AN ALTERNATIVE DESIGN OF STEEL-CONCRETE-STEEL SANDWICH BEAM

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Abstract. *A steel-concrete-steel sandwich beam represents a special form of sandwich structure. Originated in civil/structural engineering applications, it is now being developed for shipbuilding/offshore applications. The research trend is to introduce either a new shear connector system or a lightweight concrete. This paper presents an alternative construction of steel-concrete-steel sandwich beam in which the new concept design of aligning the shear connector in the inclined direction is proposed. The novel bi-directional corrugated-strip-core system is presented. The possibility of implement this core system using available sandwich construction techniques is presented. The advantages of the novel bi-directional corrugated-strip-core steel-concrete-steel sandwich beam are preliminarily studied in both the unfilled and concrete-filled state. The analytical study based on the force-distortion relationship technique of the repetitive unit cell shows that the transverse shear stiffness of the unfilled sandwich beam depends on the inclined direction of the proposed core. The numerical study of the concrete-filled sandwich beam type also shows the possibility to increase the transverse shear strength.*

1 INTRODUCTION

The need for large structures with higher specific strength and stiffness is increasing. This is especially true of recent engineering structures where there is an interest in increasing payload to structure weight ratios. To deliver such structures, engineers can either find a new structural material or produce a new structural topology. The former method is however quite difficult to complete because qualification of new materials is expensive and time consuming. The latter method is more realistically possible because engineers can select any combination of existing materials and arrange them into a desired structural topology such as a sandwich structure.

A steel-concrete-steel (SCS) sandwich beam represents a special form of sandwich structure. It consists of steel face plates and concrete core which are connected together by mean of a series of shear connectors. The state-of-the-art construction forms of SCS sandwich structures are (1) double-skin sandwich construction (DSC), (2) Bi-Steel sandwich construction (Bi-Steel), and (3) alternative SCS sandwich construction. They are different only due to the pattern of their shear connectors, as shown in Fig. 1.

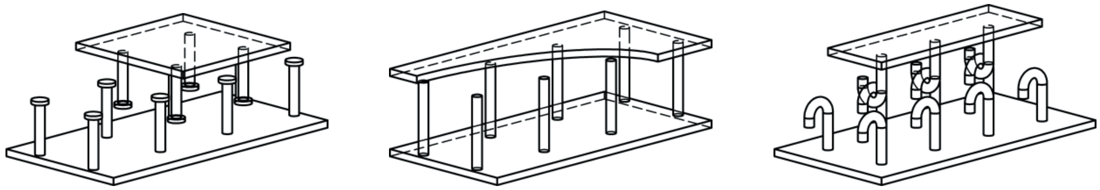


Figure 1: Sketch of (a) double-skin, (b) Bi-Steel, and (c) an alternative SCS sandwich construction

Being an alternative construction technique, the DSC was introduced for the Conwy River submerged-tube-tunnel crossing project in the mid of 1980s. Although the DSC is similar to steel-concrete composite construction, it was not qualified for this project due to the difficulties of in-site construction, especially control of depth of sandwich core [1]. The Bi-Steel form overcame some of the existing on site construction problems of the DSC. Having the innovative prefabrication technique developed by British Steel (later Corus) [1], both ends of shear connector can be simultaneously fixed to steel face plates. As a result, it can minimise some construction problems on site. An alternative SCS sandwich construction with the innovative J-J hook connectors has also been recently proposed by [2] as a competitive construction form. It seems to be an advantageous solution of simplified low-cost-construction technique because it just requires simplified construction tools which are now generally available at construction site.

Although the SCS sandwich construction was originated in civil/structural engineering application, it has been further researched and developed not only for civil application but also for shipbuilding/offshore application [3]. The behaviors of the SCS structures have been widely researched, for example in [4, 5, 6]. However, the recent development trend for shipbuilding may be obviously divided into two fields: to introduce either a lightweight concrete core [6] or a new shear connector system [2]. This paper deals with the later trend in which a new concept design of shear connector is introduced.

Considering the existing construction forms of SCS structures, it may be seen that all of the current types of shear connector are similar in alignment pattern. They all align in the vertical direction – the axis of shear connector is normal to the face plates. However, it is known that a concrete-filled sandwich beam under bending load suffers diagonal cracks [4]. In the opinion of the authors, this may be alleviated using inclined shear connectors. Therefore, it is purposed to further research this alternative engineering solution.

