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Experimental studying bending behavior of cold-formed steel-concrete composite beam using perfobond shear connection

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KEYWORDS

Bending behavior
Perfobond shear connector
The cold-formed steel-concrete composite beam
Deflection
Load capacity

ABSTRACT

An experimental program was carried out on two large-scale steel-concrete composite beams to investigate the effect of the concrete slab dimension on the bending behavior of these beams. The steel-concrete composite beams used cold-formed steel and perfobond shear connectors. The webs of two cold-formed steel and perfobond shear connectors were attached by screws. The parameters evaluated in this program were load capacity, vertical deflection, and the relative slip between the steel beam and the concrete slab. The results showed that the thickness of the concrete slab and the shear connector width enhanced the load capacity and reduced the vertical deflection of steel-concrete composite beams.

1. Introduction

Cold-formed steel construction is widely recognized as an important contributor to sustainability and green construction, and cold-formed steel has the advantage because of inflame, low cost, fast installation, almost no expansion, and shrinkage. The cold-formed steel-concrete composite beam has been used popularly for bearing structures. This structure is suitable for light-loading structures, easy erection, quick construction, and low cost. Many studies have been carried out with small specimens using push-out tests and large-scale beamstoo investigate the structural behavior of specimens. Cheng-Tzu Thomas Hsu (2012) introduced a composite beam system consisting of three elements: reinforced concrete slab on corrugated cold-formed metal, back-to-back cold-formed steel joists, and cold-formed furring shear connector. The test program was carried out on six large-scale bending tests to observe the positive moment capacity, vertical deflection, and end slip of the proposed composite beam system [1]. Nadim Wehbe (2013) performed a series of full-scale test specimens representing concrete/CFS flexural elements under gravity loads to investigate the structural performance of concrete cold-formed steel simple beams and concrete cold-formed steel continuous headers. The results indicate that concrete/CFS composite flexural elements are feasible and their structural behavior can be modeled with reasonable accuracy [2]. Ahmed Youssef Kamal and Nader Nabih Khalil (2017) executed a series of bending tests, to examine the influence of encasing cold-formed steel (U-section) in a reinforced concrete beam on the beams' capacities, mode of failure, and ductility. The test results show that the cold-formed steel (U-section) increased the beam load capacity and improved beam ductility. It has been observed that encasing the formed steel sections reduced the influence of the steel sections' local buckling [3]. M Lawan (2019) tested six large-scale steel concrete composite beams to determine the flexural capability as well as the behavior of the CFS-SCC composite beam specimens [4]. M. M. Tahir et al. (2019) tested eight large-scale steel composite beams assembled by two CFS C-lipped channels back to back to construct I-beam sections. The composite beams were drastically stronger and stiffer than non-composite beams [5]. S. Sathyan (2019) studied the behavior of four composite SCC beams. The results show that the composite SCC beams raise the ultimate load-carrying capacity and drop the ultimate mid-span deflection for increasing the load and reducing the flexural crack widths, in comparison with that of the reinforced concrete beam [6]. Valsa Ipe. T. studied the behavior of cold-formed steel channel section beams with an infill of concrete [7]. The experiment program was carried out on 12 large-scale beams, with six infilled concrete and six hollow section beams. This study evaluated the effect of the depth-to-thickness ratios on the bending behavior of steel concrete composite beams. Sumiati (2021) investigated the structural behavior of steel concrete composite beams using C cold-formed steel substituting for reinforcement in lightweight concrete beams. The results showed that these beams could increase the stiffness, ultimate load, and modulus of rupture of the beam [8]. P. Sangeetha tested six small steel-concrete composite beams with a length of 1000 mm to study the flexural behavior of the cold-formed galvanized steel–concrete composite beam with or without headed stud connectors [9]. Nhu The Nguyen (2022) studied the structural behavior of shear connectors of cold-formed steel by push-out test. This study investigated the effect of parameters on load capacity, the relative slip and failure mode of shear connectors used for steel-concrete composite beams.

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This study investigates the effect of the slab concrete dimensions on the bending behavior of steel-concrete composite beams using cold-formed steel with perfobond shear connector.

