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Flexural Resistance of Steel-Coconut Shell Concrete-Steel Composite Beam with Normal and J-Hook Shear Studs

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Abstract: Many researches on double skin sandwich having top and bottom steel plates and in between concrete core called as steel-concrete-steel (SCS) were carried out by them on this SCS type using with different materials. Yet, use of coconut shell concrete (CSC) as a core material on this SCS form construction and their results are very limited. Study investigated to use j-hook shear studs under flexure in the concept of steel-concrete-steel (SCS) in which the core concrete was CSC. To compare the results of CSC, the conventional concrete (CC) was also considered. To study the effect of quarry dust (QD) in its place of river sand (RS) was also taken. Hence four different mixes two without QD and two with QD both in CC and CSC was considered. The problem statement is to examine about partial and fully composite, moment capacity, deflection and ductility properties of CSC used SCS form of construction. Core concrete strength and the j-hook shear studs used are influences the moment carrying capacity of the SCS beams. Use of QD in its place of RS enhances the strength of concrete produced. Deflections predicted theoretically were compared with experimental results. The SCS beams showed good ductility behavior.

Keywords: Double-skin steel plates, coconut shell concrete, composite beam, shear stud, flexural behavior

1. Introduction

Coconut shell (CS) is used as coarse aggregate in producing lightweight concrete (LWC) [1]-[5]. Steel-concretesteel (SCS) form construction technology that has long been recognized as one of the most economical structural systems for buildings. Many research and development have been taken place in this SCS technology for the past four decades [6]-[11]. Recently the combinations coconut shell concrete (CSC) and SCS beam was studied for its flexural behaviour in which it was used without and with shear connectors [12]. Since shear connector is a steel projection provided on the plates used to develop a shear transfer mechanism between plate and core concrete to enable the composite action, conventional shear studs are generally used for this purpose. However, many types of shear connectors such as headed studs; j-hooks; angle and bi-steel connectors; bi-directional corrugated-strip-core system and plate connectors are used to integrate the steel plates and the concrete core. An overlapping of the shear connectors plays a vital role in shear transfer mechanism between plates and concrete core [11]. Each shear connector type has its own uniqueness. Out of all other types of shear studs, manufacturing the j-hook studs are comparatively requiring not much energy because j-hook type studs can be made by bending the steel bar itself and also possible to produce in different sizes for the requirements of the SCS elements as well. Since the combinations of CSC and SCS are very limited and only conventional shear studs were used in the earlier study, therefore this study is used j-hook as shear studs. Most of the earlier studies on CSC are mostly produced using river sand (RS), but due to necessity for finding alternate materials for RS, in this work quarry

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dust (QD) was utilized as a substitute material for RS. As a whole, the most impact of this work is to study the flexural resistance of steel-CSC-steel combination beam using normal & j-hook shear connectors.

Nomenclature is included if necessary a
distance between support and load point b
width of plate d diameter of the stud
shank D equivalent flexural stiffness
E_c elastic modulus of concrete
E_{cm} secant modulus of concrete E_s
elastic modulus of steel
f_{ck} cylinder compressive strength of concrete
h_c depth of concrete core
h_s height of the stud
K stiffness of the shear connectors
K_c stiffness reduction factors for the compression steel
K_t stiffness reduction factors for the tension
steel L effective span m modular ratio M_{el}
elastic moment
M_{pl} plastic moment
M_y yield moment
N_{cs} forces in top compression plates
N_{cu} concrete compressive force
N_t forces in bottom tension plates
P_{RD} shear capacity of the stud t_c
thickness of compression plate t_t
thickness of tension plate W load
applied z depth of neutral axis γ_c
partial safety factor
Δ_{exp} experimental deflection
Δ_{theo} theoretical deflection ρ
density of concrete σ_c
compressive stress σ_t
tensile stress
σ_u ultimate strength of steel σ_y
steel yield stress

2. Materials Properties

Ordinary Portland cement (OPC) which conform as per IS: 12269-2013 [13], As per IS 383-2016 [14], the RS used falls in to grading zone III. This RS was used for producing CSC and conventional concrete (CC). QD had fine particles of size passing 4.75 mm sieve were used as it is and the QD used was falls in to grading zone IV was used as a substitute material in its RS place. Materials properties are given in Table 1.