This paper presents the novel SCS sandwich beam with bi-directional corrugated-strip-core system. The aims of the paper are to present the possibility to implement this novel core system using the available construction techniques and to present the possible advantages of this novel SCS sandwich beam. Both unfilled and concrete-filled sandwich beam types are studied and presented in this paper. The unfilled sandwich beam type is analytically studied using the force-distortion relationship technique of the repetitive unit cell. The concrete-filled sandwich beam type is studied using the existing numerical method.

2 AN SCS SADNWICH BEAM WITH BI-DIRECTIONAL CORRUGATED-STRIP-CORE SYSTEM

2.1 Configuration of Unfilled Sandwich Beam

Figure 2 shows the unfilled stage of an SCS sandwich beam with bi-directional corrugated-strip-core (CSC) system. The CSC system consists of a series of corrugated-strip plates which can be aligned in both x- and y-direction. It functions as the structural sandwich core for the unfilled stage and later as the shear connector for the concrete-filled stage.

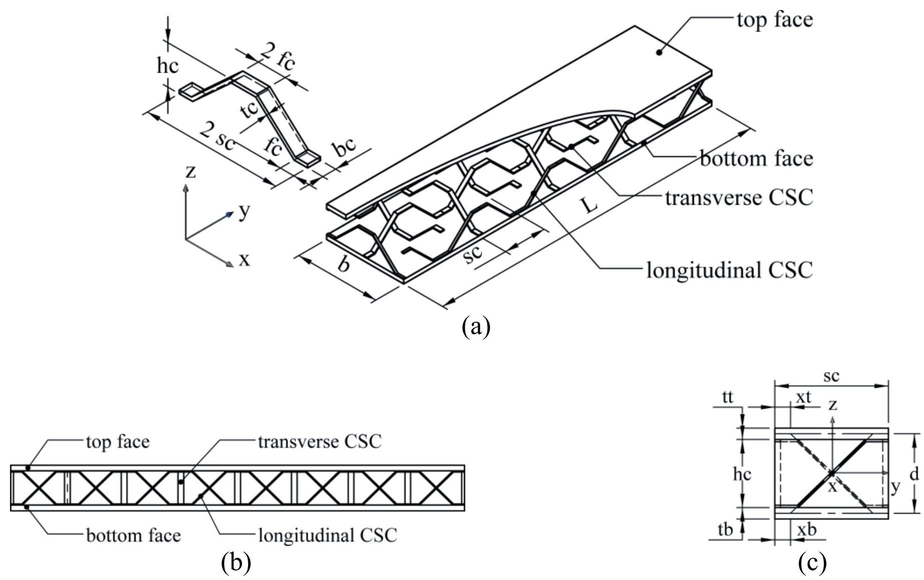


Figure 2: Configuration of an SCS sandwich beam with bi-directional CSC system (a) isometric view, (b) front view, and (c) a repetitive unit cell

The dimensional geometry of sandwich beam is defined by five conventional parameters: thickness of top face plate t_t, thickness of bottom face plate t_b, depth of sandwich core h_c, width of beam b, and length of beam L. The geometry of a repetitive unit of corrugated-strip plate is defined by five parameters: width of strip plate b_c, thickness of plate t_c, horizontal length of corrugation unit s_c, height of corrugation h_c, and length of flat leg f_c. The corrugated-strip plates are arranged in equal spacing s_c in x- and y-direction. However, it is not necessary to use the same configuration in both x- and y-direction.

The corrugated-strip plate also consists of two inclined parts. These parts align in angle θ with the y-axis – the longitudinal axis of sandwich beam. Parameter θ can be expressed in terms of previously defined parameters as Eq. 1 where s_x is equal to $\mathrm{s_c} - \mathrm{x_t} - \mathrm{x_b}$ (approximately a horizontal projection of inclined part, see Fig. 2(c)).

