MINIMUM CROSS TIE RATIO OF STEEL PLATE CONCRETE BEAMS

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ABSTRACT

For a Steel plate Concrete (SC) module to behave effectively, a full interaction between the steel plate and concrete is necessary. Different forms of construction for SC modules have been proposed in the past. Cross ties method is considered to be one of the most efficient forms of construction of a SC module and has been proven to play an important role in ensuring the integrity of SC structures. However, the design codes or guidelines do not have specific provision on a minimum cross tie ratio for SC beams. This paper presents the experimental work in establishing a minimum cross ties ratio of SC beams. The test results show that SC beams failed prematurely in a brittle manner when insufficient amount of cross ties are provided. An increase in the amount of cross ties resulted in a ductile behaviour. Based on the test results from this study, a minimum cross tie ratio for SC beams is recommended; which is greater than that specified by ACI 318 code for reinforced concrete structures.

INTRODUCTION

The use of new composite Steel plate Concrete (SC) structures have increased rapidly in the recent decades. They are widely applicable in structural engineering practice, i.e. containment walls for nuclear power plants (Yamamoto et al. 2012), tall buildings, shield tunnel, etc. (Tolloczko 2001; Zhang 2009; Yan et al. 2014). One of the major applications of SC structures is its use in the construction of shielding building in AP1000 nuclear power plant.

From the mechanics point of view, SC structures can take the full advantage of individual material strength if the integrity between two distinct materials is achieved. Various methods are used to ensure the force transfer mechanism between the steel plate and concrete, such as: tie bars, shear studs, J-hooks, and profiled/surfaced preparation on steel plates (Subedi 2003; Hossain and Wright 2004). In practice, cross ties, also known as tie bars or transverse bars which connect the two external steel plates and fully embedded in concrete, are the most buildable, efficient and reliable form of SC construction in terms of time, cost, and quality control (Xie et al. 2007; Ramesh 2013).

A minimum amount of cross ties is necessary to prevent a sudden brittle failure. Three codes commonly referred for designing SC structures are ACI 349 Code (2006), design guidelines by Steel Construction Institute (Narayan et al. 1994), and technical guidelines for aseismic design from Japanese Electronic Association (JEAG 2005). The design codes, however, do not have clear provision for the minimum amount of cross ties except the recommendations of ACI 349 Code (2006). ACI 349 Code specifies the minimum shear reinforcement area ($A_{v,min}$) for reinforced concrete (RC) as:

$$A_{v,min} = 0.75\sqrt{f_c'}\frac{b_w s}{f_{yt}} \geq 50\frac{b_w s}{f_{yt}}, \tag{1}$$

Where b_w is member width, s is spacing of transverse steel, $f_c^{'}$ is specified compressive concrete strength, and f_{yt} is the specified yielding strength of shear reinforcement. Hence, the minimum shear reinforcement ratio for RC specified by ACI 349 Code ($\rho_{t,ACI}$) is

$$\rho_{t,ACI} = 0.75\frac{\sqrt{f_c^{'}}}{f_{yt}} \geq 50\frac{1}{f_{yt}} \tag{2}$$

This provision, however, adopts ACI 318 Code (2005), which is basically a design code for reinforced concrete structures. Therefore, the applicability of ACI 349 Code to SC structures is still questionable and requires experimental investigation.

Figure 1 shows a SC nuclear containment vessel and a strip of the cylindrical wall. At the regions close to foundation and at connections with other structural components, SC nuclear containment is subjected to out-of-plane shear (Oesterle and Russell 1982; Walther 1990). This paper reports a series of scaled-down SC beam tests. A minimum cross tie ratio for SC beams is proposed based on the test results.

