

STRUCTURAL PERFORMANCE OF STEEL-CONCRETE-STEEL SANDWICH COMPOSITE BEAMS WITH CHANNEL STEEL CONNECTORS

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ABSTRACT

This paper investigates the structural performance of steel-concrete-steel (SCS) sandwich members comprising a concrete core sandwiched in between two steel plates which are interconnected by channel steel connectors with large interval. Angle steel is adopted to serve as the connection between channel steel and surface plates. The behavior of a series of 8 large-scale, simply supported tests was investigated, covering a wide range of applied shear span to depth ratios from 1.5 to 5.5. Other parameters include the interval of channel steel and axial tension force. Although critical inclined cracks appeared in most of the beams (except for the beam with shear span to depth ratio 5.5), the observed modes of failure were all ductile failure characterized by yielding of the tension steel plate. Unlike the negligible dowel action of longitudinal reinforcement in reinforced concrete members, the dowel action of steel plate in SCS member seems to play a decisive role. Other shear performance differences between SCS members and reinforced concrete (RC) members were also analyzed. Test results are compared with current design recommendations.

INTRODUCTION

In recent 30 years, a new structural system, steel-concrete-steel (SCS) sandwich composite, has been on the rise with good potential. This structure features good integrity, ductility, and the ability to prevent leakage, impact and explosion. It has been widely used in infrastructure construction, such as that for nuclear power plants, offshore structures, and high-rise buildings, etc.

There are a number of types of shear connectors have being used in practice such as welded shear studs[1], friction-welded bar connectors in Bi-Steel SCS sections[2,3] and J-hook connectors[4,5], etc. Welded studs terminate within concrete and their prime functions are to resist longitudinal shear and plate/concrete separation. Bar connectors or J-hook connectors provide direct connection to the two face plates and their main functions are to resist both longitudinal and transverse shear, and to prevent plate buckling. The Bi-steel SCS system can only be manufactured in a factory environment and the core thickness is limited to 200~700mm. When the sandwich depth is shallow, welding of straight bar connectors at both ends to the steel face plates is not possible, and double J-hook connectors can be adopted with minimum core thickness of 50 mm[4].

Many experimental research works have been conducted to investigate the load carrying capacity of SCS composite beams subject to bending and shear [6,7].

T.M. Roberts and D. N. Edwards conducted test on eleven SCS sandwich beams ($b=400$ mm; $h=150$ mm). The observed modes of failure were yielding of the tension plate and slip yielding of the tension plate connectors. Significant shear cracking occurred in several of the beams but was not the primary cause of failure [6]. Eighteen beams having a range of span, depth, plate thickness and bar spacing have been tested under static loading by M. Xie and N. Foundoukos [7], four elementary modes

of failure were observed: tension plate yielding, bar shear, bar tension and concrete shear. Results were compared with Bi-Steel design and construction guide [8]. It was found that, for most cases, experimental transverse shear resistance exceeds the failure load given by the guide.

When the thickness of SCS sandwich member is large, such as that used in nuclear power plant, transverse shear becomes more significant. Information available on shear resistance of thick SCS sandwich elements is so limited that it is imperative to generate more results.

This paper is concerned with the behavior of SCS sandwich beams with another kind of shear connectors—channel steel connectors. This kind of connectors can extend the range of core thickness to a value larger than 700mm. 8 large-scale simply supported beams under static loading were tested, covering a wide range of applied shear span to depth ratios from 1.5 to 5.5. Other parameters include the interval of channel steel and axial tension force.

DETAILS OF TEST SPECIMENS

Fabrication details of the test beams are presented in Table 1 and Figure 1. All the beams had concrete depth $h=734$ mm, width $b=762$ mm, nominal tension and compression plate thickness $t_s=14$ mm, C14b channel steels with interval $S_c=1220$ or 610mm. The stud connectors were 19 mm diameter by 150 mm long. All studs in a beam were equally spaced longitudinally and transversely with spacing $s=152$ mm. Stud connectors were welded to the plates using a stud welding gun (Figure 2). Stud could be tapped to form a 90 degree bending to confirm the integrity of the weld (Figure 3).