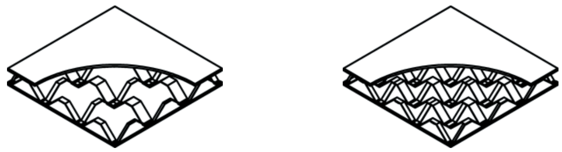
$$\frac{1}{\tan\theta} = \frac{s_x}{d} = \frac{(s_c - 2f_c)}{(h_c - t_c)} \tag{1}$$

Having the inclined parts of each corrugation unit, it can be seen that the whole CSC system also consists of a series of inclined and vertical members as can be seen from the front view (Fig. 2(b)). These inclined members would therefore act as additional bracing members for the unfilled SCS sandwich beam and as inclined shear connectors for the concrete-filled SCS sandwich beam.

2.2 Fabrication Technique

Generally, the construction process of SCS sandwich beam can be divided into two major stages: (1) the unfilled stage and (2) the concrete-filled stage. Since the second stage may follow the qualified procedure of the other SCS constructions, for example [7], this paper presents only the first stage.

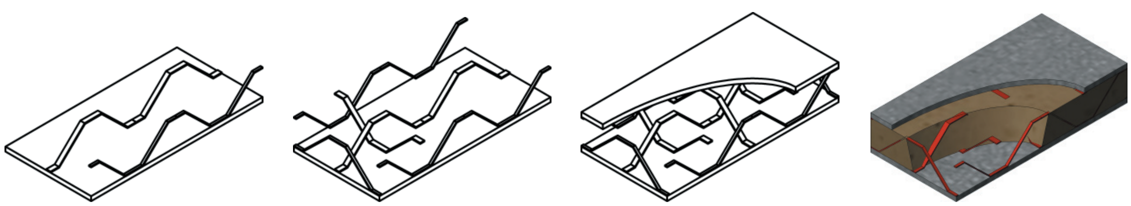
Conceptually, the novel unfilled SCS sandwich beam proposed in this paper can be fabricated and assembled. This is because that the components of the unfilled stage, i.e. steel face plate and corrugated-strip plate, are similar to existing engineering applications. In addition, the similar techniques to arrange the corrugated-strip plates in both x- and y-direction and to assembly them with steel face plates have been found in the existing corrugated-core sandwich construction [8, 9] as shown in Fig. 3.



(a) (b)

Figure 3: Sketch of (a) bi-directional corrugated core [8] and (b) cross corrugated core [9] sandwich panel

Figure 4 illustrates the conceptual process of fabrication technique proposed by the authors. First, the longitudinal CSC may be placed on the bottom face plate and may be firmly fixed to the plate (Fig. 4(a)). Second, the transverse CSC, if required, may be moved downward and slid into the hole of the longitudinal CSC (Fig 4(b)). It may be firmly fixed to the plate. Then, the top face plate may be placed on and fixed to both the longitudinal and transverse CSCs (Fig. 4(c)). In authors' opinion, there is a possibility to bond the bottom and top face plate to the flat leg of corrugated-strip plates as instructed in [8, 9]. As a result, the top and bottom face plates can be internally fixed to core. An SCS sandwich plate may be later assembled from sandwich beam modules. Then, concrete can be poured throughout the unfilled core (Fig. 4(d)).



(a) (b) (c) (d)

Figure 4: Conceptual construction process of an SCS sandwich beam with bi-directional CSC system

3 STUDY OF UNFILLED SANDWICH BEAM

3.1 Analysis of Transverse Shear Stiffness

Having the inclined parts of the CSC system, the unfilled SCS sandwich beam may have additional transverse shear stiffness. To understand this stiffness, a simplified approach based on the force-distortion relationship technique of a repetitive unit cell can be used [10, 11, 12]. Nevertheless, this paper presents the adopted technique – a combination of the force-distortion and the modified stiffness matrix methods (MSM) – to overcome the high indeterminacy of the proposed core topology.

