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Experimental study on flexural behaviour of partially encased cold-formed steel composite beams using rebar as shear connector

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Abstract. This paper focuses on the composite action of two samples each consisting of two composite beams and a composite slab with bent up rebar as a shear connector. The specimens were knowingly adapted to have different shear transfer capacities along the interfaces with different geometries of the composite beams. By using the four-point bending tests of the two full-scale specimens, the authors experimentally evaluated the flexural behaviour of the partially encased composite beams. Therefore, this paper presents experimental works on the structural performance of composite beams consisting of cold-formed steel (CFS) section with self-compacting concrete (SCC) by means of the shear connection mechanism of the proposed using deformed reinforcement bar. The results have shown that the theoretical value of flexural capacities designed agrees well enough with the experimental results. Based on the present beam tests results it was realised that the new composite system showed slightly higher results than predicted with ultimate moment ratios between 0.89-0.91% and 0.83-1.08% for the 250 mm and 150 mm beam respectively. According to the experimental bending test results, the composite section can reach the ultimate strength without compression buckling failure or local shear when the proposed shear connector was presented in the composite action. Analysis and design of composite beams are studied to validate the present test results.

1. Introduction

CFS is used widely in ships, mining head frames, steel and concrete bridges, gantry cranes and aircraft. But there are numerous reasons why CFS structures must be given more attention in their analysis and design. In CFS beams the shear stresses and strains are moderately higher than that those in a solid beam. This arises questions into the usual hypothesis of bending theory, that is, that plane sections remain plane over the entire cross-section of a box girder. CFS is also susceptible to local



buckling if the in-plane stress reaches their critical values. This means that CFS structures must be designed against both local buckling and overall buckling. Therefore, infilling a box section with concrete will redistribute stresses which leads to enhancing the resistance of the CFS section to local and global buckling.”

Composite beams are one of the most widely used members in the construction industry and have been extensively used for its reliability, rapid erection, cost-effectiveness, and strength. However, one property they all have in common is that they are very light compared with alternative structures and, therefore, they are used extensively in long-span bridges and other structures where weight and cost are prime considerations. Recently, researchers have shown an increasing interest in the application of cold-formed steel in the construction industry by utilizing it in composite sections to provide lighter weight of the structural system. Therefore, to bring back symmetry and decreases lateral-torsional buckling effect a boxed section was created by orienting two CFS lipped C-channel sections toe-to-toe as in Figure 1. These two advantages retain by the system, encourage the use of CFS sections in a wider range of structural applications [1,2,3].

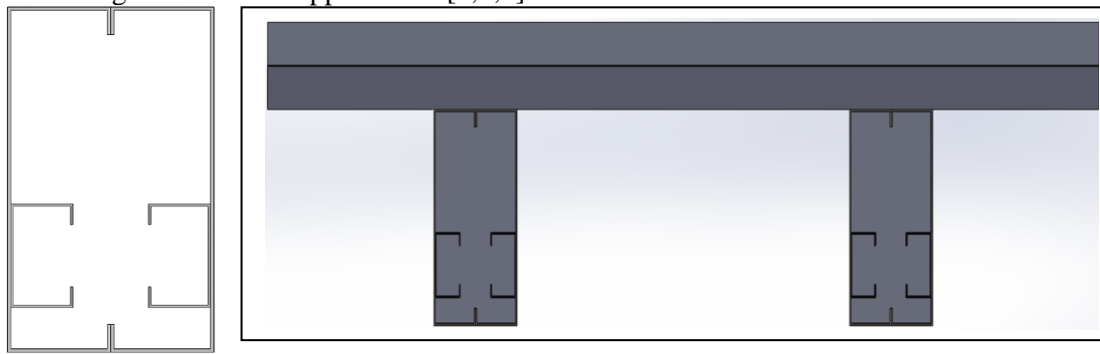


Figure 1. CFS box section.

