Behaviour of steel-concrete composite beams using bolts as shear connectors

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Abstract. The paper presents an experimental program on the application of bolts as shear connectors for steel-composite beams. Four steel-concrete composite beams and a reference steel beam were made and tested. The aim of the testing program is to examine which forms of the steel bolts can be used effectively for steel-composite beams. The four types of the bolts include: Type 1 the bolt with the nut at the end; Type 2 the bolt bending at 900 hook; Type 3 the bolt without the nut at the end and Type 4 the bolt with the nut at the end but connected with the steel beam by hand welding in other to be connected with the steel beam by bolt connection as in the first three types. The test results showed that beside the traditional shear connectors like shear studs, angle type, channel type, bolts can be used effectively as the shear connectors in steel-composite beams and the application of bolts in Types 1 and 2 in the composite beams gave the better performance for the tested beam.

1. Introduction

Because of the benefits of associating the advantages of the two materials, Steel-concrete composite (SCC) structures have been widely applied throughout the world for the construction of bridges and civil building [1, 2]. The majority application of this type of structure is in the kind of composite beam where the beam is formed by a steel beam, a concrete slab, and mechanical shear connectors. The shear connectors are the link between the concrete slab and the steel beam and are responsible for shear force transfer at the concrete-steel interface. Therefore, they are the key elements for ensuring the composite beam works effectively in sustaining bending moment. There are many kinds of shear connectors that have been applied and the welded headed shear stud is the most popular type of mechanical shear connector used in steel-concrete composite flexural members because of their relatively faster installation process [3]. However, headed shear studs are welded to the top flange of the steel beam using a special equipment that requires high voltage power for operation which may be dangerous in the installation process. Besides, in some cases, when large number of shear studs is needed to transfer safely the relatively large amount of lateral forces, the designers are challenged with the struggle of placing the sufficient number of shear studs on the steel beams [4]. Therefore, beside the welded headed shear stud, others shear connectors such as channel type, angle type, U type, perfobon and bolt have been developed.

The behaviour of SCC beam depended not only on the properties of the steel beam and the concrete slab but also on the degree of shear connection which was determined by the arrangement and the
strength of the shear connectors. Based on the degree of shear connection, SCC beams can be divided as no shear connection beams, partial shear connection beams, and full shear connection beams [5]. To date, many experimental and analytical studies have been investigated to understand the behaviour of such beams, especially the partial shear connection beams. Sanghyo et al. [6] examined three SCC beams with different stud diameters. This study showed that the elastic stiffness, ultimate load, and yield load of the beams were affected by the degree of shear connection. Xing et al. [7] studied the behaviour of SCC beams with the variation of sectional dimensions, studs, and degree of shear connection and their study showed that a relatively larger degree of shear connection can lengthen the elastic stage and delay the development and spread of slip but may decrease the ductility of the SSC beam. Vasdravellis and Uy [8] tested 14 SCC beams and 1 steel beam. Their study showed that the main factors affecting the shear capacity of an SCC beam are the slab thickness and degree of shear connection.

Although a large number of experimental and analytical studies have been conducted, engineers are still facing with many challenges. Firstly, the installation of headed studs requires special skilled workers, which may take additional cost so that reducing the other advantages of composite beams. Secondly, the application of short channels or angles with their bottom flanges welded to the steel beam may help in reducing the cost associated with shear connector installation but controlling of the quality of the welded to ensure reliable shear connectors in this case may take the installing process more complicated. In addition, the use of channels or angles may cause congestion to the longitudinal steel bars in the concrete slab. Therefore, the application of bolts as shear connectors may be a merit solution for this problem and in this paper the results of an experimental program on SCC beams with using bolts as the shear connectors are introduced. The experimental program which was carried out at Ton Duc Thang structural lab included testing 4 SCC beams with using bolts as shear connectors and one steel beam referred as the control specimen. The results of the tests showed that bolts can work effectively as shear connectors in SCC beams and the application of this type of connectors is prospective.

2. Experimental program

2.1 Test specimens

Four SCC and 1 steel beams denoted as Specimen D₁ to D₄ and D₀, respectively were tested under 4 points bending. The steel beam D₀ has a length of 4.5m with an I section of 150mm x 250 mm (Figure 1). It was composed of two flanges with the sectional area of 150 mm x 12 mm and a web with the sectional area of 250 mm x 8 mm. The SCC beams (D₁ to D₄) have the steel beams the same as Specimen D₀ but with a concrete slab having sectional area of 600mm x 120 mm connected with the steel beams at the top flange via four different types of bolts which were used as shear connectors.