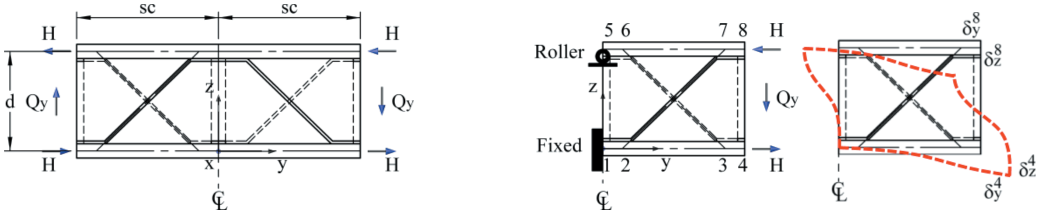


Figure 5: (a) A unit cell (b) one-half of unit cell and its deformation shape

Fig. 5(a) shows a 2D simplified unit cell of the proposed core. In static equilibrium of force condition, it is subjected to a transverse shear force Q_y and a couple of horizontal force $Q_y \times s_c/d$ [10]. Under configuration of symmetrical structure subjected to anti-symmetrical load, the unit cell can be reduced into one-half of the structure with supplementary boundary conditions at the plane of symmetry Fig. 5(b). Introducing the force-distortion relationship technique and the assumption that the core is so sufficiently stiff in the vertical direction that the depth of core is always constant, the transverse shear stiffness D_{Qy} of the unit cell can be expressed as Eq. 2 [12].

$$D_{Qy} = \frac{Q_y}{\frac{\delta_y^4+\delta_y^8}{d}+\frac{\delta_z^4}{s_c}} \tag{2}$$

To account for such a compatibility constraint condition, the conventional relationship between effort forces and displacements, i.e. $\{F\} = [K]\{\Delta\}$, must be partitioned to separate the displacement matrix $\{\Delta\}$ into two parts: (1) the compatibility constraint displacements $\{\Delta_c\}$ and (2) the free displacements $\{\Delta_f\}$, as Eq. 3 where $\{F_c\}$ are the known forces applied to each point of the unit cell and $\{F_f\}$ are the unknown effort forces applied to the constraint points so that the compatibility constraint condition at these points is achieved.

$$\begin{Bmatrix} F_f \\ \cdots \\ F_c \end{Bmatrix} = \begin{bmatrix} K_{cc} & \vdots & K_{cf} \\ \cdots & & \cdots \\ K_{fc} & \vdots & K_{ff} \end{bmatrix} \begin{Bmatrix} \Delta_c \\ \cdots \\ \Delta_f \end{Bmatrix} \tag{3}$$

After inversion of Eq. 3, as shown on the left hand side of Eq. 4, the inverted stiffness matrix $[K]^{-1}$ is partitioned to give the right hand side of Eq. 4.

$$\begin{Bmatrix} \Delta_c \\ \cdots \\ \Delta_f \end{Bmatrix} = \begin{bmatrix} K_{cc} & \vdots & K_{cf} \\ \cdots & & \cdots \\ K_{fc} & \vdots & K_{ff} \end{bmatrix}^{-1} \begin{Bmatrix} F_f \\ \cdots \\ F_c \end{Bmatrix} = \begin{bmatrix} K_{cc}^I & \vdots & K_{cf}^I \\ \cdots & & \cdots \\ K_{fc}^I & \vdots & K_{ff}^I \end{bmatrix} \begin{Bmatrix} F_f \\ \cdots \\ F_c \end{Bmatrix} \tag{4}$$

As a result, the unknown effort forces $\{F_f\}$ can be expressed as Eq. 5.

$$[K_{cc}^I]\{F_f\} = \{\Delta_c\} - [K_{cf}^I]\{F_c\} \tag{5}$$

Equation 5 is used to achieve the unknown effort forces at point 4 and 8, i.e. the transverse shear forces at the top and bottom faces, which correspond to the compatibility constraint condition at these points. A summation of these two forces would be equal to the effort transverse shear force Q_y. Introducing the compatibility constraint condition $\delta_z^4 = \delta_z^8 = \delta_z$ and letting Q_y^b as the transverse shear force acting on the bottom face, one can yield that

$$[K_{cc}^I]\begin{Bmatrix}-Q_y^b\\ Q_y^b\end{Bmatrix} = \begin{Bmatrix}\delta_z\\ \delta_z\end{Bmatrix} - [K_{cf}^I]\{F_c\} - [K_{cc}^I]\begin{Bmatrix}0\\ -Q_y\end{Bmatrix} \tag{6}$$

