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Flexural and shear performance of steel-concrete-steel sandwich slabs under concentrate loads

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ABSTRACT

This paper studies the flexural and shear performance of steel-concrete-steel (SCS[1]) sandwich slabs. Six simply supported slabs with different shear spans, section depths and steel configurations were tested under concentrate loads applied at the center. After the tests parts of the steel plates were taken off to observe the crack distribution. The observed modes of failure included flexural yielding and shear punching. The former was initiated by tensile yielding of the bottom steel plate, while the latter was primarily due to punching shear failure of the concrete core. After flexural yielding or concrete punching, the carrying capacities could further increase under large deflections, owning to the shear stiffening of the top steel plate and the membrane action of the bottom steel plate. The top steel plate showed significant shear contribution after concrete punching. A theoretical model is developed to predict the resistance of SCS slabs under concentrate loads. The flexural capacity is calculated with the yield-line method, and the punching shear resistance is analyzed with the radial sector model. The shear contribution of the tie bars is also analyzed experimentally and theoretically.

1. Introduction

1.1. Development of SCS structures

Steel-concrete-steel (SCS) sandwich structures are constructed with the outer steel skins and the concrete core. Composite action is achieved through headed studs, tie bars and other mechanical connectors like angle steel, channel steel, J-hook, etc. [1]. They comprise the advantages of both reinforced concrete (RC) and steel structures, including high bearing capacity, good ductility and integrity, as well as excellent performance in impact resistance and leakage prevention [2]. The steel skins act as both longitudinal reinforcement and permanent formwork, promoting the construction efficiency. In recent years SCS structures have been used in off-shore constructions, submerged tube tunnels, nuclear facilities, bridges, and the application field is still expanding.

During the past 40 years the general performance of SCS structures have been improved greatly with the development of the connection techniques, from the earliest chemical bonding with epoxy [3], to the various mechanical connectors like the overlapped headed studs (in the double skin composite system) [4], the steel bars (in Bi-steel structures) [5], the J-hook connectors [1,6], the channel and steel plate connectors [1]. These connectors attempt to improve the structural performance and construction accessibility, and to enhance the out-of-plane shear and impact resistance. The strength/weight performance is also improved by the use of some innovative ultra-lightweight core materials [1,6].

Various research works have been conducted on SCS specimens, most of which were focused on uniaxial beams, columns and plane shear walls [7–17]. However, two-way slabs are different from beams or columns that forces are transferred in two directions, and both concrete and steel are in tri-axial stress states. It necessarily result in different failure patterns, but research information on SCS sandwich slabs is limited currently. As in practical engineering the SCS panels are usually supported on all four sides and subject to permanent or accidental patch loads, the study of the slab behavior is necessary.

1.2. Research progress on SCS sandwich slabs

Pioneer study on SCS panels was performed by Solomon et al., who proposed the sandwich concept for use in roadway decking and large span bridges in 1976 [3]. In their tests the steel plates were bonded to hardened concrete with epoxy. The specimens failed suddenly by interfacial slippage and separation once concrete was punched through. The strength was not significantly improved yet. Later Shanmugam et al. [18] tested 12 simply supported SCS slabs connected with overlapped headed studs. With a relatively large span/depth ratio (clear span 1400 mm, depth 100 mm), the specimens showed a high degree of

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[1] SCS: steel-concrete-steel.

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flexural characteristics, and they focused on finite element simulations of the slab behavior.

Sohel et al. [19] carried out tests on eight SCS sandwich slabs with J-hook connectors and ultra-lightweight concrete core, and they concluded that the failure modes and crack patterns were similar to RC slabs. The membrane stretching effect after flexural yielding was considered in their study.

Yan et al. [20–22] conducted tests on 17 SCS slabs with headed stud connectors and ultra-lightweight cement composite, which is proposed to be used in arctic offshore structures to resist ice contact. The investigated parameters included stud spacing, core strength, steel plate thickness, section depth and fiber fraction, and punching shear failure was dominant in their tests. A five-stage load-deflection behavior and two peak resistances were summarized from test results. Analytical models, developed by modifying the code equations from ACI 318-11 and Eurocodes, were developed to calculate both flexural and punching strengths.

1.3. Some classical theories on RC slabs

The force transfer mechanism and failure modes of SCS slabs are in many aspects analogous to that of RC slabs. The strength behavior of RC slabs itself is a complicated problem, so most of the design codes are based on (semi-) empirical equations. But there are also some significant theories revealing the force mechanism in RC slabs. These classical theories are applicable to SCS members after proper modifications.

To deal with flexural yielding failure, the yield-line theory is most widely recognized [23]. Although the upper bound method may give unsafe estimations, it effectively solves the complex problem. As for punching shear failure, some widely used mechanical models include the sector model proposed by Kinnunen et al. [24], and the subsequent critical shear crack theory developed by Muttoni [25,26]. Another method is the upper bound solution based on virtual work equations [27].

