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Static Behaviour of Precast Cold-Formed Steel-Concrete Composite Beams with an Innovative Shear Transfer Enhancement

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Abstract
A new connection device, based on bent-up tab shear transfer enhancement called bent-up triangular tab shear transfer (BTTST), has been studied through a cold-formed steel (CFS)-concrete composite beam subjected to a static bending test. BTTST provides an alternative connector system unique to CFS where CFS sections are usually thinner than hot-rolled sections and welding of headed-stud shear connectors is inapplicable. Coupled with the back-to-back arrangement of two CFS channels where symmetricity of the built-up section is restored, the resulting composite floor system has been proven to possess adequate strength, stiffness and ductility properties under static loads. The work has shown specimens employed with BTTST increase the strength capacities and reduce end slips of the specimens as compared to those relying only on the natural bond between CFS and concrete.

Keywords: cold-formed steel (CFS), composite beams, precast beams, shear transfer mechanisms.

1. Introduction

Cold-formed steel (CFS) sections, usually between 1.2 and 3.2 mm thickness [1], have been recognised as an important contributor to environmentally responsible, sustainable structures in the developed countries, and CFS framing is considered a sustainable 'green' construction material for low rise residential and commercial buildings. Their use however limited to structural roof trusses and a host of non-structural applications [2].

One limiting feature of CFS is the thinness of its section that makes it susceptible to torsional, distortional, lateral-torsional, lateral-distortional and local buckling. Resorting to a composite construction of structural CFS sections and a reinforced concrete deck slab, minimises the distance from the neutral-axis to the top of the deck and reduces the compressive bending stress in the CFS sections and arranging two CFS channel sections back-to-back restores symmetricity and suppresses lateral-torsional and to a lesser extent, lateral-distortional buckling. The two-fold advantage promised by the system promotes the use of CFS sections in a wider range of structural applications.

An efficient and innovative floor system of built-up cold-formed steel (CFS) sections acting compositely with a concrete deck slab has been developed to provide an alternative composite system for floors and roofs in buildings. The system, called Precast Cold-Formed Steel-Concrete Composite System, is designed to rely on composite action between the CFS sections and a reinforced concrete deck where shear forces between them are effectively transmitted via another innovative shear transfer enhancement mechanism called a bent-up triangular tab shear transfer (BTTST) as shown in Figure 1.

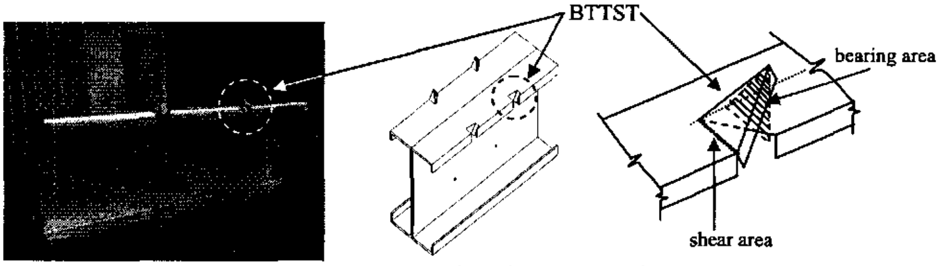

Figure 1 Bent-up triangular tab shear transfer (BTTST)

2. Large-Scale Flexural Test Program

The purpose of large-scale tests is to evaluate and determine the behaviour of CFS-concrete composite beams. The specimens were tested by using four-point load bending test. Four-point load bending test is actually a flexural test which provides a pure bending moment section without any shear force occurred along the section.

2.1. CFS-Concrete Composite Beam Test Specimens

The beams are 3m long and are spanning 2.7m between supports. The width of the concrete slab is 675mm, calculated based on the value of one quarter span (span/4) [3,4,5]. The width is taken as the effective width, b_e by neglecting the lag effect. The thickness of the slab is 90mm, chosen to represent the closer beam-to-beam construction. Cold-formed steel I-section beam was formed by back-to-back lipped channels with the top flanges cast into 675mm wide x 90mm depth concrete slab. To increase the efficiency of the shear connection, BTTST formed in the flanges is employed. The welded wire fabric reinforcement consist of 8mm diameter bars with grid spacing of 100mm x 100mm and steel grade 460 are used for the reinforcement. The use of wire meshes in the slab shown gave higher flexural stiffness and capacities then if rebars were used instead [6]. Figure 2(a) and (b) show the formwork and casting work respectively. Figure 3 shows the composite beam test specimen. Total of 15 composite beam specimens were used and detail descriptions of each specimen are summarized in Table 1.