It was at first customary to design the steelwork to carry the whole weight of the concrete slab and its loading, but by about 1950 the development of shear connectors had made it practicable to connect the slab to the beam, and so to obtain the T-beam action that had long been used in concrete construction. Composite construction takes advantage of the qualities of concrete and steel. The steel beams and profiled steel sheeting act as permanent falsework and formwork for the wet concrete. Once cured, the concrete can provide all or most of the compression force needed for bending resistance of the floor slab or beams. The steel beam provides all the tension force for bending resistance and, due to the stabilizing effect of its connection to the concrete slab, as much compression force as is called for. The functionality of the composite slab to endure loads is governed by the interaction level of the two main structural parts which called the degree of shear connection. consequently, whenever the connection between these two substances is improved, the stiffness and capability of the composite slab enhanced [4,5].

The development of new types of composite beams and shear connectors has become increasingly popular in the past decades and the effectiveness of applying CFS sections to beams to either help reduce the costs or eliminate the construction difficulty associated with the shear connectors or prevent CFS failure modes.

In the present research, a new composite beam with CFS infilled with self-compacting concrete has been experimentally and analytically studied to achieve higher strength and ductility, as well as to yield a more economical design purpose. A full-scale four-point load testing has been done to evaluate the performance of the innovative shear connector for the proposed composite structure illustrated in Figure 2.

In the new proposed composite system, each concrete slab was connected to two parallel CFS infilled beams using deformed bent-up rebar. system comprises of a corrugated steel deck to support a cast-in-place self-compacting concrete slab with transverse reinforcement on top of two CFS beams parallel to each other each consisted of two toe-to-toe C-sections and a bent-up rebar as a shear

connector to link the CFS beam and the composite slab as a way to offer vertical interlocking and horizontal shear resistance. Self-drilling fasteners are used for connecting all the steel parts. Thus, the key part of an effective composite structure comes from a novel shear connector within the concrete slab, cold-formed steel joists, fasteners, and metal deck so that all structural components in this composite floor system are acting together as one unit to transfer the applied loads without failing [5].