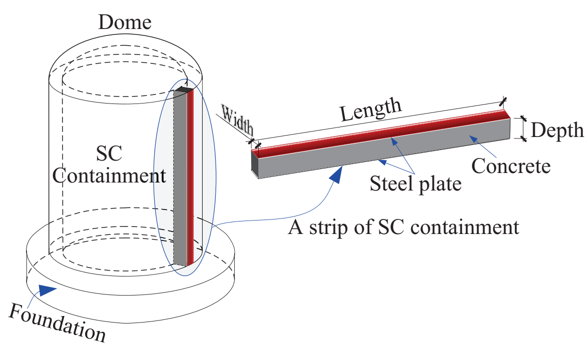
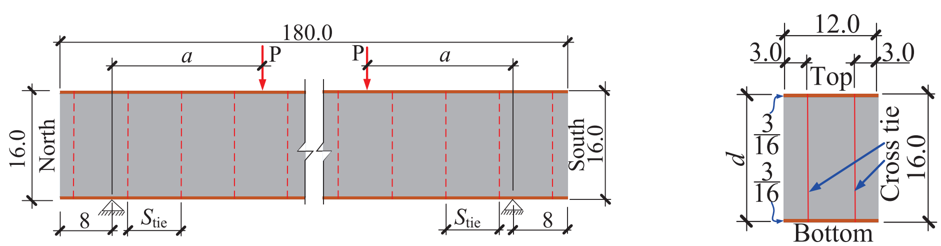


Figure 1. SC Nuclear containment and a strip of cylindrical wall

EXPERIMENTAL PROGRAM

Test Program

A strip of a nuclear containment structure (Figure 1) is considered as the study specimen and it is scaled down by a factor of 4/9 (Varma et al. 2011). Figure 2 shows the geometric properties of the SC beams. The length, width, and depth of each SC beam are 15.0 ft. (4572 mm), 12.0 in. (304 mm), and 16.0 in. (406 mm), respectively.



(a) Elevation of SC beams b) Cross setion dimensions

Figure 2. Dimensions of SC beams (unit: inch)

The experimental matrix showing different test parameters is arranged in Table 1. The main test parameters are the shear span-to-depth (a/d) ratio which is selected as 1.5, 2.5 and 5.2, and cross ties ratio $\rho_{t,test}$ which ranges from 0.102% to 0.205%. The amount of cross ties was increased in specimens SC2, SC3, and SC4 till they exhibited a certain shear ductility. Moreover, specimens SC5 and SC6 were tested to investigate the behaviour of SC beams under different *a/d*.

Deformed mild steel No. 2 reinforcing bars were used as shear reinforcement, and high-strength low-alloy structural steel (ASTM A572-50) was used as top and bottom steel plates (ASTM 2014). The yield strength of No. 2 re-bars ($f_{y,t}$) and yield strength ($f_{y,sp}$) of steel plate are 60.8 ksi (419 MPa) and 55.0 ksi (379 MPa), respectively. Specimens SC1 to SC6 were cast in three different times, and concrete compression strength ($f_c^{'}$) varied from 5.82 to 8.13 ksi (40.1 to 56.0 MPa).

Table 1: Experimental matrix, strength, and failure mode

Specimen	a/d	s_{tie}# (in.)	$f_c^{'}$* (ksi)	$\rho_{t,ACI}$ (%)	$\rho_{t,\text{test}}$ (%)	$\rho_{t,\text{test}} / \rho_{t,ACI}$	F_{peak}** (kips)	Ductility δ†	Failure Mode
SC1 north	2.5	8.00	8.13	0.111	0.102	0.92	27.4	——	Brittle
SC1 south	2.5	8.00	8.13	0.111	0.102	0.92	26.1	——	Brittle
SC2 south	2.5	7.00	5.80	0.094	0.117	1.25	26.9	0.730	Brittle
SC3 north	2.5	6.00	5.82	0.094	0.137	1.45	31.7	1.17	Ductile
SC3 south	2.5	6.00	5.82	0.094	0.137	1.45	34.9	1.79	Ductile
SC4 north	2.5	5.00	7.37	0.106	0.164	1.54	42.7	1.58	Ductile
SC4 south	2.5	4.00	7.37	0.106	0.205	1.93	53.0	1.65	Ductile
SC5 south	1.5	6.00	8.00	0.110	0.137	1.25	55.9	1.43	Ductile
SC5 north	1.5	5.00	8.00	0.110	0.164	1.49	64.7	1.48	Ductile
SC6	5.2	6.00	8.00	0.110	0.137	1.25	29.3	1.99	Ductile