2. Test program

2.1. Specimens

Two steel-concrete composite beams were made from cold-formed steel and concrete slab. Perfobond shear connectors were used to prevent the relative slip between the steel beam and the concrete slab. Perfobond shear connectors were made from a steel plate with 2.4 mm in thickness. The length of steel-concrete composite beams is 4 meters. Screws were used to attach shear connectors and cold-formed steel beams, as shown in Figure 1. The concrete slab had dimensions of 500 mm in width, 4000 mm in length, and 100 mm or 120 mm in thickness. The cold-formed steel beams were made from channel steel C200x75x15x2.0. Reinforcements with a diameter of 10 mm were placed on the steel surface to enhance the shear capacity of the specimen. Figure 2 describes the detail of the steel-concrete composite beam with all participating components. The length of the shear connector is 200 mm, the clearance is 100 mm, and there are two steel bars of 10 mm in diameter in each clearance. The only difference between the two steel-concrete composite beams is the thickness of the concrete slab. The concrete slab thickness of Beam 1 is 100 mm, and that of Beam 2 is 120 mm, as shown in Figure 3.

Figure 1. Practical image of cold-formed steel and perfobond shear connectors.

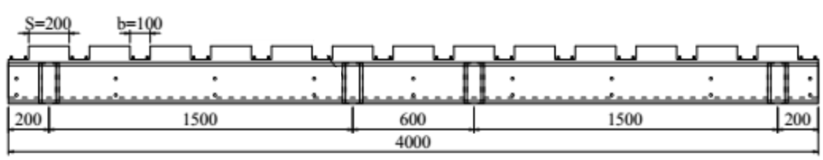
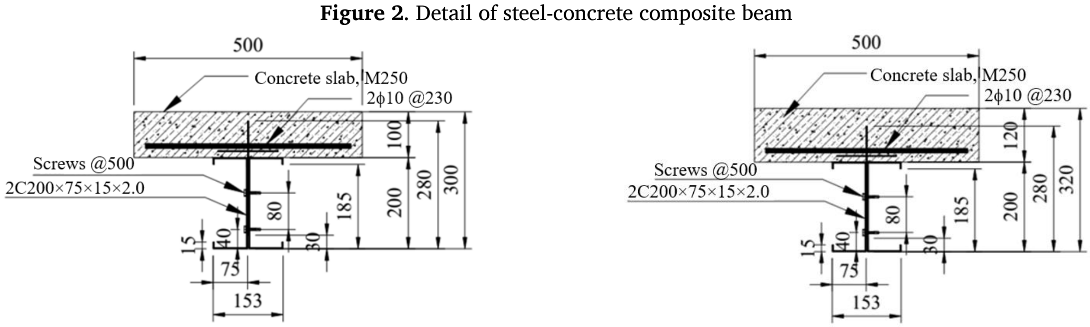


Figure 2. Detail of steel-concrete composite beam



a. Cross section of Beam 1

b. Cross section of Beam 2

Figure 3. Cross section.

2.2. Material properties

2.2.1 Concrete

The concrete used for the beams is M250. The concrete was cured and tested after 28 days. The concrete mechanical characteristics are listed in Table 1.

Table 1. The concrete mechanical characteristics.

Specimen	No. 1	No. 2	No. 3
Failure load (kN)	635.0	629.0	617.0
Concrete compressive strength (MPa)	28.20	27.90	27.40
Elastic modulus (MPa)	29.0×10^3	29.0×10^3	29.0×10^3

2.2.2 Cold-formed steel

Cold-formed steel is galvanized with a thickness of 2.0 mm used for steel beams and 2.4 mm used for perfobond shear connectors. The mechanical characteristic of cold-formed steel is presented in Table 2.

Table 2. The mechanical characteristic of cold-formed steel.

Thickness (mm)	2.4	2.0
Yield strength (MPa)	520	510
Ultimate strength (MPa)	540	530
Elastic modulus (MPa)	190×10^3	190×10^3

2.2.3 Reinforcement

The reinforcement used in this study was Posco CB4, with 10 mm in diameter. There were three groups of specimens, and each group had three specimens. The test results are presented in Table 3.

Table 3. Mechanical characteristic of reinforcement.

Specimen	No. 1	No. 2	No. 3
Nominal diameter (mm)	9.7	9.7	9.8
Length (mm)	601	602	602
Mass (gram)	349	351	353
Nominal cross-section (mm^2)	78.5	78.5	78.5
Average yield force (kN)	41.31	38.93	38.00
Yield strength f_y (MPa)	526.0	495.7	483.8
Ultimate force (kN)	49.86	47.87	46.59
Ultimate strength f_u (MPa)	634.8	609.5	593.2
Elastic modulus E (MPa)	2.0×10^5	2.0×10^5	2.0×10^5

2.2.4 Screw

The screw used to attach two cold-formed steel C200×75×15×2.0 was stainless steel with strength and a nominal diameter of A2-70, 5.5 mm, and a thread length is 20 mm. The test results are shown in Table 4.

Table 4. Result of screw test.