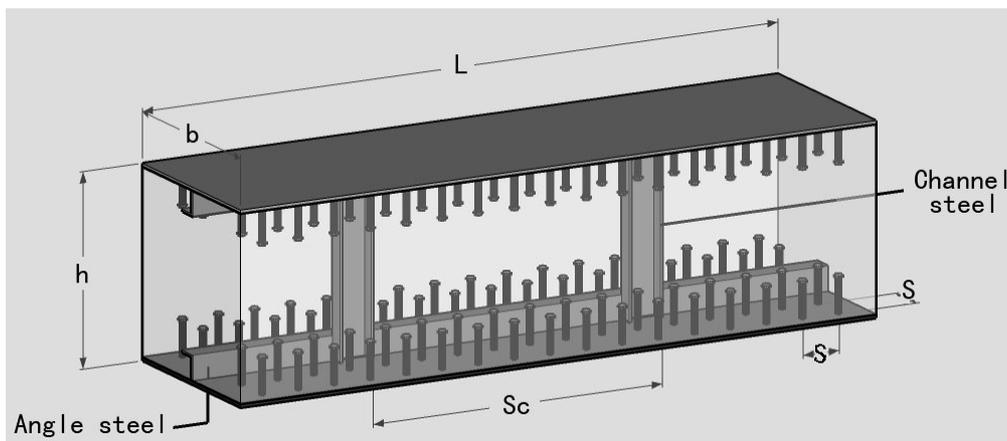


Figure.1 Schematic arrangement of the SCS sandwich structure with channel steel connectors

Table 1: Details of test specimens and modes of failure.

Beam	L [mm]	λ	Axial tension	S_c [mm]	Load condition	Model of failure
WS5.5	10480	5.5	-	1220	A	Bend
WS3.0	7815	3.0	-	1220	A	Bend+Shear
WS2.0	4148	2.0	-	1220	B	Shear
WS1.5	3386	1.5	-	1220	B	Shear
WS'1.5	3386	1.5	-	610	B	Shear
WS'2.0	4148	2.0	-	610	B	Shear
WS3.0T	9586	3.0	$0.5A_sF_y$	1220	C	Shear
WS1.5T	7400	1.5	$0.5A_sF_y$	1220	C	Shear

Load condition: A—Two point loads; B—One point load; C—Two point loads with tension



Figure.2 Welding of studs



Figure.3 Tapped stud

The beams were filled with ready-mix concrete of Grade C35, which would nominally give a cube strength $f_{cu}=35\text{N/mm}^2$. Before concreting, sections of steel plate were cut from the ends of the plates, from which tensile test specimens were made and tested. Tensile tests were also conducted on C14b channel steels. Material test results for concrete, plates and channel steels are given in Table 2. After concreting the beams were cured under wet hessian, for approximately 28 days, prior to testing.

Table2: Material Properties of Test Specimens- Mean Values [N/mm²].

Beam	f_{cu}	Steel plate		C14b		L100*80*10		Stud	
		f_y	f_u	f_y	f_u	f_y	f_u	f_y	f_u
WS5.5	43.4	330	485	293	401	255	430	395	418
WS3.0	34.5	295	450	270	390	255	430	395	418
WS2.0	33.7	290	440	270	390	255	430	395	418
WS1.5	38.8	305	445	270	390	255	430	395	418
WS'1.5	37.7	300	400	270	390	255	430	395	418
WS'2.0	45.2	280	430	270	390	255	430	395	418
WS3.0T	36.4	315	440	270	390	255	430	395	418
WS1.5T	27.5	285	425	270	390	255	430	395	418

SUPPORT AND LOADING CONDITIONS

The test beams were simply supported and subjected to either one or two point loads, as shown in Figure.4. Loads were applied to the beams under force control before the load capacity was reached, and then, transferred to deflection control to obtain the descending segment of load vs. deflection relationship.