(a)

(b)

Figure 2 (a) Formwork and (b) Casting of composite beam specimen

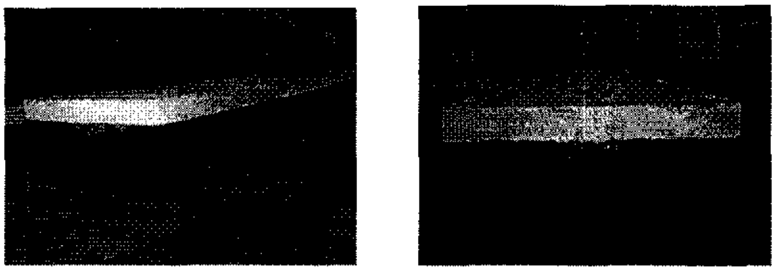
Figure 3 CFS-concrete composite beam specimen

Table 1 Composite Beam Test Specimens

Series	Group	Specimen	Type of Enhancement	Dimension (mm x mm)	Angle (degree)	Spacing (mm)	CFS Thickness (mm)
G25	L1	L1a,L1b,L1c	BTTST	25 x 25	45	150	2.4
	L2	L2a,L2b	BTTST	30 x 30	60	150	2.4
G35	L3	L3a,L3b	Control	-	-	-	1.9
	L4	L4a,L4b	LYLB	25 x 25	45	150	1.9
	L5	L5a,L5b	BTTST	30 x 30	60	150	1.9
	L6	L6a,L6b	BTTST	30 x 30	60	200	1.9
	L7	L7a,L7b	BTTST	30 x 30	60	150	2.4

2.2. TEST SETUP AND PROCEDURES

All precast cold-formed steel-concrete composite beam specimens were tested using Universal Testing Machine (UTM IPC 1000) subjected to four-point bending test system. Four-point load bending test is actually a flexural test which provides a pure bending moment section without any shear force occurring along the section. This situation can clearly be clarified from its shear force and bending moment diagrams. The shear force between the two loading points is zero and therefore provides a pure bending moment on that area. This test method evaluates the flexural performance of toughness parameters by testing a simply supported beam under two concentrated loads. Each specimen supported with a pin at one end and a roller at the other end to indicate that the test is a simple support beam structure. The instrumentation setup is shown in Figure 4. Slips were measured with transducers that were attached at the top of the cold-formed steel lipped channels and the centerline of the slab cross section. A slip is defined as the difference in the deformation of the two elements. All measurements were connected to a data logger.

Figure 4 Instrumentation test setup

All of the composite beams were tested in the same manner. The load was applied using hydraulic ram and measured with load cells placed above the rams. Each ram applies load to a "distribution beam" that is supported by the test specimen. All loads from the ram were distributed to the two points on the test specimen. Initially, about 15% of its predicted capacity was loaded onto the beam. Then it was unloaded where all measurements were "zeroed". This is to make sure that the testing specimen is sitting on a proper position before testing is continued [4]. The load applied was then increased and all measurements after each increment were recorded. Thereafter, the beam was loaded in increments of mid-span deflection until failure of the specimen was observed or until very large deflections happened.

3. Test Result

The purpose of the flexural bending test was to determine the behaviour of the precast CFS-concrete composite beams and to determine the effect of the bent-up tabs shear transfer (BTTST) enhancement arrangement. The results that can be sustained by each specimen is summarised in Table 2. The average results of each group of specimen were used later for parametric study.

Table 2 Experimental results

Group	Spec.	Ultimate Load, P_u (kN)	Average P_u (kN)	Deflection at P_u, δ_u (mm)	Average δ_u (mm)	Ultimate Moment, $M_{u,exp}$ (kNm)
L1	L1a	168.2	167.8	36.7	39.1	113.3
	L1b	168.2		35.2		
	L1c	166.9		45.3		
L2	L2a	173.0	172.6	36.5	38.2	116.5
	L2b	172.1		39.9		
L3	L3a	132.6	131.6	42.6	44.9	88.8
	L3b	130.5		47.1		
L4	L4a	146.0	144.2	41.8	41.5	97.3
	L4b	142.4		41.2		
L5	L5a	155.0	155.2	30.0	38.0	104.8
	L5b	155.3		45.9		
L6	L6a	154.6	153.7	34.8	34.7	103.7
	L6b	152.7		34.5		
L7	L7a	182.0	182.0	39.9	39.9	122.8
	L7b	*		*		

*Electrical interruption

4. Parametric Study

4.1. Shear Transfer Enhancements

Testing for group L3, L4 and L5 was setup to investigate the effect of difference type of shear transfer enhancement in CFS-concrete composite beam. The ultimate load that can be sustained by each specimen is summarised in Table 3. It was found that the CFS-concrete composite beams specimen with shear transfer enhancements showed an increase in capacities of ultimate moment, $M_{u,exp}$. Referring to Table 3, the ultimate capacity of specimen L4 (with LYLB) is 9.6% higher than that of specimen L3 (without enhancement). L5 (with BTTST) shows a 18% increase in ultimate capacity over specimen L3. A comparison of the capacities of LYLB and BTTST indicates that the BTTST result was 7.7% higher than that of specimen L4 with LYLB. Therefore, it can be concluded that the ultimate moment resistance of CFS-concrete composite beams with BTTST are better than CFS-concrete composite beams with LYLB.