Test	The thickness of cold-formed steel	Strength capacity P_{max} (kN)	Failure mode
Shear	2.4mm	24.3	Split
	1.9mm	15.1	Split
Tensile	2.4mm	4.3	Pull
	1.9mm	3.0	Pull

2.3 Bending test

The bending test was carried out on two large-scale steel-concrete composite beams to evaluate the effect of concrete slab dimensions on the bending behavior of composite beams. The concrete slab had a dimension of 100×500×4000 mm (Beam 1) and 120×500×4000 mm (Beam 2). The tests were performed with four bending point models, as shown in Figure 4. The vertical deflection of beams was measured by linear variable differential transformers (LVDT) named V1, V2, and V3 at distances 1800 mm, 1200 mm, and 600 mm from support, respectively. The relative slips between the cold-formed steel beam and the concrete slab were measured by LVDT named H1, H2, H3, and H4 attached at mid-span, 1200 mm, 600 mm from support, and at the end of beams, respectively.

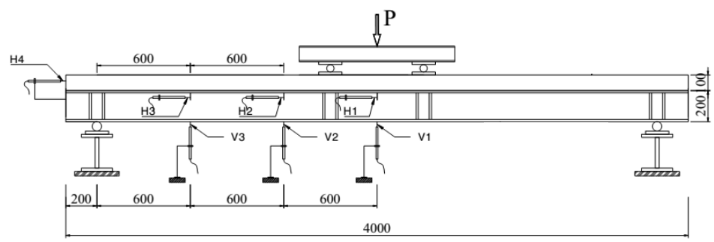


Figure 4. Testing model.

The loading procedure was performed complying with Eurocode 4 [11]. This procedure had 3 stages, as shown in Figure 5:

- Stage 1: Increasing load from 0 to 40% P_{max}, and then repeat 2 times.
- Stage 2: Increasing load from 10% P_{max} to 40%P_{max}, and then repeating 25 times. This stage is to eliminate the adhesive force, friction, and residual strain of testing.
- Stage 3: After ending stage 2, increase load from 10% P_{max} to failure load, continue increasing load until the load remains 90%P_{max}, and stop testing.

In which, P_{max} is the predicted maximum load.

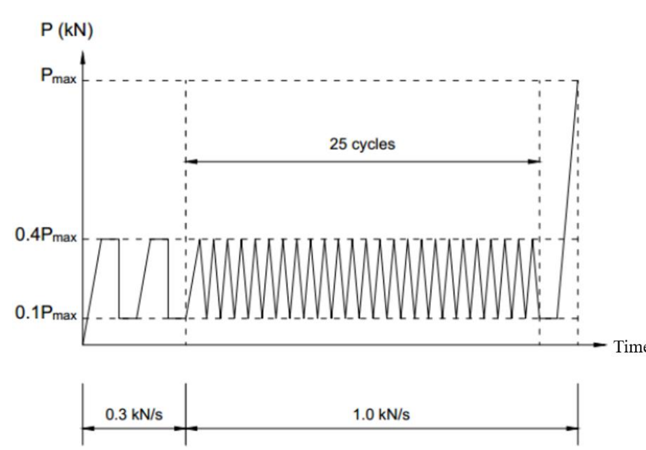


Figure 5. Incremental loading procedure.

3. Test results and discuss

3.1 Test results

The bending test results of steel-concrete composite beams are presented in Table 5. This Table shows that the load capacity of Beam 2 is higher than that of Beam 1, and the relative slip between the steel beam and the concrete slab at mid-span is smaller than that at the end of the beam.

3.1.1 Load–deflection curve

Figure 6 shows the load-deflection curve of the beams at mid-span. The load capacity of Beam 2 is 127.11 kN and that of Beam 1 is 107.73 kN. This means the load capacity of Beam 2 is higher than that of Beam 1 about 18%. With higher thickness, Beam 2 is supposed to enhance the load capacity of steel-concrete composite beams.

At the failure load, the deflection of Beam 2 is higher in comparison with that of Beam 1. However, at the failure load of Beam 1, the deflection at the mid-span of Beam 2 is 27.30 mm, and smaller than that of Beam 1 (49.21 mm) by about 54.1%, as shown in Figure 7. The increasing concrete slab thickness results in the stiffness of the steel-concrete composite beam, and this reduces the deflection of the composite beam.

Table 5. Test results of deflection at mid-span.