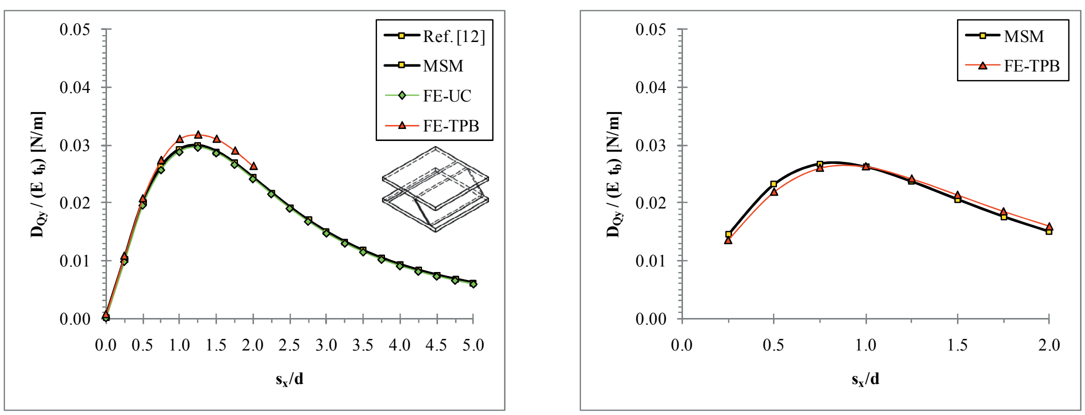
Having the solution for Q_y^b from Eq. 6, one can then solve for the free displacements $\{\Delta_f\}$ from the other partitioned matrix of Eq. 4. Then, the transverse shear stiffness D_{Qy} of the unit cell can be calculated from Eq. 2.

3.2 Analytical Results and Discussions

The presented MSM method is first used to analyse the transverse shear stiffness D_{Qy} of an extruded-truss core sandwich beam and then is validated with the analytical solution provided by [12] and finite element solutions of both 3D three-point-bending beam (FE-TPB) and 3D unit cell (FE-UC). It can be seen from Fig. 6(a) that the presented analytical solution agrees very well with the numerical solutions. For the proposed core, the MSM method is validated with only the FE-TPB method. It can also be seen from Fig. 6(b) that both methods are not significantly different.

In Fig. 6(b), the stiffness D_{Qy} of the proposed core (see Fig. 2) is plotted against s_x/d. The configuration of presented sandwich beam is $100 - 12 \times 120 \times 12$ $[b - t_t \times h_c \times t_b]$ and the corrugation unit is $25 \times 2 \times s_c \times 20 \times h_c$ $[b_c \times t_c \times s_c \times f_c \times h_c]$. Here, s_c depends on the value of s_x/d.

It can be seen that increasing s_x/d from 0.25 to 0.75 yields an increasing value of D_{Qy}. As s_x/d continues to in 2.0, then, D_{Qy} gradually reduces. This trend infers that the alignment angle of the inclined part of the proposed core significantly affects to the transverse shear stiffness of the sandwich beam. The optimum point of the stiffness D_{Qy} occurs at $s_x/d = 0.75$ – approximately 40°. At this configuration, the stiffness D_{Qy} is approximately 80% greater than that of $s_x/d = 0.25$ and of $s_x/d = 2.00$.



(a) (b)

Figure 6: Relationship between D_{Qy} and s_x/d of (1) extruded-truss core [12] and (2) proposed core

4 STUDY OF CONCRETE-FILLED SANDWICH BEAM

4.1 Fundamental of Diagonal Shear Crack in Concrete Core

According to the experimental studies, the diagonal shear crack of concrete core of SCS sandwich beam has been reported as one of the major failure modes [4, 5]. This failure mode occurred in a pattern as shown in Fig. 7. It is similar to the diagonal shear crack of other structural beams, for example, a solid-core sandwich beam [13] and a conventional reinforced-concrete (RC) beam [14].

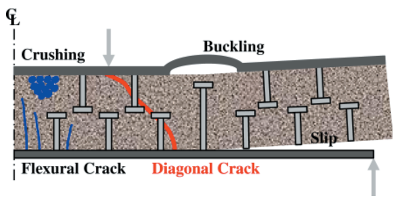


Figure 7: Major failure modes of an SCS sandwich beam (modified from [4])