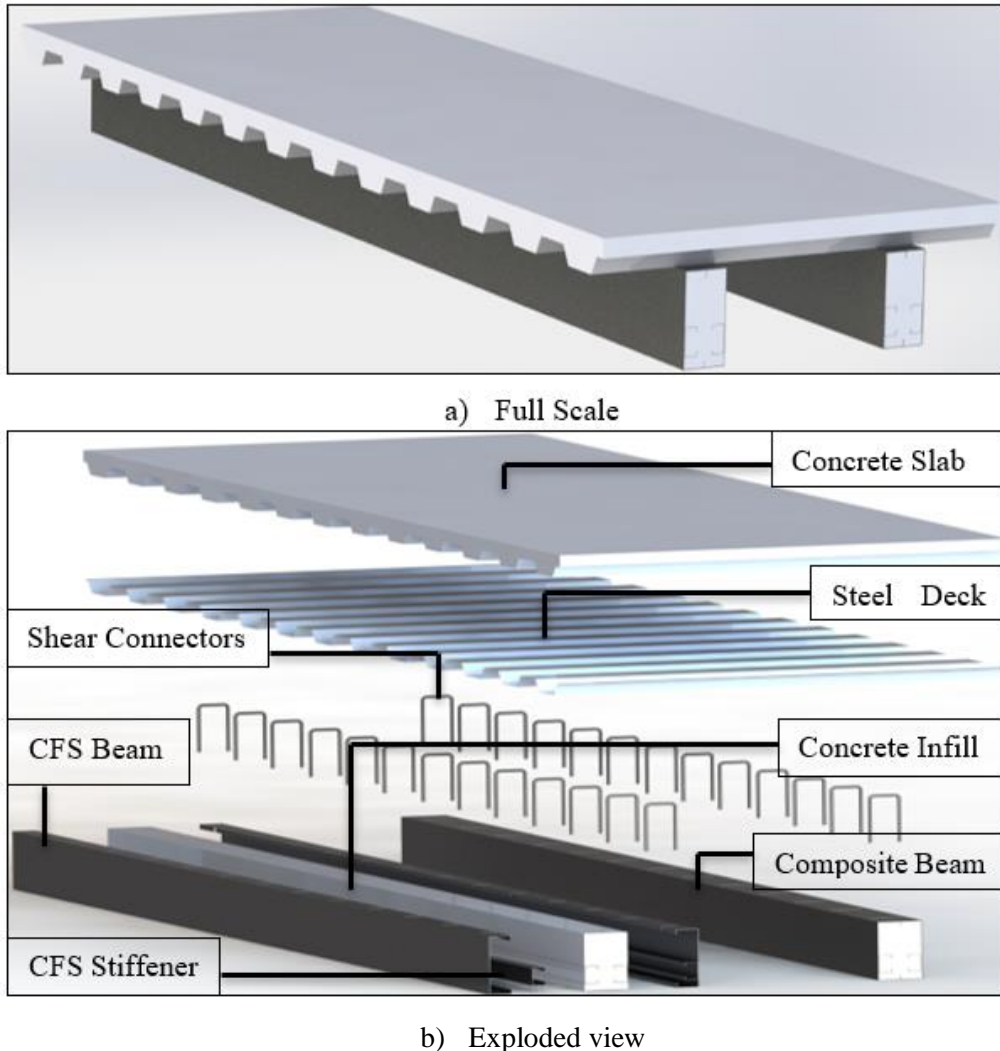


Figure 2. The proposed composite system.

2. Material and methods

2.1. Material

Material used in this study are CFS of lipped C-channel section with the width of 150 mm, the depth of 250 mm, and lipped depth of 20 mm and a thickness of 2.4 mm with a yield strength of 450 N/mm^2 is used for the proposed encased composite beam with a modulus of elasticity taken as 210 kN/mm^2 . The CFS beam material will be formed into Box-profile (Toe-to-Toe) linked with top and bottom arc welding. The steel properties were obtained according to BS EN 10002-1 using INSTRON 600 DX as shown in Table 1 [6]. Three samples were collected from the web of the CFS profile and three more samples were collected from steel reinforcement. The proposed shear connector made from deformed bent-up rebar of 12 mm diameter with a steel grade S460, the shear connectors was embedded in the SCC through a CFS flange that has been cut to install the shear connectors. BRC welded wire mesh

A142 with a diameter of 6 mm with a spacing of 200 mm in both directions was used as reinforcement mesh and SCC of grade 40 N/mm² at 28 days respectively are the material used in this study.

SCC was a ready-mix from LAFARGE company and was cast in the laboratory, without the need of extra formwork. The profile steel deck yield strength of 350 MPa, the nominal thickness is 1.0 mm and profiled sheeting rib height of 50 mm, the composite sample dimensions are showed in Table 2 [7,8,9].

Table 1. CFS coupon tensile test results.

Properties N/mm ²	Thickness mm	Web		Flange		Average	$\frac{f_u}{f_y}$
		Wb1	Wb2	Fln1	Fln2		
Yield Stress (f_y)		570	571	546	555	560.50	
Ultimate Stress (f_u)	2.4	639	649	623	636	636.75	1.14
Elastic Modulus (E_s)		188000	187000	176000	177000	182000	

Table 2. Composite Specimen Dimensions.

Specimen ID	Length	Slab		CFS Beam			Shear Connectors		
		Width	Depth	Thickness	Depth	Transverse Spacing	Number	Size	Height
		(mm)	(mm)	(mm)	(mm)	(mm)		(mm)	(mm)
TT-250-12-12	4000	1500	100	2.4	250	750	13	12	75
TT-150-12-12	4000	1500	100	2.4	150	750	13	12	75

2.2. Test setup loading protocol and instrumentation

All full-scale composite beam specimens were tested using hydraulic jack machine with a maximum capacity of 1000 kN. The specimen was subjected to four-point bending load test where the load was applied 1000 mm from the supports. A load cell is used between the jack and spreader beam in order to measure the applied load by connecting the load cell to the data logger. The load was applied to the specimen through a spreader beam that receives the load from the jack and transfers it to the concrete slab. A strip of gasket rubber under the point loads is used to absorb any imperfections in the concrete slab surface and to provide uniform contact surface between the concrete slab and the point load.