Specimen	Maximum load	Vertical deflection	Relative slip at the end of the beam	Relative slip at the mid-span of the beam
	P_{max} (kN)	$f_{mid\text{-}span}$ (mm)	δ_{end} (mm)	$\delta_{mid\text{-}span}$ (mm)
Beam 1	107.73	59.48	1.22	2.41
Beam 2	127.11	73.82	3.84	2.88

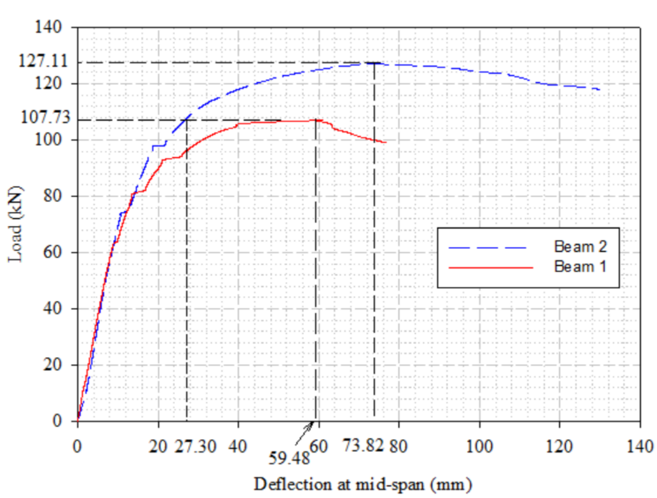


Figure 6. Load–deflection curve of Beam 1 and Beam 2.

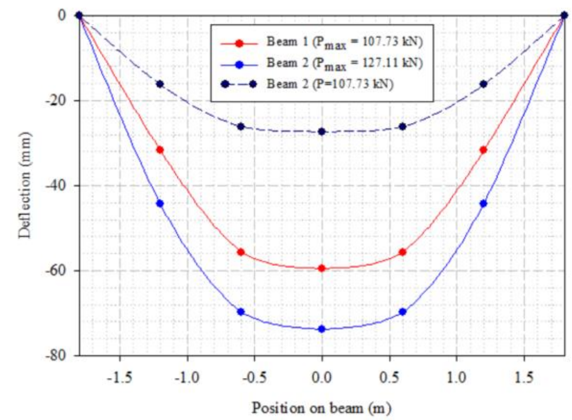


Figure 7. Deflection of Beam 1 and Beam 2.

3.1.2 The relative slip

The test results show that all relative slip values of the beams are smaller than 6 mm, so the shear connectors are considered ductile connectors. The relative slip between the steel beam and the concrete slab at positions along the beam length is almost confused. In many cases, the relative slips at the end of beams are higher than that at the mid-span of the beam. In both Beam 1 and Beam 2, at about 60% failure load (P_{max}), the relative slip at the end of the beam is very small. After 60%P_{max}, the relative slip of beams begins increasing, as shown in Figure 8 and Figure 9. At the failure load, the relative slip at the end of Beam 2 is greater than that of Beam 1. At the low load level, the relative slip at the end of Beam 2 is smaller than that of Beam 1, as shown in Figure 10. At the higher load level, the effect of the concrete slab dimensions on the relative slip is not clear because of the screw's cutting. When the screws are cut, the structure will no longer be a composite beam anymore.

At the mid-span of the beam, the effect of concrete slab thickness on the relative slip between the steel beam and the concrete slab is rather clear. At failure load (P_{max}), the relative slip of Beam 1 is smaller in comparison with that of Beam 2, noting that the failure load of Beam 2 is greater than the failure load of Beam 1. However, at the failure load of Beam 1 (P_{max} = 107.73 kN), the relative slip at the mid-span of Beam 2 is very smaller than that of Beam 1. The relative slip at this position of Beam 2 is just equal to 0.36 times in comparison with that of Beam 1. This means the concrete slab thickness partially affects the relative slip between the steel beam and the concrete slab at the mid-span position of the beam.

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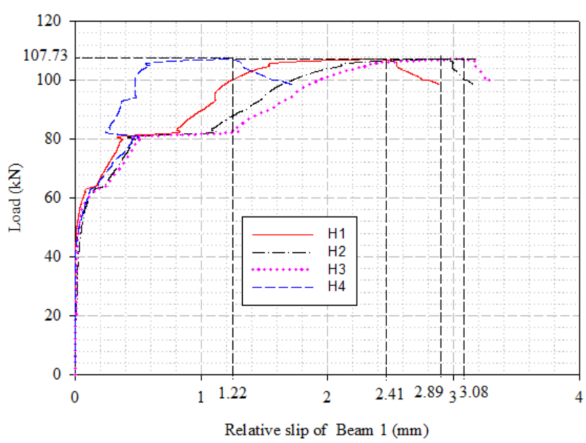

Figure 8. Load–relative slip curve of Beam 1.