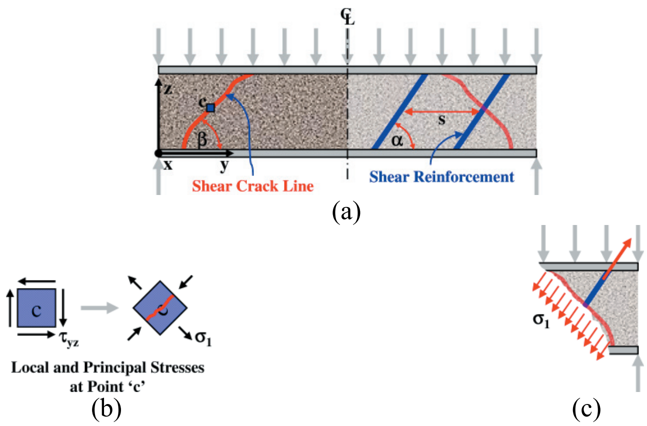


Figure 8: (a) An SCS sandwich beam with and without transverse shear reinforcement, (b) principle stress at diagonal crack section, and (c) free-body diagram of beam with transverse shear reinforcement at diagonal crack section

The phenomenon of a diagonal shear crack may be approximately expressed using simplified mechanics of solids. Considering the principle tensile stress σ_1 of plane stress element cut from a point of concrete core subjected to normal and shear stresses in local y- and z-direction, as shown in Fig. 8(b), σ_1 may be expressed as Eq. 7 as follows

$$\sigma_1 = \frac{M_y E_c z}{2D^2} + \sqrt{\left\{\frac{M_y E_c z}{2}\right\}^2 + \left\{V_{yz}\left[E_t t_t \bar{z} + \frac{1}{2}E_c\left(\left(\bar{z} - \frac{t_t}{2}\right)^2 - z^2\right)\right]\right\}^2} \quad (7)$$

Here, M_y and V_{yz} are the internal moment and transverse shear force at the location of the considered element cut from the SCS sandwich beam. E_c is the modulus of elasticity of concrete. D is the bending stiffness of SCS cross section. $\bar{z}$ and z are the location of neutral axis of SCS cross section and the location of cut element, respectively. It should be noted that the bending stiffness D and the neutral axis of SCS cross section $\bar{z}$ defined in this paper are calculated with the assumptions of (1) the tensile strength of concrete is negligible [15] and (2) the strain compatibility of SCS cross section is linear.

According to Eq. 7, the principle tensile stress and its principle direction of concrete core can be calculated. Figure 9 illustrates the direction of principle tensile stress occurred in concrete core of an SCS sandwich beam. It may be seen that the principle tensile directions are mostly aligned in inclined angle to the neutral axis of sandwich beam. Therefore, the concrete core more likely cracks in diagonal direction.

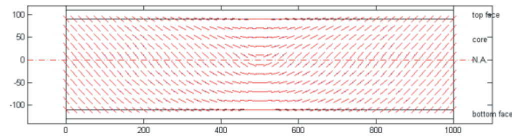


Figure 9: Direction of principle tensile stress in concrete core of SCS sandwich beam

4.2 Rationale for Transverse Shear Reinforcement System

In addition to preventing a structural beam from failing in other failure modes such as tension plate failure or connector shear failure [5], the diagonal shear crack failure must be prevented to ensure that the structure is safe for public use. Unlike the flexural failure, the diagonal shear crack failure of concrete structure is considerably a brittle failure mode. This failure mode may happen without advanced warning in RC beams without effective transverse shear strength [16]. Therefore, it is reasonable to prevent this failure mode to ensure that the structure would fail in other ductility modes.

There are several possible ways to overcome the diagonal shear crack failure, for example: (1) reducing the applied load, (2) rearranging the position of support, (3) increasing the thickness of beam, (4) changing the material, and (5) providing some kind of transverse shear reinforcement. In the authors' opinion, the first four solutions may be less advantageous than the last solution because they may affect the architectural criteria, service requirements, weight of structure and cost of construction. The fourth solution may indeed not be applicable since the high strength material is usually much more expensive. In addition, concrete is an extremely low-tensile-strength material; as a result, subjecting it to tensile stress must be minimised. The last solution may be the better solution to overcome the diagonal shear failure. It may prevent crack propagation, increase the strength and ductility of the beam without affecting the depth and weight of the structural beam and the architectural requirements. This is because the transverse shear reinforcement will replace concrete and only function inside the structure. The concept of providing transverse shear reinforcement is generally found in conventional RC beam [15]. It is also used in SCS sandwich beam [7].