The sample was fixed in a simply supported position. To measure the vertical deflection at mid-span of the beam specimen, deflections of the specimen were measured using six linear variable displacement transducers (LVDT's) positioned at the critical zones at loading points and mid-span of the test specimen as in Figure.3. Slips were also observed using two LVDT's attached to the centreline of the concrete slab faces at the support's sides i.e. roller and pin. All LVDTs were connected to data logger where the displacements were measured in "mm". Strain gauges were installed in the critical zones at the bottom flange of the steel beam as well as the top surface of the concrete slab at the maximum shear and bending areas.

After the test specimen was setup and instrumented, the specimen was loaded up to 15-20% of its expected ultimate capacity and waited for 5 minutes, then unloaded to make sure that the specimen and instrumentation were settled. All the readings of load, LVDTs and strain gauges were zeroed to insure equilibrium. Subsequently, the load was applied to the specimen by loading increment with a

pause of 5 minutes between each increment. The reason of using this mode is to provide enough time for observing and visualizing the specimen until failure. The load was increased until the ultimate capacity of the specimen. The specimen considered failed where there was a considerable deformation of the test specimen was spotted or a substantial drop in the applied load [10,11,12].

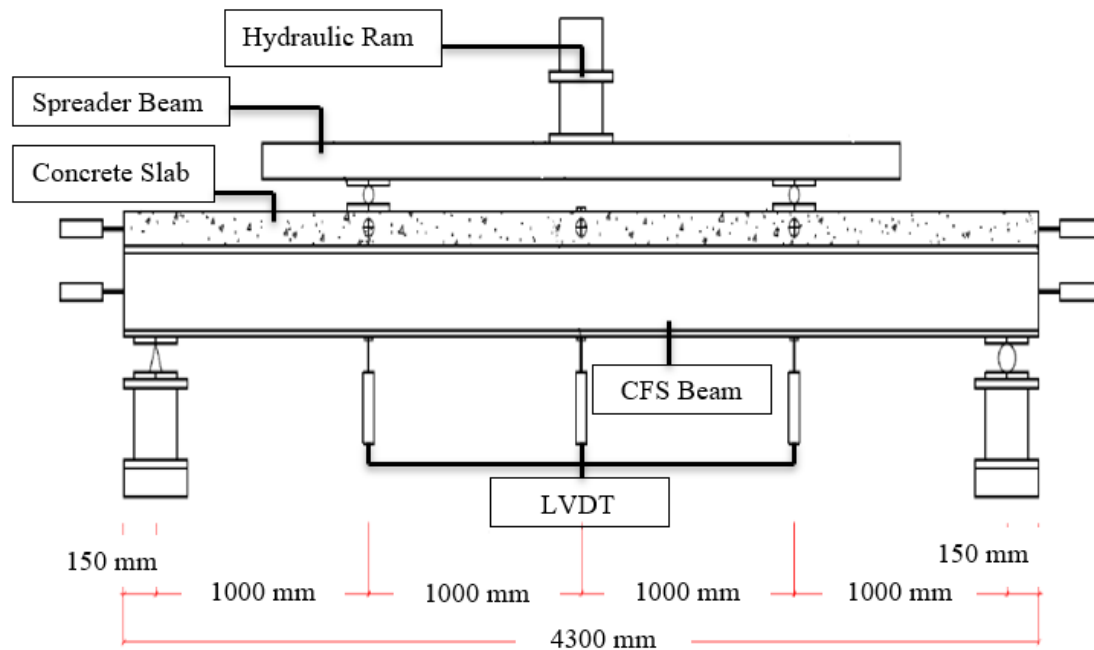


Figure 3. Schematic diagram of a test arrangement.