Specimen WS1.5T and WS3.0T were subjected to proportionally increasing axial tension and out-of-plane shear loading. The ratio of the axial tension (T) to out-of-plane force (P) was equal to 3:1. The maximum axial loading was limited to 50 percent of the yield strength ($A_s F_y$, steel area multiplied by nominal yield stress) of the SCS section. The axial loading was maintained constant after reaching this value, and the out-of-plane force was increased either to failure or to the loading capacity of the test setup.

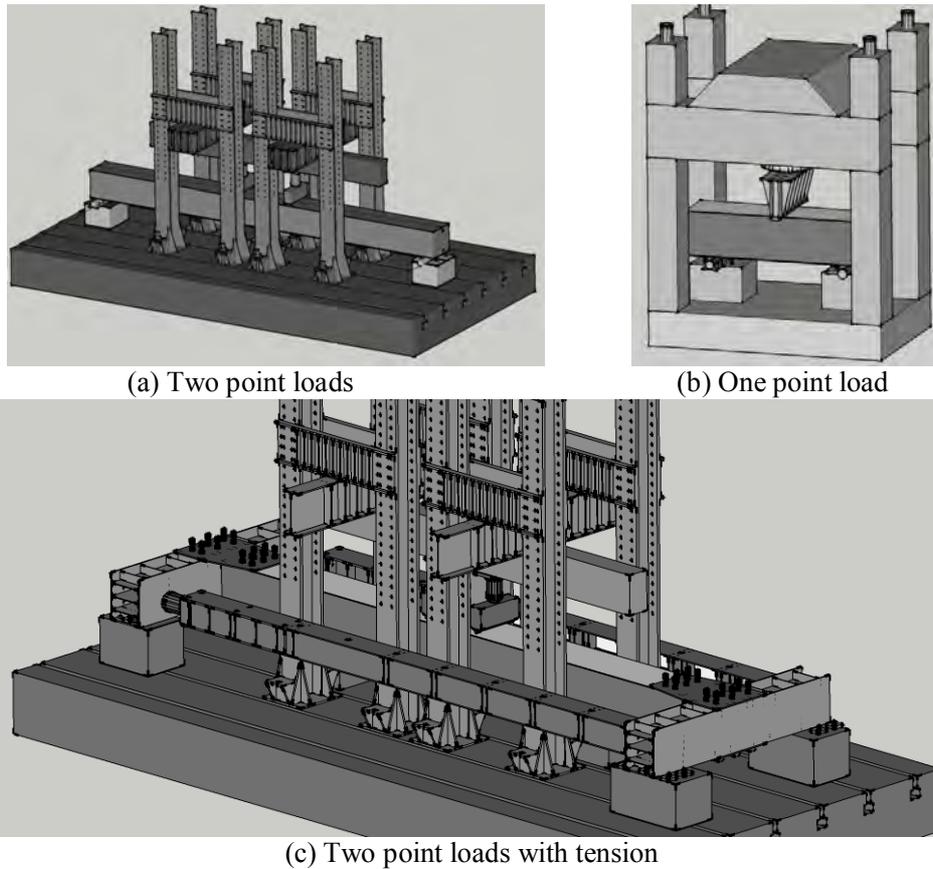


Figure.4 Schematic test setup

INSTRUMENTATION

Strains in the tension and compression plates were measured at several locations using resistance strain gauges. Concrete strains at the centers of the beams were measured using a 100 mm gauge. Slip between steel and concrete was indicated by grid lines along the length of the bottom and top plate, and measured using a displacement transducer at four points on the bottom plate. Vertical deflections at the mid span and the supports were measured by displacement transducers. Magnitudes of applied load, strain, deflection and slip were recorded by data acquisition equipment. Digital camera was fixed at a position to record successive visible changes, principally concrete cracking process at each load steps.

TEST RESULTS AND COMPARISONS

Failure loads and modes

The modes of failure for the tested 8 beams are presented in Table 1. All the beams failed (rapidly increasing central deflection or reduction in load carrying capacity) due to either tension plate failed at mid span (bending failure) or tension plate failed at shear span followed with critical inclined cracks opening (shear failure). The load/deflection relationships of the specimens with different shear span to depth ratio are illustrated in Figure 5. Load capacity increased with the decreasing of shear span/depth ratio.