The simplified mechanism of transverse shear reinforcement may be illustrated by Fig. 8(c). Considering the beam with inclined transverse shear reinforcement, the equilibrium of force in z-direction at the diagonal crack section may be approximately expressed as Eq. 8 where A_v and f_v are the cross section area and the allowable tensile stress of transverse shear reinforcement, respectively. σ_1 is the average principle tensile stress at diagonal crack section calculated from Eq. 7. α and β are angular alignment of the reinforcement and the diagonal crack line measured from horizontal axis. l is the length of diagonal crack section which can be expressed in term of s_c and both angles α and β. Here, the diagonal crack line is passed through by one transverse shear reinforcement spaced horizontally at distance s_c. It should be noted that the strength contribution of top and bottom face plates is neglected in this paper.

$$A_v f_v \sin\alpha = \sigma_1 b l \cos\beta = \sigma_1 b \left(s_c \frac{\sin\alpha}{\sin(180-\alpha-\beta)} \right) \cos\beta \tag{8}$$

Equation 8 can be further simplified in terms of the strength index of transverse shear reinforcement k_v as Eq. 9 in which k_v depends on α and β angles.

$$A_v f_v = k_v \sigma_1 b s_c = \left(\frac{\cos\beta}{\sin(180-\alpha-\beta)} \right) \sigma_1 b s_c \tag{9}$$

To study the behaviour of k_v, the relationship of k_v and α where β is assumed as $45°$ [16] is presented in Fig. 10. It can seen that the minimum value of k_v occurs when α is equal to $45°$, i.e. the transverse shear reinforcement aligns at $45°$ to the horizontal axis. In the other words, the transverse shear reinforcement aligns at $90°$ to the diagonal crack section. This may imply that the stress in transverse shear reinforcement should be optimum if the transverse shear reinforcement aligns in normal direction to the diagonal crack line. As a result, the transverse shear strength of cross section of beam would be considerably increased. This simplified expression may support the concept of aligning shear connectors of SCS sandwich beam in an inclined direction to increase the transverse shear strength of beam.

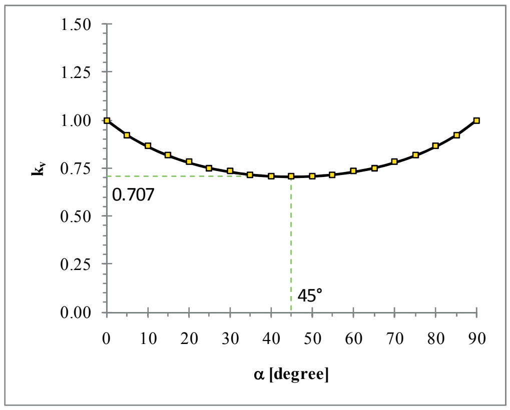


Figure 10: The relationship of k and α, at $\beta = 45°$

In conventional RC beam, there are many evidences and researches supporting this concept [15, 17, 18]. However, it can be obviously seen that the current design of the shear connector of the state-of-the-art SCS sandwich beams is limited to vertical alignment pattern only. Therefore, it may imply that the current application would be not now the most effective solution. In the authors' opinion, an SCS sandwich beam with inclined shear connectors should be further researched and developed to achieve the possible advantage of this alternative engineering solution.

5 CONCLUSIONS

An alternative SCS sandwich beam with bi-directional CSC system is presented. The novel core performs as bracing system in unfilled sandwich beam and as inclined shear connector in concrete-filled sandwich beam. This novel system of SCS sandwich beam is presented as an alternative solution for the future of SCS sandwich construction. The implementation of this novel core is conceptually presented.

The unfilled sandwich beam is studied in the advantage of transverse shear stiffness D_{Qy}. The analytical solution based on the presented modified stiffness matrix and the force-distortion relationship of unit cell shows that D_{Qy} significantly depends on s_x/d. The optimization point of stiffness D_{Qy} is at $s_x/d = 0.75$, i.e. ~40°, for the case study presented in this paper. At this point, it could be seen that the shear stiffness D_{Qy} is increased by approximately 80% compared to $s_x/d = 0.25$ and $s_x/d = 2.00$.

The numerical study of the concrete-filled sandwich beam also shows the possibility to improve the efficiency of transverse shear strength. The simplified mechanism of beam with transverse shear reinforcement shows that the most effective alignment angle of shear connector occurs when it aligns normal to the diagonal shear crack line. This solution has been evidently proved in conventional RC beam. The research to understand this behaviour of SCS sandwich beam is still in process.

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