3. Experimental results and validation

Both samples failed in the same manner due to a combination of high shear force and bending moment at critical sections (loading points and support zones). The failure mode originated by the creation of longitudinal cracks along the line of shear connectors on the surface of the concrete slab. As loads increased, new cracks developed in the concrete slab towards the loading points. The concrete start cracking at the top surface of the slab near the support zone with and extending transverse crack, followed by crushing of concrete, local buckling of CFS at loading zone and a clear expansion of the support transverse crack due to the combination of maximum moment and maximum shear. The load was monotonically increased until failure occurred.

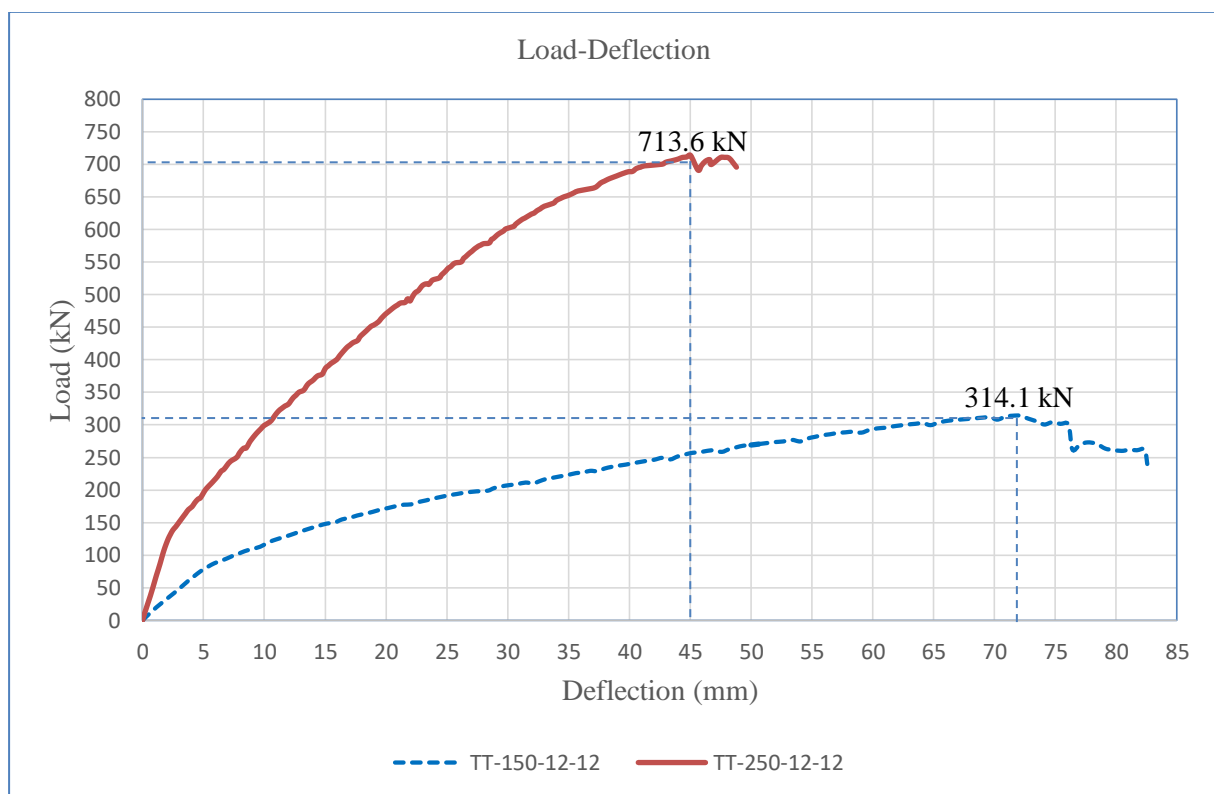
Table 2 shows a comparison between the predicted ultimate moment capacity values following the EC 4 and EC 3 and the ultimate moment capacity obtained in the experiments [13,14,15,16]. The predicted values using both stress block method and interpolation method. The predicted values by the interpolation method gave more accurate results compared to the stress block method.