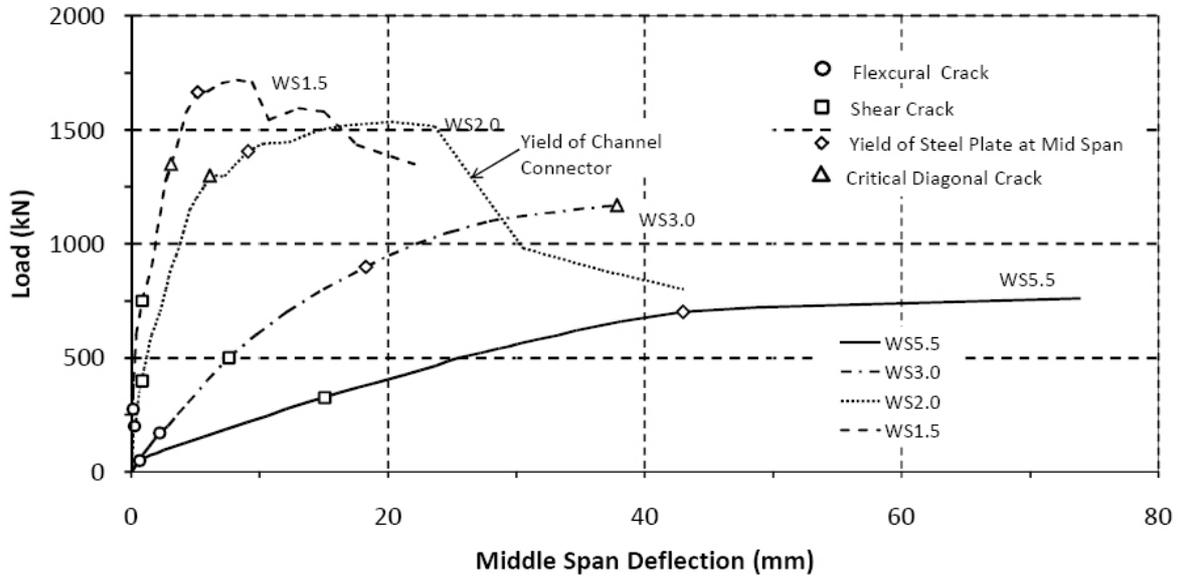


Figure.5 load deflection relationship of specimens with different shear span to depth ratio

Tension plate failure at mid span

The failure mode of specimen WS5.5 is characterized by the tension plate failure at mid span. The failure behavior is almost the same as the bending failure of doubly reinforced concrete beams with symmetrically placed reinforcements. When the load increased to 50kN, the initial flexural crack appeared at the bottom of the beam in pure bending zone, and penetrated rapidly towards the top of the section, showed the first turning point on the load/deflection curve. The second turning point appeared at about 700kN due to the yielding of tension steel plate at mid span, and after which, the load ceased to increase with the increasing of the deflection. The failure of the beam is characterized by the large deflection and pronounced curvature at the failure section in mid span (figure 8).