Rankine et al. [23] discussed the failure initiation in conventional slab-column specimens, including yielding of the reinforcement (flexure), crushing of the concrete (flexure) and internal diagonal cracking (shear). The failure mechanism is revealed in detail, which helps to understand the slab behavior. Long et al. [28] presented a method for the calculation of punching capacities, based on the elastic thin-plate theory, which described the relationship between the concentrate load and bending moments in the slab. These theories provide powerful insight into the force mechanism in both RC and SCS slabs.

This paper studies the structural behavior of SCS sandwich slabs under concentrate loads through experiments. Based on the observed failure modes and resisting mechanisms, analytical solutions are developed to deal with the carrying capacities of SCS slabs.

2. Experimental investigations

2.1. Test specimens and material properties

Six simply supported sandwich slabs were tested under concentrate loads applied at the center, four of which were typical steel-concrete-steel (SCS) specimens and the other two were steel-concreter (SC[2]) specimens. Normal concrete with density about 2400 kg/m^3 was used as the core material. Fig. 1 depicts the fabrication details of the test slabs. The main purpose was to study the behavior of SCS slabs, and the SC specimens were designed for comparison. In the SCS sandwich assembly shown in Fig. 1(a), the headed studs connected the outer steel plates and the concrete infill, and the round steel bars (also known as tie bars) welded to the steel plates at both ends contributed to vertical shear. Specimens DH-1-4 × 2.35 and DH-1-4 × 3.7 were SC elements, as shown in Fig. 1(b). In these two specimens, the top steel plate and tie bars were removed, so that the shear contribution of the top steel plate and tie bars can be revealed through direct comparisons with specimens D-1-4 × 2.35 and D-1-4 × 3.7. The shear span/depth ratio λ, referring to the ratio of the clear span (a–b) to the section depth h, ranged from 2.35 to 6.0. Specimen D-1-4 × 6 with $\lambda = 6.0$ was expected to failed in the flexural pattern. Specimen B-1-4 × 3.5 was designed in larger size, so that the deformation shape, failure pattern and crack distribution can be observed more clearly. The specific parameters are listed in Table 1.

Panel assembly was finished in workshop conditions. The studs were welded to the steel plates with a stud welding gun. The steel plates were perforated in advance at the designed positions of tie bars, and the diameter of the holes was slightly larger than the diameter of the tie bars. Then the tie bars passed through the holes and were welded to the steel plates from the outside to form the steel skeleton, as shown in Fig. 2.

The yield and ultimate strengths of the steel plates, studs, tie bars and longitudinal steel bars were obtained from coupon tensile tests. 150 mm concrete cubes were prepared and tested on the same day of the slab tests to obtain the concrete strength. The material properties of steel and concrete are summarized in Table 2.

2.2. Test set-up and measuring scheme

The test device is shown in Fig. 3. The tested panel was simply supported on the rollers on all four sides. The corners were free to lift up. The rollers were supported on rigid steel girders, and the girders were supported on four square columns, so that strain gauges and displacement sensors can be arranged on the bottom surface. The roller supports need to be carefully positioned to ensure the loading to be symmetric in all directions. Square patch load was applied at the center under force control before reaching the first peak resistance, and then transferred to deflection control to obtain the plastic behavior and the descending segment of the load-deflection curves.

During the tests vertical deflections and strains of the steel plates were measured at each load increment. The tensile strains of the tie bars were also tested in specimen B-1-4 × 3.5. The development of the diagonal cracks can be reflected from the tensile strains of the tie bars. Fig. 4 shows the arrangement of the strain rosettes and displacement sensors in specimen D-1-4 × 3.7, as an example.

3. Test results

Typical failure modes of SCS slabs in the tests can be broadly recognized as either shear punching or flexural yielding. Specimen D-1-4 × 6 failed due to flexural yielding, characterized by the global flexural deformation as shown in Fig. 5(a). The upper figure corresponds to the moment of flexural yielding (point 1) on the load-deformation curve in Fig. 7, and the deformation is magnified by 10 times, while the lower figure corresponds to the moment of top steel plate failure (point 2) without magnification. At the flexural yielding moment, the slab showed global flexural deformations except for some local bulge around the load vicinity. The bulge was limited within a distance h from the load perimeter. During the process from point 1 to point 2, yielding of the bottom steel plate initiated from the center and gradually progressed towards the support. At ultimate state, the top steel plate was sheared off, and the bulge was more obvious.

After the test, the steel plate was taken off partially to visualize the concrete cracks, as shown in Fig. 5(b). On the bottom surface, the cracks can be distinguished into tangential and radial cracks. The tangential cracks, or termed as circumferential cracks, developed around the loading vicinity and concentrated near the load vicinity. The radial cracks, on the other hand, extended from the loading region towards the edge, and distributed intensively in the sector region marked in the image. Such a crack pattern was consistent with the theory of radial and tangential moment distributions, as will be explained below.

[2] SC: steel-concrete, with only single steel skin on one side