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Table 1 - Materials properties

Studied on	CA	CS	QD	RS
Maximum size (mm)	12.5	12.5	4.75	4.75
Water absorption (%)	-	24	-	-
Specific gravity	2.82	1.05-1.20	2.64	2.56
Fineness modulus	6.94	6.26	2.54	2.57
Bulk density (kg/m^3)	1650	650	1700	1685
Shell thickness (mm)	12.5	2-8	-	-

Crushed coconut shell (CS) and conventional coarse aggregate (CA) of size passing 12.5 mm sieve was used to produce both the concretes. In the form of saturated surface dry condition of CS was used for the production of CSC mixes. The same mix proportions adopted for different concretes in the earlier study [12] were used for this study also. However, the properties found on different concretes are provided in Table 2 in which CC produced with QD and CSC produced with QD mixes are designated as CCQ and CSCQ, respectively.

To develop the concept of SCS, for top and bottom, mild steel (MS) plate having size 2400 × 1500 × 4 mm was used. Depth 230 mm was covered for SCS beam as selected in the earlier study [1], [2]. Fig. 1 and Fig. 2 illustrates the schematic SCS beams with normal and j-hooks shear studs used and Fig. 3 and Fig. 4 illustrates the typical SCS beams with normal and j-hooks shear studs used SCS beam, respectively.

Table 2 - Different concrete properties determined

Studied on	CC	CCQ	CSC	
Compressive strength targeted (N/mm²)	25	25	25	CSCQ
Slump (mm)	9	0	6	25
Compaction factor	0.92	0.91	0.89	0
Plastic concrete density (kg/m³)	2495	2645	2100	0.90
28- day density (kg/m³)	2475	2600	1980	2215
28-day strength (N/mm²)	30.18	32.78	26.83	2150
28-day cylinder strength (N/mm²)	24.15	26.22	21.46	29.05
Elastic modulus (N/mm²)	26926	27545	8780	23.24
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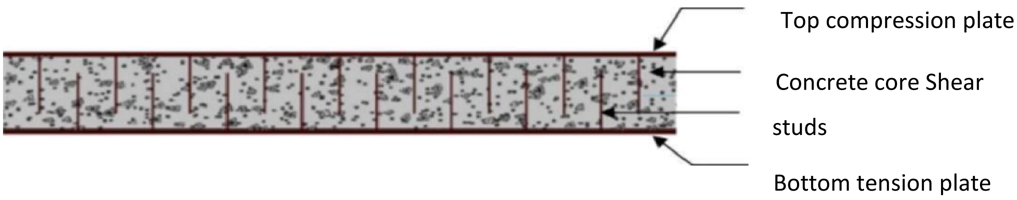

Fig. 1 - Schematic diagram of SCS beam with normal shear studs

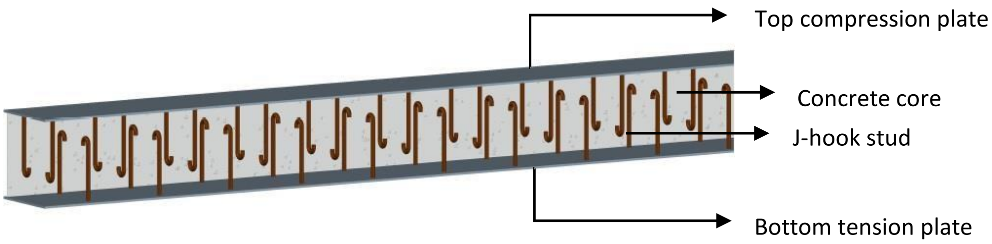

Fig. 2 - Schematic diagram of SCS beam with j-hooks shear studs

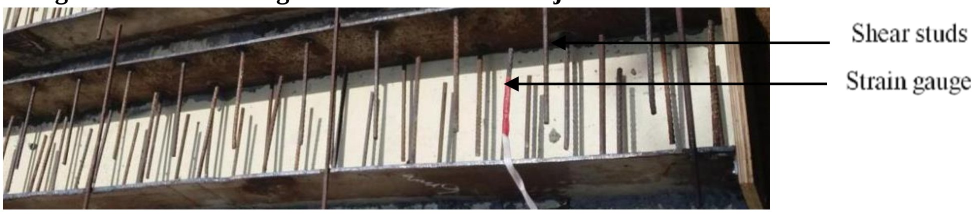

Fig. 3 - SCS beam with normal shear studs

Fig. 4 - SCS beam with j-hooks shear studs

3. Analytical Prediction

Both theoretical elastic and plastic approaches performed to find the flexural behavior of composite beam. Similar to traditional design method assumption, neglect the tensile strength contributed by the concrete and the flexural stiffness of the MS plates on their own axes is ignored. Also, on testing of SCS beams under bending, the tensile stresses in the steel plates and the compressive stresses in concrete are assumed to be elastic and linear Considering these assumptions, Liew et al. [15] suggested a conventional design equation to calculate the neutral axis position 'z' as specified in Eq. (1):