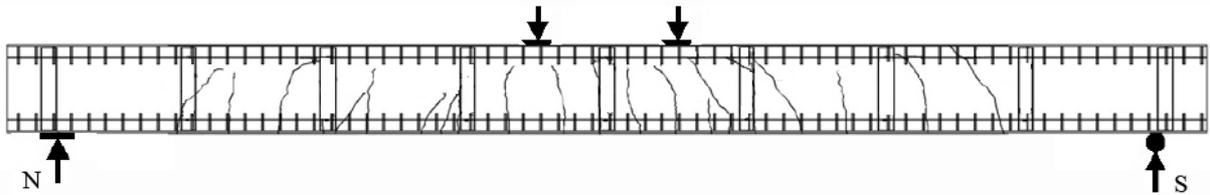


Figure.6 Crack pattern of specimen WS5.5

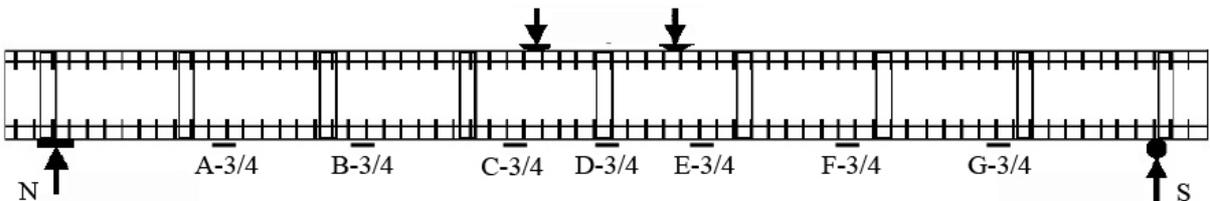


Figure.7 Load condition of specimen WS5.5 and strain gages arrangement on bottom plate

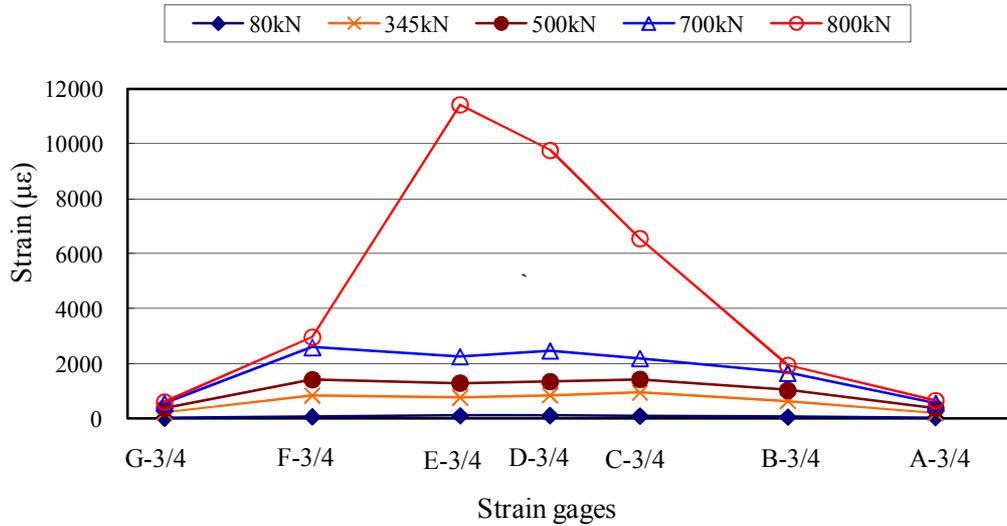


Figure.8 Bottom steel plate strain distribution at different load level of WS5.5

Tension plate failure at shear span

Expect for the specimen WS5.5, all the other 7 specimens are characterized by the tension plate failure at shear span. Figure 9 shows the crack pattern of specimen WS1.5. Figure 11 shows the strain distribution of bottom steel plate at different load level. At failure stage, maximum strain appears at A3/4 in shear span. There exist distinct differences for the diagonal failure performance between RC beams and SCS Beams.

For SCS beams, after the appearing of critical inclined crack, there is a sudden increasing of the tensile stress in the bottom steel plate within shear span, due to which the diagonal crack widens and extends directly to the load point. The tension force in bottom steel plate at mid span is balanced by the compression force in symmetrically placed top steel plate. Nearly no concrete contributes to the compression in top zone. This forms the essential difference with RC beams, in which a certain quantity of compression concrete is needed.

