Journal of Constructional Steel Research 106 (2015) 89–98

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Failure mechanism and shear strength of steel–concrete–steel sandwich deep beams

Yu-Bing Leng, Xiao-Bing Song *, Hai-Lin Wang

Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 7 July 2014
Accepted 11 December 2014
Available online 26 December 2014

Keywords:
Steel–concrete–steel
Deep beams
Failure modes
Shear strength

ABSTRACT

In steel–concrete–steel (SCS[1]) sandwich deep structural members the shear performance becomes rather critical. This paper describes an experimental study on the shear behavior of SCS continuous deep beams. Three beams with different shear spans were tested under anti-symmetric concentrate loads, and the failure pattern is found to be different from reinforced concrete members. Tests show that the shear capacity depends strongly on the steel plates and the shear connectors, and the membrane action of the outer steel plates provides the beams with excellent strength and ductile performance. On the basis of the experimental observations (both the continuous beam tests in this paper and the simple beam tests conducted earlier), a plastic limit analytical model is developed to explain the force transfer mechanism and predict the shear strength of both simple and continuous members. Considering equilibrium and boundary conditions, the lower bound approach shows satisfactory predictions for the shear performance of SCS deep beams.

1. Introduction

Steel–concrete–steel (SCS) sandwich composite structure, which comprises a concrete core sandwiched between two steel plates, was proposed by Solomon et al. over 30 years ago [1]. In the past 30 years extensive research programs have been conducted on this potential structural system.

In the early works carried out by Solomon [1], the steel plates were bonded to hardened concrete with epoxy, which was prone to slip failure between the two material layers. In the late 1980s Tomlinson et al. [2] proposed the double skin sandwich (DSC) system in which shear studs were used as mechanical connectors. Shear forces are effectively transferred between different material layers through headed studs [3–5]. However, without any inter-connection between the two outer skins, impact and shock loads tend to separate the face plates out from the concrete core [6]. To achieve better integrity a new product named Bi-steel was developed [7], proposing that the plates can be inter-connected by transverse round steel bars simultaneously friction welded at both ends. Recently there have been many research programs revolving the Bi-steel structures [8,9]. In spite of the thickness limitation and dependence on production machines in construction, the Bi-steel system has outstanding advantages like high strength and impact resisting capacity.

Steel–concrete–steel composite system, developed on the basis of reinforced concrete (RC) structures, features high bearing capacity, good ductility and integrity, as well as excellent performance in impact resistance and leakage prevention. The steel plates can effectively limit the concrete crack width in every direction. The steel skins also act as moulds during concreting, promoting construction efficiency. As a result, in recent years SCS structures are widely used in large sized structures like bridges, tube tunnels, nuclear power plants and core tube of high-rise buildings, which are all strictly required on their seismic performance [10].

For an SCS beam with symmetric steel skins, the moment of a section is resisted mainly through the top and bottom steel plates, as similar to the behavior of doubly reinforced concrete sections with equivalent tension and compression reinforcements, provided that composite action is achieved through shear connectors [4,11]. The moment resisting mechanism is relatively clear. In contrast, the shear resistance is difficult to predict accurately, due to the indeterminacy of the force transfer pattern after diagonal cracking [12]. In fact, the shear resisting mechanism of concrete and reinforced concrete members has long been a difficult problem, so the shear strength is commonly quantified by (semi-) empirical equations in most design codes, such as the ACI 318-05 [13], Eurocode 2 [14] and so on.

It is difficult to predict the shear capacity through a unified formula [15]. However, despite the indeterminacies, it is viable to analyze the shear resistance under some certain failure modes, according to the load paths and shear resisting mechanism. As shear becomes rather critical in thick structural members, such as that used in offshore structures and road decking, experimental study and research become an essential work.

* Corresponding author at: Department of Civil Engineering, No. 800 Dongchuan Rd., Shanghai 200240, PR China. Tel.: +86 13636545501.
E-mail addresses: xbsong14@163.com, xbsong@sjtu.edu.cn (X.-B. Song).

[1] SCS: steel–concrete–steel.

http://dx.doi.org/10.1016/j.jcsr.2014.12.012
0143-974X/

Based on the failure modes of simply supported beams observed in Ref. [11], as well as that of the continuous beams tested in this paper, a mechanical model is proposed to consider shear failure of SCS deep beams under concentrate loads. The model deals with (1) the force transfer mechanism of SCS deep beams after critical diagonal cracking; (2) the potential failure modes of deep beams; and (3) the ultimate shear strength after critical diagonal cracking.

2. Definition of deep and slender beams

Forces are always transferred to supports through the most direct and rigid way. According to Kuo et al. [15], a reasonable range of the angle of diagonal concrete strut is from 26.5° to 63.5°. Struts with inclined angle less than 26.5° cannot transfer force effectively. In other words, struts with small inclined angles (less than 26.5°) are unlikely to develop.

Appendix A of the ACI 318-05 code [13] has some similar provisions, showing that the angle between the concrete strut and beam axis shall not be taken as less than 25°. In ACI 318-05, the shear span in a beam is divided into B-regions and D-regions. A D-region is one where the stresses and strains are disturbed by the concentrate force or abrupt change of the cross section. So it is assumed that the D-region is located within a distance about one beam height h from the concentrate force or geometric discontinuity, according to St. Venant's principle. A B-region, on the other hand, is one where stress and strains distribute regularly, without external disturbance, so it is expected to locate between two D-regions (Fig. 1).