$$z = -m(t_c + t_t) + [m^2(t_c + t_t)^2 - m(t_c{}^2 - 2t_t h_c - t_t{}^2)]^{1/2} \qquad (1)$$

where, m = E_S /Ec, Ratio of the elastic modulus between steel and concrete materials. Similarly, as proposed by Liew et al. [11], assuming that the initial yield takes place at the bottom plate (i.e., $\sigma_t = \sigma_y$) the moment of resistance of the sandwich beam is calculated using Eq. (2), and the beam is considered to be fully composite.

$$M_y = bt_c\left(\frac{z}{3} + \frac{t_c}{2}\right)\sigma_y \frac{z + t_c/2}{h_c - z + t_t/2} + \sigma_y bt_t\left(h_c - \frac{z}{3} + \frac{t_t}{2}\right) \qquad (2)$$

Shear connectors which are provided in the beam should resist the maximum longitudinal force produced in the steel plate so that it develops fully composite action. The required quantity of shear stud connectors is based on the capacity of the individual shear studs which are placed in the depth of concrete layer. If $N_{cs(max)}$ is considered as maximum longitudinal force, this force must be withstand by the competency of shear studs arranged between the points from zero and maximum moment for fully composite and then it can be calculated as $N_{cs(max)} = \sigma_y bt$. The value of N_t(max) for fully composite action is calculated using $N_{t(max)} = n_s P_{RD}$, considering $N_{t(max)}$ is maximum at the bottom tension plate. Similarly the value of $N_{t(max)}$ for partially composite action can calculated by using $N_{t\,(max)} = n_p P_{RD}$ The maximum tensile stress at the bottom plate can be computed from $\sigma_t = (n_p P_{RD})/bt_t$, where n_s = sum of shear studs from initial to ultimate moment for fully composite action, n_p = sum of shear studs between the points from zero to ultimate moment for partially composite action and P_{RD} = Shear resistance of the stud capacity.

The moment of resistance for a partially composite beam is computed using Eq. (3);

$$M_p = n_p P_{RD} \left[\left(\frac{t_c}{t_t}\right)\left(\frac{z + t_c/2}{h_c - z + t_t/2}\right)\left(\frac{z}{3} + \frac{t_c}{2}\right) + \left(h_c - \frac{z}{3} + \frac{t_t}{2}\right)\right] \qquad (3)$$

As put forwarded by Liew et al. [11], if $t_c = t_t = t$, the plastic resisting moment for fully composite action is computed using Eq. (4);

$$M_{ult} = \sigma_y bt(h_c + t) \qquad (4)$$

and finally for the partially composite beam section, the plastic resisting moment is ascertained by using Eq. (5) as proposed by Liew et al. [11];

$$M_{pl} = n_p P_{RD}(h_c + t) \tag{5}$$

Eurocode 4 [16] permit the equations to foretell the studs shear strength for conventional concrete and LWC as specified in Eq. (6) and Eq. (7), respectively.

$$P_{RD} = 0.8\,\sigma_u \left(\frac{\pi}{4} d^2\right) / \gamma_v \tag{6}$$

$$P_{RD} = \frac{0.29\alpha d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_v} \tag{7}$$

where, d = Shank diameter of the shear stud; σ_u = ultimate tensile strength of the shear stud which should be ≤500 MPa; f_{ck} = characteristic cylinder strength of concrete; Partial safety factor for material suggested for the shear stud connector (γ_v) = 1.25; α= 0.2 (hs/d +1) for 3 ≤ hs/d ≤ 4 or α = 1.0 if hs /d ≥ 4; hs = gross height of the shear stud; E_{cm} = secant modulus of concrete. The values of P_{RD} for different mixes are given below based on the studs used in this study: P_{RD} for normal concrete and conventional concrete with quarry dust = 15.60 kN, for coconut shell concrete and for coconut shell concrete with quarry dust, P_{RD}= 6.45 kN and 6.82 kN. Number of studs required, $n_s = \square_y b t_t / P_{RD}$. If the tension steel plate stiffness reduction factor is k_t and k_c is the compression steel plate stiffness reduction factor, then k_t and k_c are calculated from Eq. (8).