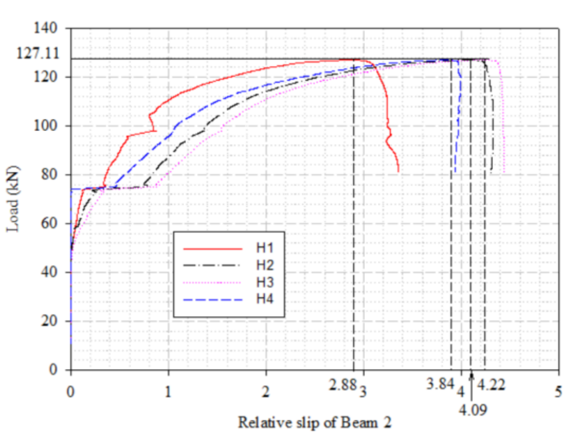

Figure 9. Load–relative slip curve of Beam 2.

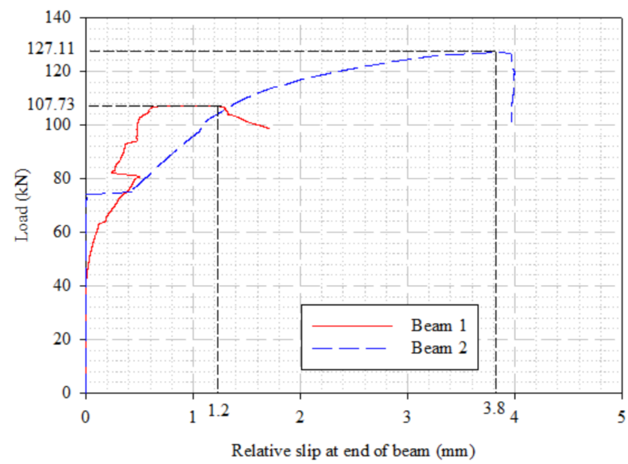

Figure 10. Load–relative slip curve at the end of Beam 1 & Beam 2.

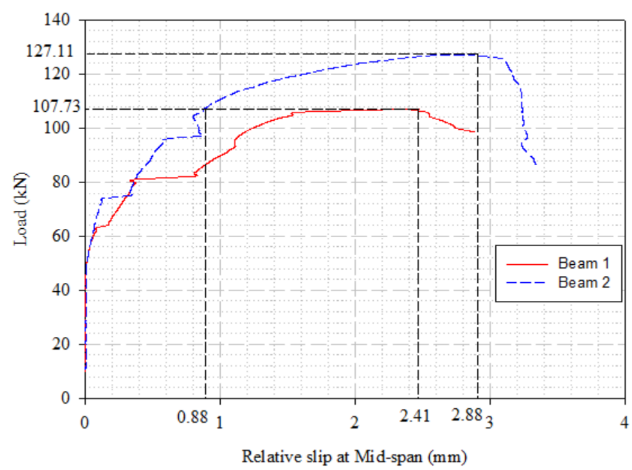

Figure 11. Load–relative slip curve at the mid-span of Beam 1 & Beam 2.

3.2. Failure modes

Failure modes almost happened at the mid-span of the beam, especially at applied load positions. The concrete slab surface is cracked with a high deflection of beams.

For Beam 1: at failure load, P_{max} = 107.07 kN, the bottom of the steel beam is teared, and the bottom fiber of the concrete slab at the applied load positions occurred cracks. At these positions, the top surface of the concrete slab occurred cracks in the horizontal direction of the beam, as shown in Figure 12.

For Beam 2: at failure load, P_{max} = 127.11 kN, the contact surface between the steel beam and the concrete slab is separated from each other, as shown in Figure 13. At the support, the screws connected to the steel beam and perfobond shear connectors are completely cut, and the top flange of the steel beam is bent at the mid-span of the beam.

Figure 12. The failure mode of Beam 1.

Figure 13. The failure mode of Beam 2.

4. Conclusions

Experimental studying the effect of concrete slab dimensions on the behavior of steel-concrete composite beams using cold-formed steel, the test results show that:

The increase in the concrete slab dimension improves the load capacity and reduces the deflection of steel-concrete composite beams. The load capacity of Beam 2 can increase by about 18% in comparison with that of Beam 1. The deflection of Beam 2 reduces by about 54% in comparison with the deflection of Beam 1 at the failure load of Beam 1.

The relative slip between the steel beam and the concrete slab is not clear because of the screws cutting. The effect of the concrete slab dimension is realized in the low load range.

The failure mode can be steel tearing, concrete cracks, and screw cutting. The failure modes often occurred at the applied load positions.

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