The load carrying capacity of the tested specimens or Load against mid-span deflections curves for specimens is shown in Figure 4. The ultimate loads (P_u , exp.) of the specimens were 713.6 kN and 314.1 kN with a 45.5 mm and 71 mm recorded mid-span deflections at an ultimate loads level for the 250 mm and 150 mm beam respectively.

From table 2 and figure 4, it's noticeable that the difference in section capacity between the two specimens is high, the 250 mm beam carry the higher load with lower mid-span deflection while the 150 mm beam has significantly higher deflection than the ultimate for the ultimate limit state. The failure modes of the specimens were local buckling of CFS and cracks of the concrete slab as shown in Figure 5.

Table 2. Experimental and theoretical capacities of composite specimen.

<i>Specimen ID</i>	<i>TT-250-12-12</i>	<i>TT-150-12-12</i>
f_{ck} at test day (N/mm^2)	60.55	60.55
Ultimate load P_u , exp (kN)	713.6	314.1
Mid-Span Deflection at P_u , exp (mm)	45.5	73.62
Ultimate Moment M_u , exp (kNm)	356.8	157
Interpolation Method M_u , theory (kNm)	390.04	145.28
M_u , exp / M_u , theory	0.91	1.08
Stress Block Method M_u , theory (kNm)	401.18	188.23
M_u , exp / M_u , theory	0.89	0.83

**Figure 4.** Load-deflection curve.

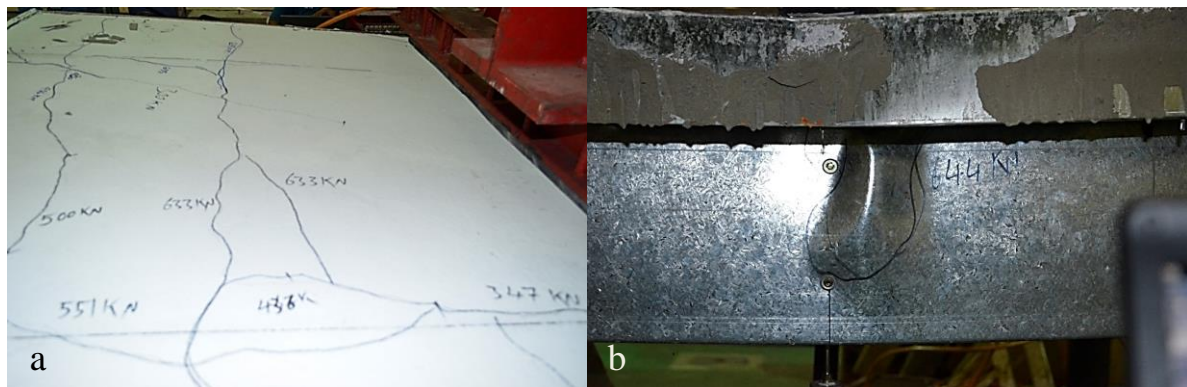


Figure 5. Failure modes of composite specimens, (a) transverse and longitudinal cracks in concrete slab surface, (b) local buckling on CFS web.

4. Conclusions

Based on the results from the experimental and analytical work completed in this research, the following significant conclusions may be drawn:

1. By looking at the mid-span deflection, the 250mm beam appears to have stiffer behavior compared to the 150 mm leading to higher section capacity.
2. The infilled CFS beam showed higher capacity compared to normal slender sections by reaching to the yield stress.
3. The proposed analysis and design methods herein have been found to be able to predict the ultimate strength capacity of the proposed composite system by using the procedure adopted from EC4.
4. Using bent-up rebar as shear connector gives a high degree of composite action ratio which means attaining higher yield strength of the composite section. It's because the continuous shear connector has helped move upward the neutral axis of the composite section, thus prevented the top flange of CFS to buckle under compression.
5. The experimental specimens of the partially encased composite beams consistently showed ductile flexural behavior. The high flexural strength and ductility observed in each specimen suggest that the partially encased composite beam can be adopted in future practice.
6. The partially encased steel beam is an efficient technique for enhancing its flexural capacity.

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