![Elevation](image1.png)  ![Cross-section](image2.png)

**Figure 1**: The steel specimen

The dimensions of the SCC beams and the arrangement of the shear connectors are shown in Figure 2. A total of 42 bolts arranged at two lines with the space ranging from 160 mm to 240 mm were used as the shear connectors for each SCC beams. This amount of the shear connectors was calculated basing on the design code EC4 (1992) [9]. As shown in Figure 2, the top and bottom reinforcement of the
concrete slab are similar and composed of seven deformed steel bars, for each layer, having a diameter of 12mm placed as the longitudinal reinforcement. The same steel bars were used as transverse reinforcement for the top and bottom layers but with a spacing of 100 mm.

Figure 2: Dimensions of the SCC beams and the arrangement of the shear connectors

Figure 3. The shear connectors in specimens from D₁ to D₄
The only difference between each specimen from specimens D₁ to D₄ is in the types of the bolts used as the shear connectors. Figure 3 illustrates the difference of these specimens. In Specimen D₁, M16x130 SD 8.8 bolts with diameter of 16 mm and length of 130 mm were used, giving an embedded length of 100 mm of the bolts into the concrete slab (Figure 3a). In Specimen D₂, M16x250 SD 8.8 bolts with diameter of 16 mm and length of 250 mm were used, giving an embedded length of 220 mm of the bolts into the concrete slab. Difference from Specimen D₁, in Specimen D₂ the bolts did not have the nut but they were bended at 90° hooks along the beam as shown in Figure 3b. Specimen D₃ was also using M16 SD 8.8 bolts with a diameter of 16 mm as the shear connectors as in Specimen D₂ but the length of the embedded bolts into the concrete slab is only 100 mm and the bolts without the nut at the end were also used. In all three specimens from D₁ to D₃, the bolts were connected with the top flange of the steel beam using bolted connections. Difference from the remaining specimens, Specimen D₄ is the same as Specimen D₁ but the shear connectors were connected with the top flange of the steel beam via hand welded links (Figure 3d).

2.2 Material properties

The normal concrete mixing at the laboratory was used for casting all the SCC specimens. The contents of all the components for mixing a cubic meter of concrete included 420 kg of Holcim PC40 cement, 0.438 m³ of river sand, 0.845 m³ of stone aggregate, and 186 litres of water. All the SCC specimens were casted at same time and then curing at the same condition. The compressive strength of the concrete was determined by testing three 100mm x 200 mm cylinder samples which was casted using the same concrete with the one using for casting the specimens. At the age of 28 days the average compressive strength of the concrete was 25.4 MPa.

The tensile tests were taken for the plate steel which was used for composing the steel beams and for the reinforcement of the concrete slabs. There were two types of plate steel, including the 8 mm thickness and the 12 mm thickness. For each type of the steel, three similar samples having the width of 50 mm and the length of 500 mm were tested and the average yield strength of the steel plates was 343 MPa corresponding to an average yield strain of 1.9%. The average ultimate strength of the steel plates was 446 MPa corresponding to an average ultimate strain of 13.5%. Three samples of the steel reinforcement were tested and the average yield strength of the reinforcement was 335 MPa corresponding to an average yield strain of 1.6%. The average ultimate strength of the steel reinforcement was 476 MPa corresponding to an average ultimate strain of 21.5%.

3. Test setup and loading procedure

Four-point bending tests were implemented for all five Specimens. The test setup is illustrated in Figure 4. As shown in the figure, the beam was simply supported at the ends and two similar point loads which were created by two identical hydraulic actuators, were applied at its one-third points. The hydraulic actuators were set to work parallel at the same displacement speed and displacement control protocol during the test. The displacement speed of the hydraulic actuators was set to be 20 mm per minute until reaching the ultimate state. As the distance from the end of the beam to the supporter was 150 mm for both ends, the span of the tested beams were 4200 mm. For these setups, the beam segment between the point loads was mostly under pure bending while the remaining parts of the beam were mostly under constant shear and linearly increasing bending moment.

The loads were measured by using two load cells placed at the top of the hydraulic actuators and the displacements at the point loads were recorded by using two displacement transducers attached at the point load beneath the beam. The slip between the concrete slab and the upper flange of the steel beam at the end of the beam was measured by using one displacement transducers attached at the end of the beam. All the load cells and the displacement transducers were connected to a data logger which was set for collecting data every second.
4. Test results and discussion

The relation between the load and deflection of the tested beams is shown in Figure 5. In the figure, the average values of the load and displacement at the two loading points are illustrated. For the steel beam D₀, the loading included two stages. In the first stage, the beam was loaded to the yielding load for checking the correction of the measured system and performance of the loading frame. The load was removed to zero and then the second loading stage was started. For the specimens from D₁ to D₄, only one loading stage was applied as the loading frame and the measured instruments were double checked and they worked reliably after testing the specimen D₀.