$$k_t = \frac{n_a K}{n_a K + 2bt_t E_s/L} \quad \text{and} \quad k_c = \frac{n_a K}{n_a K + 2bt_c E_s/L} \tag{8}$$

where, K = stiffness factor of the shear connectors, calculated from the load slip graph of the push-out test. The average stiffness for CC, CCQ, CSC and CSCQ mixes are 27820 N/mm, 28140 N/mm, 24620 N/mm and 24990 N/mm respectively, n_a = sum of shear connectors placed from zero to maximum moment. Eq. (9) gives the deflection of beam subjected to two-point loading acting on the span.

$$\Delta = \frac{Wa}{24\,D}(3L^2 - 4a^2) \tag{9}$$

where, D = EI (flexural stiffness of the composite beam) Considering cracked section, the equivalent moment of inertia shall be calculated from Eq. (10) and 'D' from Eq. (11).

$$I_{eq} = \frac{bK_c t_c{}^3}{12} + (bk_c t_c)\left(z + \frac{t_c}{2}\right)^2 + \frac{\left(\frac{b}{m}\right) z^3}{3} + \frac{bK_t t_t{}^3}{12} + (bk_t t_t)\left(h_c - z + \frac{t_t}{2}\right)^2 \tag{10}$$

$$D = E_s \left\{ \frac{bK_c t_c{}^3}{12} + (bk_c t_c)\left(z + \frac{t_c}{2}\right)^2 + \frac{\left(\frac{b}{m}\right) z^3}{3} + \frac{bK_t t_t{}^3}{12} + (bk_t t_t)\left(h_c - z + \frac{t_t}{2}\right)^2 \right\} \tag{11}$$

4. Experimental Investigation

Eight SCS beam specimen were placed under a two-point load with depth of core 230 mm, span length 2400 mm, width 150 mm and steel plate of 4mm thickness were used. Fe 415 steel rods having 8mm diameter, length equivalent to 165 mm were used for normal and j-hook shear stud connectors welded on both compression and tension plates across the length of the beam with center-to-center spacing of 150mm. A clear cover of 25 mm was kept around the beam and the beams, CC, CCQ, CSC and CSCQ to be tested were simply supported having a clear length of 2200 mm. TML-10 millimeter having the resistance of 120 W electrical strain gauge was fixed to measure the development of strains and the wires from the strain gauges were abuted to the ten channel data logger. The deflections on one-third of the specimen were recorded by a linear variable displacement transducer (LVDT) and one dial gauge was fixed on the middle of the beam bottom and two dial gauges fixed on both sides at the bottom of the beam. A schematic representation of the loading arrangement to test the beam is illustrated in Fig. 5. Results obtained and the behaviour of SCS beam element with normal and j-hook connectors, failure moment at ultimate, deflection arid ductility possessions are discussed.

5. Results and Discussion

Figs. 6(a), (b) and (c) shows a SCS beam test at different stages; before, during arid after testing. The moment capacity predicted for SCS beams based on both elastic and plastic theories are given in Table 3. Compared to elastic theory, moment capacity predicted for SCS beams from plastic theory approach are higher and therefore plastic and experimental moments are taken and determined the capacity ratios.

