f_{ck} b h_c + f_{ys} A_h - f_{ys} A_{lb} \]  
(30)
\[ \frac{N}{N_{pl,Rk}} \]

Fig. 28. Proposed N-M interaction model against Eurocode 4 prediction, test and FE results.
where \( e = e_0 + \frac{h_2}{2} + \frac{h_3}{3} \) and \( \varepsilon_0 \) is the tension force by steel plate in tension side.

Fig. 28 illustrates the validation against the test and FE results, showing a reasonable and conservative estimation on the combined resistance of SCS sandwich wall. This suggests that the proposed model can offer close and conservative predictions for combined compression and bending resistance of SCS sandwich wall that filled with ultra-lightweight cement composite. Considering the accuracy of the predictions, Eqs. (27)–(31) are recommended for the check of the resistance of SCS sandwich wall under combined compression and bending.

12. Conclusions

Novel J-hook connectors and new ultra-lightweight cement composite (ULCC) core material with density as low as 980 kg/m³ have been developed to enhance the strength to weight ratio and the structural performance of sandwich composite structures. Experimental and analytical studies were carried out to investigate the structural behaviours of SCS sandwich structures under static, fatigue, impact and blast loads. Based on these experimental and analytical studies, the following conclusions can be drawn:

(1) The use of ultra lightweight cement composite material and high strength steel was feasible to produce slim form of SCS sandwich structure and to achieve higher strength to weight ratio compared to stiffened plate construction.

(2) Novel mechanical connectors were developed to offer effective shear and tensile bond between the steel face plates and the cement composite core. Design equations to predict the shear, tension, and shear-tension interaction resistances of the J-hook shear connectors were developed and the accuracy was verified against numerical and experimental results.

(3) Flexural and shear behaviours of the SCS sandwich beams have been studied experimentally. Design formulae to predict the bending and shear resistances have been proposed and verified against test results.

(4) Results from fatigue tests on SCS beams showed that their fatigue life was affected by both the fatigue stress range and maximum applied stress. The maximum applied stress and stress range affected the structural behaviour of the SCS sandwich system. Their fatigue life reduced when the load range or maximum applied load increased. A new three-parameter fatigue design equation was proposed based on calibration with test data.

(5) Instrumented drop weight tests have been conducted on a number of SCS sandwich slabs to evaluate their resistance against large mass projectile/fragment impact. The steel plate strength and thickness, and the tensile resistance of the J-hook connectors are the controlling parameters that affect the punching resistance of the SCS sandwich plate subject to low velocity impact. The proposed interlocked J-hook shear connectors provide additional resistance to prevent tensile separation of the face plates and enhance the shear resistance of the sandwich panel. An energy balance model is proposed to analyse the energy absorption capacity of SCS sandwich slabs. The deflection of the SCS sandwich slabs can be determined with reasonable accuracy using this model, and this can be used to assess the damage levels of the SCS sandwich slabs subject to impact load provided the failure was not due to projectile punching through the top plate.

(6) Blast tests were carried out on SCS sandwich plates and their performances were compared with stiffened steel plates. The blast performance of SCS panels improved with the increase in the overall flexural stiffness and the weight of the internal core material as compared to steel plates without the internal core material. The permanent deformations of the SCS sandwich plates subject to blast load were lower compared to the equivalent stiffened steel plates subject to the same blast load. The blast performance of SCS sandwich structures coupled with their engineering flexibility and construction economy make them suitable to be used as protective structures.

(7) Tests on the curved SCS sandwich shells subjected to patch load were carried out. The SCS shells have better design resistance against high punching shear force compared to flat panels because of the arching action. Design formulae to predict the punching shear resistance of the SCS sandwich shell structure were proposed and verified against the test results. The design formulae considered the rise-to-span effect, steel plate thickness and failure mode of shear connectors in the SCS sandwich shell.

(8) Tests on SCS sandwich walls subjected to compression and moment were performed. Test observations showed that SCS sandwich walls exhibited excellent compression resistance and post peak ductility if J-hook connectors were provided to prevent separation of the face plates. A new M-N interaction model was proposed and its accuracy was verified against the test and FE results. Comparison of results showed that the proposed method provided reasonable and conservative estimations compared to the Eurocode 4 method.

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