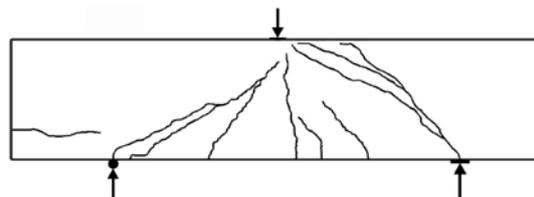


Figure.9 Crack pattern of specimen WS1.5

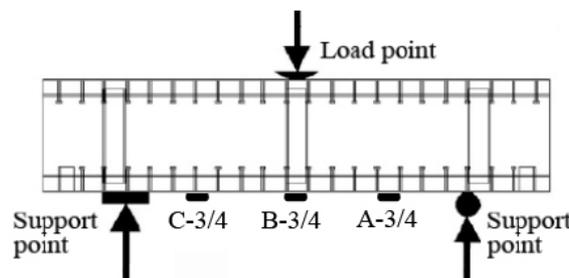


Figure.10 Load condition of specimen WS1.5 and strain gages arrangement on bottom plate

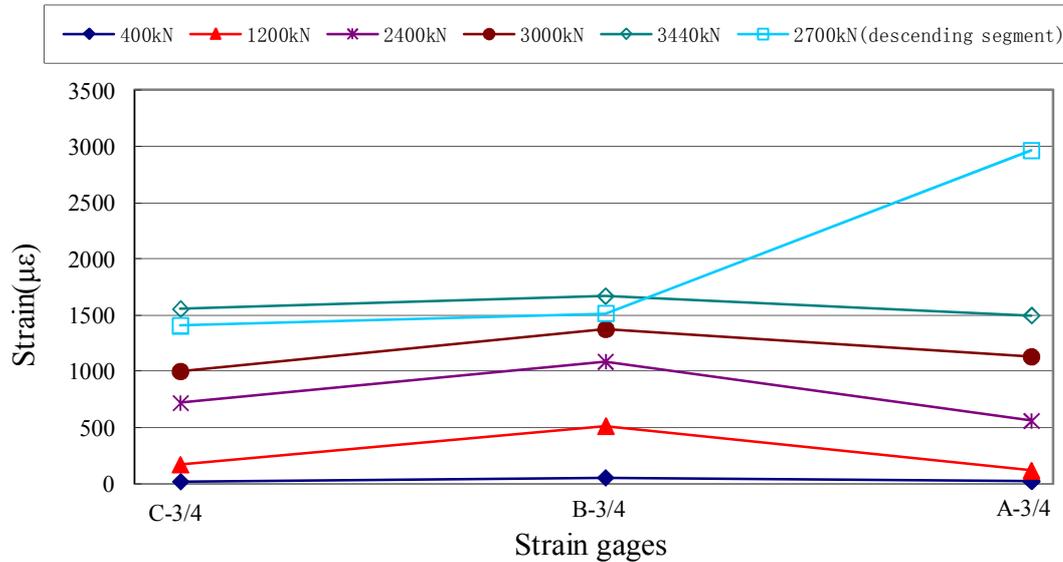


Figure.11 Bottom steel plate strain distribution at different load level of WS1.5

For RC beams, the direct cause of diagonal section failure is the compression failure or tension failure of the top compression zone concrete. For SCS composite beams, top steel plate is strong enough to resist the compressive force, top concrete compression zone is usually small, and no obvious failure is observed in this zone. The diagonal section failure of a SCS composite beam is caused mainly by yielding of tension steel plate in shear span followed with crushing of concrete in the web zone (Figure 12)

Unlike the unreliable dowel action of longitudinal reinforcement in RC beams, which may develop tearing tensile stress in the concrete between the rods, the studs between steel plate and concrete endow the connection with reliable integrity. The dowel action of steel plate in SCS sandwich beams can take an amazing portion of the total shear.

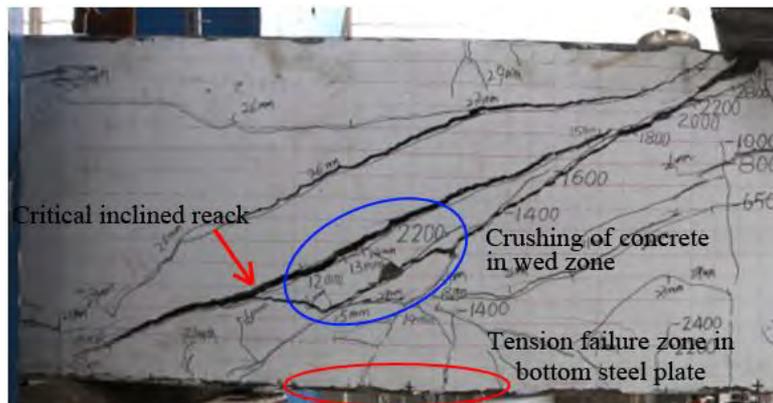


Figure.12 Typical crack pattern of SCS beams subject to combination of shear and moment