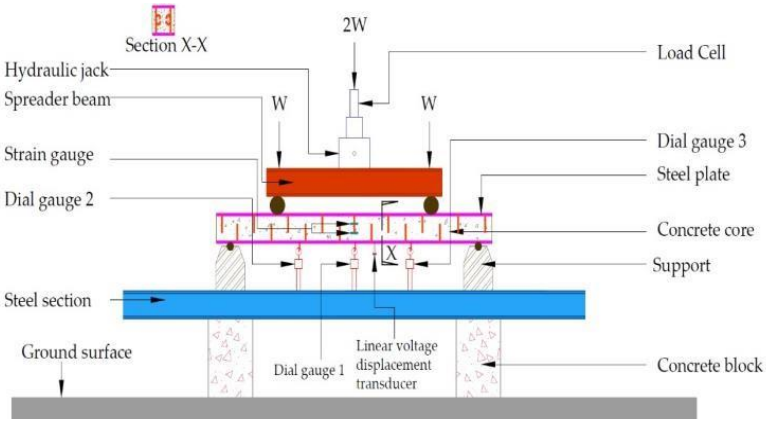

Fig. 5 - Schematic illustration of loading arrangement

(a) Before test (b) During test (c) after test

Fig. 6 - SCS beam with normal shear studs and J-Hook studs under flexural test

Table 3 - Predicted and experimental moments comparison

Mix ID	Type of composites	Neutral Axis depth (z) (mm)	Moment (kNm) Elastic M_{el} (kNm)	Moment (kNm) Plastic M_{pl} (kNm)	Experimental M_{exp} (kNm)	Capacity Ratio (M_{exp}/M_{pl})
			Normal shear studs			
CC	Fully	70.81	31.88	33.90	34.52	1.02
CCQ	composite	70.39	31.88	33.90	37.39	1.10
CSC	Partial	89.89	13.92	14.57	30.20	2.07
CSCQ	composite	89.39	14.72	15.42	33.08	2.15
			J–Hook			
CC	Fully	70.81	31.88	33.90	44.58	1.31
CCQ	composite	70.39	31.88	33.90	47.46	1.40
CSC	Partial	89.89	18.85	19.73	37.39	1.89
CSCQ	composite	89.39	19.56	20.48	38.83	1.89

Predicted ultimate moment of the SCS beams are lower than the experimental results and hence it is generally conservative. Compared to other mixes (CC mix 34.52 kNm; CSC mix 30.20 kNm; and CSCQ mix 33.08 kNm) used beams, CCQ used beams carries higher moment (37.39 kNm) capacity. Also, in each case the experimental moments are higher in case of j-hooks used beams (CC mix 44.58 kNm; CCQ mix 47.46 kNm; CSC mix 37.39 kNm; and CSCQ mix 38.83 kNm) compared to normal studs used beams. This indicates that the strength of the concrete core and the types of shear connectors plays vital role in moment capacity.

Deflection at the center of SCS beams observed approximately on the value of two-third of its moment at ultimate. This was considered as the basis to compare the theoretical deflection as mentioned in the earlier study [12]. These comparative values of deflections are presented in Table 4. It can be seen that the predicted deflections of both normal and j-hook shear studs used are higher than the experimental deflections in case of CC and vice versa in case of CSC. This is happened due to less stiffness and strength of CS compared to conventional aggregates. From this study it can be stated that the concrete strength and types of hooks controls the deflections also.

Table 4 - Predicted and experimental deflection comparisons (Service)

Mix ID	Service moments, (kNm)	Predicted deflection, Δtheo (mm)	Experimental deflection, Δexp (mm)	Δexp / Δtheo
		Normal shear studs		
CC	23.01	7.65	5.40	0.71
CCQ	24.92	7.61	5.50	0.72
CSC	20.13	3.86	5.56	1.44
CSCQ	22.05	4.06	5.18	1.28
		J–Hook		
CC	29.72	7.65	6.11	0.80
CCQ	31.64	7.61	6.35	0.83
CSC	24.93	5.23	5.77	1.10
CSCQ	25.89	5.39	5.64	1.05

If ductility ratio in deflection is more, then it means that these elements will be able to sustain the loads and will give warning before it is fails. Generally, ductility ratio should be in between 3 and 5 for any structural element subjected to seismic forces or any other dynamic forces for its adequacy [3]. Ductility ratios of the tested beams in this study are given in Table 5. Ductility ratio of all beams tested in this study are having more than 3 (Table 5) indicates that all these SCS beam elements are more ductile. Irrespective of the concrete strength of all beams gave the ductility ratio more than 3 ductility ratio which means that the steel plate and shear studs are also contributes for the improvements towards ductility.

Table 5 - Deformation ductility ratio

Mix ID	Yield deflection (mm) Δy	Ultimate deflection (mm) Δu	Ductility (μ) = Δu / Δy
		Normal shear studs	
CC	5.40	24.48	4.53
CCQ	5.50	22.54	4.10
CSC	5.56	27.40	4.93
CSCQ	5.18	26.14	5.05
		J–Hook	
CC	6.11	22.22	3.64
CCQ	6.35	20.34	3.20
CSC	5.77	26.57	4.60
CSCQ	5.64	23.46	4.16

6. Conclusion

In this study CSC was used as core concrete in the concept of SCS beam elements produced. SCS beam elements were produced using normal studs and j-hook type studs. In this type of SCS beam used with shear studs, the projected moment at ultimate is conservative. Moment carrying capacity at ultimate for the CCQ mix used SCS element is higher than the other mixes used beams because of their respective strength and the type of studs used. Use of QD in its place of RS enhanced strength of beams and therefore QD can be considered as substitute material for RS on sustainable aspect.

The deflection values of SCS beams made with CSC and CSCQ beams show alike performance of SCS beams used with CC and CCQ mixes. Predicted deflections were underestimated compared to experimental values. Good ductility behaviour was found on all SCS beams used in this study.

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