Table 3 Ultimate Strength of Composite Beams with difference shear transfer enhancement

Group	Type of Enhancement	Ultimate Moment, $M_{u,exp}$ (kNm)	$M_{u,exp}$ Increment (%)	
L3	Without enhancement (control)	88.8	-	-
L4	LYLB	97.3	9.6	-
L5	BTTST	104.8	18.0	7.7

4.2. Dimension of BTTST (size and angle)

As per discussed in [7,8,9], the augmentation in ultimate moment capacity of the CFS-concrete composite beams with BTTST have relied on the increase in shear transfer enhancement resistance, contributed by the bearing area (see Figure 1) of BTTST. The increment on dimension and angle of BTTST produces more bearing area prevents the concrete from slip. Referring to Table 4, the ultimate moment of L2 composite beam with dimension 30mm x 30mm and angle 60° of BTTST is higher than that of L1 beam with dimension 25mm x 25mm and angle 45° possessed 2.8% higher than L1 beam.

Table 4 Ultimate Strength of Composite Beams difference dimension of BTTST

Group	Dimention of BTTST ($L_f x\ L_s$, θ)	Ultimate Moment, $M_{u,exp}$ (kNm)	$M_{u,exp}$ Increment (%)
L1	25 x 25 , 45°	113.3	-
L2	30 x 30 , 60°	116.5	2.8

4.3. Degree of shear connection

The effect of the difference degree of shear connection is shown in Table 5. The table show a decreased from 104.8kNm to 103.7kNm for specimen L5 and L6, respectively as the bending moment reached its ultimate capacity. It is clear that the decreased is too small with the value about 1.1%. It is stated that the CFS-concrete composite beam practically be design with partial shear connection for equal moment capacity by reducing number of BTTST.

Table 5 Ultimate Strength of Composite Beams difference degree of shear connection

Group	Degree of shear connection	Ultimate Moment, $M_{u,exp}$ (kNm)	$M_{u,exp}$ Decrease (%)
L5	Full	104.8	-
L6	Partial	103.7	1.1

4.4. Thickness of CFS

Specimens group L5 and L7 was test to investigate the effect of difference thickness of CFS. Table 6 show a comparison between the ultimate moment, M_u, obtained experimentally using 1.9mm thick and 2.4mm thick CFS with BTTST shear transfer enhancement. The ultimate moment was recorded at 122.8kNm from specimen with 2.4mm thick compared with 104.8kNm obtained from the specimen with 1.9mm thick. It is increased by 17.2%. This result is also similar to result obtained from the work done by Lakkavalli and Liu [10]. The shear area (refer Figure 1) of the shear transfer enhancement increases when the thickness is increase. Shear area acts as the resistance for shear transfer enhancement from bending. The bending capacity of the shear transfer enhancement increases with the increase of shear area.

Table 6 Ultimate Strength of Composite Beams difference thickness of CFS

Group	CFS thickness (mm)	Ultimate Moment, $M_{u,exp}$ (kNm)	$M_{u,exp}$ Increment (%)
L5	1.9	104.8	-
L7	2.4	122.8	17.2

4.5. Concrete strength

Concrete strength is one of the parameters considered in this large-scale experimental program. Table 7 shows ultimate moments of tested specimens with f_{cu} 27.71N/mm^2 and 35.63N/mm^2. Specimens L7, with higher grade of concrete strength carried 17.3% more ultimate moment than that of specimens L2. This is expected, since the higher grade of concrete hence increases the capacity of a structure.

Table 7 Ultimate Strength of Composite Beams difference thickness of CFS

Group	Concrete compressive strength, f_{cu} (N/mm^2)	Ultimate Moment, $M_{u,exp}$ (kNm)	$M_{u,exp}$ Increment (%)
L2	27.71	116.5	-
L7	35.63	122.8	5.4

5. Conclusions

Fifteen companion large-scale specimens were tested to evaluate the strength and behavior of precast cold-formed steel-concrete composite beams. The test results can be summarized as specimens employed with shear transfer enhancements increase the strength capacities and reduced deflection of the specimens as compared to those relying only on a natural bond between cold-formed steel and concrete. In shear transfer enhancements investigated, BTTST provided the best performance in terms of strength and deflection. Strength capacities of the CFS-concrete composite beams also increase when the dimension of BTTST, thickness of CFS and concrete strength is increase. The CFS-concrete composite beam practically design with partial shear connection for equal moment capacity by reducing number of BTTST.

6. Acknowledgment

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