Influence of amount of shear connectors

Compared with the specimen WS1.5, which has no channel steel within shear span, there are two channel steels arranged in the shear span of specimen WS1.5'. Test results show the shear capacity difference caused by these two channel steels is 580kN, the contribution for one channel steel is about 290kN.

Compared with the specimen WS2.0, which has one channel steel within shear span, there are two channel steels arranged in the shear span of specimen WS2.0'. Test results show the contribution of the additional one channel steel is about 250kN.

The cross area of C14b channel is 2131mm², and the yield stress is 270MPa. The tension capacity of one C14b channel is 575.4kN. Under the experimental condition, the contribution of transverse channel steel to shear capacity is about 50% of the tension strength.

Influence of tension force to shear capacity

In general, tension force will reduce the shear capacity of RC beams. However, test results show that significant axial tension does not seem to have an influence on the shear strength of SCS beams (Figure 13). The fundamental cause of this phenomenal may lies in the fact that, after the appearing of critical inclined cracks, axial tension force is resisted mainly by steel plates, As the inclined cracks develop throughout the concrete section, axial tension force has little effect on the stress state of concrete beside inclined cracks, and the ultimate shear capacity is equal to the vertical component of the compressive force in concrete strut.

For specimens WS3.0 and WS3.0T, the initial stiffness is almost the same. At load level of 800kN, yielding of bottom steel plate causes stiffness reduction. As the load conditions for WS1.5 and WS1.5T are different, one point loading for WS1.5 and two points loading for WS1.5T, it is hardly to compare the stiffness difference between them.

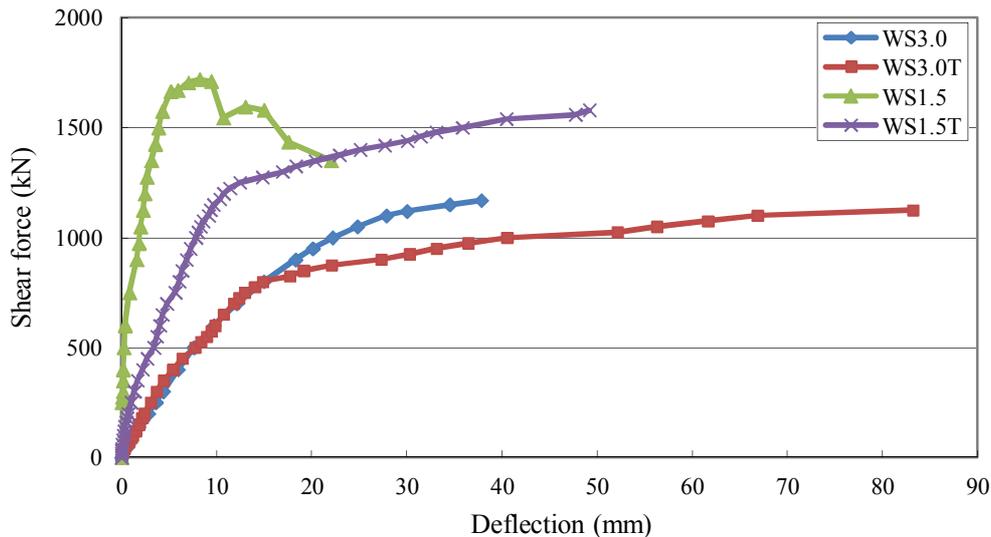


Figure.13 Load deflection relationship of specimens WS 1.5, WS1.5T, WS3.0, WS3.0T