The yield and ultimate loads about 76 and 121 kN, corresponding to the deflections of 17 and 40.5 mm, respectively, were recorded for Specimen D₀. After reaching the maximum load, the beam was released from loading and an average of unrecovered deflection of 20.6 mm was recorded. The beam was failure due to the yielding of the steel at the bottom flange of the beam. The above testing results were very close to that of the modelling of the same beam using ABAQUS where the differences of the results ranking from 1 to 3 percent in the linear stage and about 5 to 10 percent in the non-linear stage.

In Specimen D₁, a maximum average load of 241 kN was recorded corresponding to an average deflection of 64.9 mm and the unrecovered deflection of this beam was 48.7 mm. Compared to Specimen D₀, the maximum and the yield loads of Specimen D₁ improved about 100% and 90%, respectively. The stiffness of Specimen D₁ also improved from 75% to 90% compared to Specimen D₀. During the test, when the load was reaching about 60% of the maximum load, cracks of the concrete slab at the mid-span of the beam were appeared leading to reduction in the stiffness of Specimen D₁. The slip between the steel and the concrete slab of Specimen D₀ at ultimate load was recorded about 2.75 mm. After testing, the concrete slab was carved out at some places to examine the working conditions of the shear connectors. These examinations showed that the bolts in Specimen D₁ were still working effectively without any failure to be recorded (Fig. 6a). These proofs indicates that the used bolts as the shear connector as tried in Specimen D₁ could be a reasonable scheme.
Figure 5: Load-deflection curves

The load-displacement curves of Specimens D_2 and D_3 during the loading were similar to that of Specimen D_1 but with the relatively lower ultimate loads of 237 and 234 kN, respectively, were recorded. The main difference in the behaviour of Specimens D_1 to D_3 were in the slips between the concrete slab and the top flange of the steel beam. These values for Specimens D_2 and D_3 were 2.12 and 3.22 mm, respectively compared to a value of 2.75 mm in Specimen D_1. The relatively larger slip of specimen D_3 could be caused by the relative slip of the bolts and the surrounding concrete as the bolts in specimen D_3 were not bended or had nuts as they were in Specimen D_1 and D_2. The failures of the concrete due to the slip of the bolts on the concrete slab were also recorded when carving out the concrete at the bolt position (Fig. 6c). These evidences prove for this point that there were relatively large slip between the shear connectors and the concrete in Specimen D_3 during the loading process. Thus, it could be concluded that the use of bolt as the shear connectors as in Specimen D_3 is not effective.

Figure 6: The bolts in the failure specimens

Different from Specimens D_1 to D_3, a relative poorer behaviour was recorded in which an ultimate load of 191.8 kN corresponding the displacement of 27mm were measured for Specimen D_4. This load is only 79% of that of Specimen D_1. The behaviour of this specimen at the first stage, when the load was below the ultimate value, was similar to specimen D_1 but at the later loading stage the load reduced rapidly together with large explosions coming from the concrete slab. The explosions occurred during testing this specimen can be caused by the breaking of the bolts connectors because when they appeared the load reduced rapidly and the slip between the concrete slab and the steel flange of the steel beam
also increased hastily. The later examination when carving out the concrete (Fig. 6d) of this specimen also displayed the break of the bolts occurred near the welding position, whereas no failure was recorded for the bolts of the remaining specimens. This breaking showed that the welding process may cause a significant change in the properties of the bolts especially on their shear strength. A maximum slip between the concrete slab and the steel flange of 19 mm recognized for this specimen, more than three times for that of the specimens D₁ to D₃. This proved for the point that this type of the shear connectors was not effective.

5. Conclusions
The paper presented an experimental program in which five beams including four steel-concrete composite beams and a reference steel beam were made and tested. Four types of the bolts were implicated into the SCC specimens from D₁ to D₄. The behaviors of the tested beam were compared showing that the SCC beams had significantly better performances than the references steel beam. The results of the experimental program also indicated that bolts can be used successfully as the shear connectors for the SCC beam. The forms of the bolts as applied in specimens D₁ and D₂ gave the great performances of the beams so they can be considered for the implement in practice. The bolts without the nut at the end as represented in Specimen D₃ should not be used as the shear connector as the use of this kind of bolt can cause large slip between the concrete slab and the steel top flange of the beam. Using hand welding method for linking the bolts to the steel flange as applied in Specimen D₄ is also should be avoided be cause it can lead to the deterioration in the shear strength of the bolts.

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