According to ACI 318-05, a deep beam is defined as a beam with shear span/depth ratio less than 2, in which the two D-regions overlap or meet in shear span. In this case the strut is developed directly from the loading point to the end support at an inclined angle larger than 26.5°, as shown in Fig. 1(a). On the other hand, a slender beam is known as a beam in which $a > 2h$, and the two D-regions are separated by a B-region, thus some other force transfer patterns are required, such as the shear reinforcement, to steepen the diagonal strut. This paper focuses on the force transfer mechanism and failure mode of SCS deep beams.

3. Failure mode of simply supported SCS deep beams

A series of simply supported deep beams were tested in Ref. [11] to investigate the shear performance SCS sandwich panels. The beam

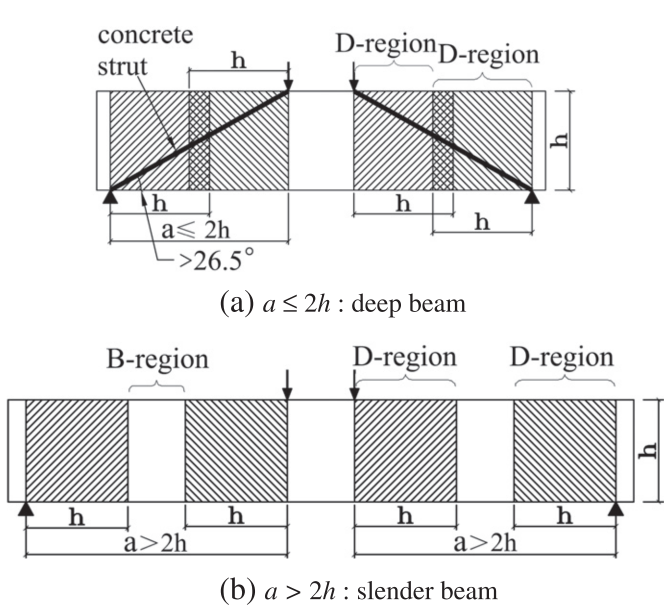

Fig. 1. Comparison between deep beams and slender beams in ACI 318-05.

assembly and general test information are present in Fig. 2. The outer steel plates and concrete infill are connected by an array of headed studs, and the channel connectors in shear span contribute to vertical shear. The angle and channel steel also enhance the out-of-plain stiffness before concreting. The specimens were tested in three-point bending with the load applied in mid-span. The geometric and material details are listed in Table 1.

The crack distribution and failure process were similar among the simply supported deep beams. A typical cracking pattern is shown in Fig. 3. The first visible flexural crack (signed No. 1 in Fig. 3) appeared in mid-span under relatively small load (about 10–20% ultimate capacity). As load increased diagonal cracks formed in shear span from the bottom surface and penetrated towards the loading point (signed No. 2), and the cracked region extended outwards gradually. Then the critical diagonal crack (take CDC[2] for short in this paper, signed No. 3) developed directly from the support to the loading point, after which the bearing capacity could still increase slightly in most cases. The ultimate shear resistance was reached until a horizontal crack appeared from beam end and penetrated inward (signed No. 4).

In reinforced concrete beams, shear failure usually include shear tension, shear compression and diagonal compression failure. Shear tension failure is caused by tension splitting of the concrete in the tip zone near the loading point. Shear compression failure results from crush of the concrete in the residual concrete compression zone above the diagonal crack. These two failure modes usually occur in slender beams. Diagonal compression failure, also known as crush of the web concrete, on the other hand, usually takes place in deep beams.

However, in SCS beams with equivalent top and bottom steel plates at the extreme outside edge, the tensile force of the bottom plate is balanced by the top plate adequately. That is why in the tests the concrete cracks usually penetrate to the bottom surface of the top steel plate once cracking, with concrete compression depth almost equal to zero. In this case shear tension failure and shear compression failure in the tip zone are unlikely to occur.

In fact, the shear failure pattern of SCS beams is different from that of RC beams. The critical diagonal crack always played a significant role in vertical shear failure. As seen in Fig. 4, at ultimate state the critical diagonal crack opened quickly, and downward deformation developed seriously near the support, accompanied with concrete crushed in this region, constituting the “triangular damaged area” and the deformed shape sketched with dashed lines. The bottom steel plate near the support deformed downward and the strain in this region increased rapidly, after which a horizontal crack penetrated inward from the beam end. Horizontal cracking marked the limit state of the beam. In other words, shear failure was characterized by yielding of the bottom steel plate near the support and horizontal cracking. This particular failure pattern observed in simply supported beams is recognized as ‘bottom triangular area damage + horizontal cracking’.

4. Tests of continuous beams

The horizontal crack usually appears in simply supported beams without much confinement at beam end. However, in continuous beams, or beams strengthened at the beam end, concrete outside the support is unlikely to crack horizontally, thus another failure pattern is expected to take place. Accordingly, three small-scale continuous beams (identified as CB2.0, CB1.5 and CB1.0) were tested under antisymmetric concentrate loads in this study. The beams were vertically strengthened outside the continuous section to prevent the potential transverse cracking, which is more consistent with the actual support conditions in large-sized constructions.

[2] CDC: the critical diagonal crack.