The test load and code recommendation

In order to demonstrate whether the shear strength of SCS beams can be estimated using ACI code provisions for shear strength of RC beams, the test results of ultimate shear load are compared with the recommendation values of ACI349-01 [9] in Figure 14. The code provisions for shear strength in ACI349-01 are summarized using the equations below. In these equations, V_c is the shear strength contribution of the concrete and V_s is the shear strength contribution from transverse shear connectors.

$$V_n = V_c + V_s \quad \text{ACI349, Equation 11-2}$$

$$V_c = 2\sqrt{f'_c}b_wd \quad \text{ACI349, Equation 11-3}$$

$$V_s = A_vf_y \frac{d}{s} \quad \text{ACI349, Equation 11-15}$$

$$V_c = 2\left(1 + \frac{N_u}{500A_g}\right)\sqrt{f'_c}b_wd \quad \text{ACI349, Equation 11-8}$$

Where f'_c is the compressive strength of concrete, b_w is concrete section width, d is concrete section height, N_u is axial force (Negative for tension), A_g is the gross cross-sectional area, A_v is the cross of transverse shear steel, f_{yv} is yield strength of transverse shear steel.

As shown in Figure 14, shear strength is estimated conservatively by the ACI code provisions, the underestimated percentage ranged from 25% to 77%, and the least accurate results appeared for specimens WS1.5, WS1.5T and WS3.0T.

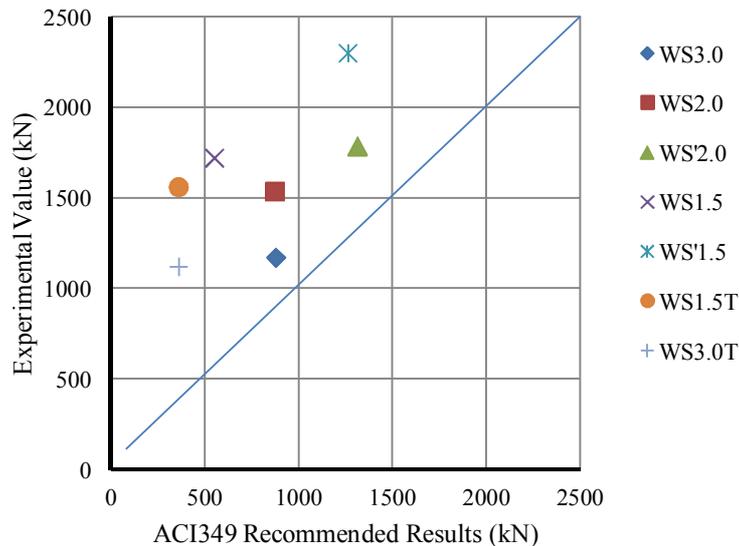


Figure.14 Tested shear resistances and ACI349 recommended results

CONCLUSIONS

Test results show that the bending failure mechanism of SCS composite member is almost the same as that of RC beams with symmetrically reinforced section, for transverse shear, the way in which SCS beams fail are rather different in their nature from the ways in which RC beams do. The main differences are:

1. While the direct cause of diagonal section failure of a RC beams is the compression failure or tension failure of the compression zone concrete, the diagonal section failure of a SCS composite beam is caused mainly by yielding of tension steel plate in shear span followed with crushing of concrete in the web zone.
2. Dowel action of steel plate contributes significantly to shear resistance and should not be neglected.
3. The contribution of transverse channel connectors crossing the diagonal section is about 50% of the tension yielding strength of channel connectors.
4. Axial tension promotes the yielding of steel plates, thereby reduces the bending stiffness, but significant axial tension does not seem to have an influence on the shear strength of SCS beams.

Although the calculation results are conservative, ACI349-01 code provisions for shear strength of RC beams cannot provide satisfactory assessment for SCS beams. In consideration of the behavior differences between SCS beams and RC beams under combined shear and bending, it is necessary to grope for a new shear capacity model which can correspond with the unique shear mechanism of SCS members. This work is in progress in Shanghai Nuclear Engineering Research and Design Institute and Shanghai Jiaotong University, and the study is to be published later on.

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