\# s_{tie} = spacing of cross ties
* $f_c^{'}$ = concrete compressive strength from concrete cylinder (6.00″×12.0″), tested on the test day
** F_{peak} = peak shear capacity
† δ = deflection at the peak /deflection when cross ties yielded
1.0 in. =25.4 mm, 1.00 kips= 4.40 kN, 1.00 ksi = 6.89 MPa

Test Setup

The specimens were subjected to vertical loading provided by north and/or south actuators with a capacity of 600 kips (2670 kN) each, as depicted in Figure 3(a). The loads and displacements of the actuators were controlled by the MTS Flex system. The tests were performed under displacement-controlled loading protocol with a constant loading rate of 0.10 in. (2.54 mm) per 15.0 minutes. During each loading step, the loading might be put on hold and resumed to check and record the cracks. Each test lasted 3 to 5 hours.

(a) Loading arrangement (b) Setup of LVDT

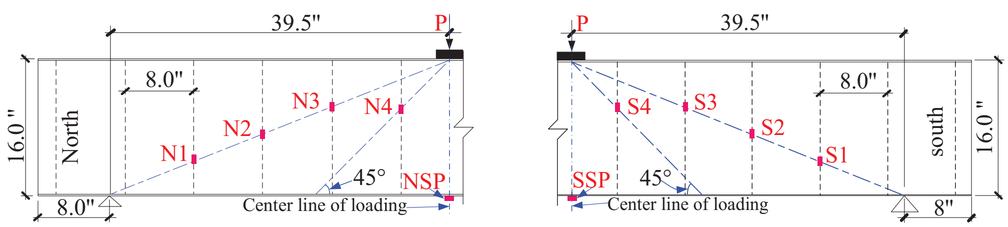
Figure 3. Test setup of specimen

Specimens SC1 and SC3 were loaded simultaneously at both north and south ends. Specimen SC2 was only loaded at the south end due to premature failure at the north end prior to the testing. For specimens SC4 and SC5, each end was tested individually. The ends with lesser shear reinforcement ratio for specimen SC4 (north) and SC5 (south) were tested first. Before testing the other end (SC4 south, SC5 north), the support at the tested end was moved to the nearest un-cracked section. Moreover, specimen SC6 was loaded in the middle span using only one actuator.

Instrumentations

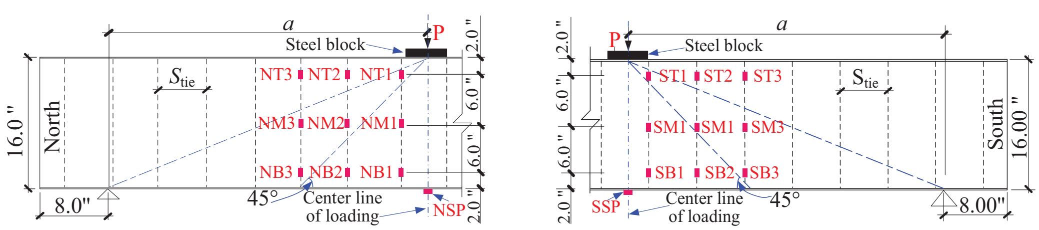
Load cells installed under the supports as shown in Figure 3(a), were used to measure the shear forces in the specimens. Linear Variable Displacement Transducers (LVDTs) were placed vertically at the two supports and under loading point to measure the settlement of the supports and the total deflection of each specimen, respectively. The net deflection of the specimen were calculated by subtracting the support settlement from the total deflection. LVDTs forming a rosette were installed on the side faces of the specimens to get the smeared strains within the critical zone (Figure 3(b)).

Strain gauges (SGs) were pasted on the surface of cross ties to measure the local strains of cross ties embedded in concrete. SGs were also pasted on the surface of bottom steel plate under actuator to measure the maximum tensile strain in the bottom steel plate. Figure 4 shows the arrangement and label of strain gauges in specimen SC1, and Figure 5 shows the typical arrangement and label of strain gauges in specimens SC2 to SC6. Label of strain gauges in specimens SC2 to SC6 contains two letters and one number. The first letter indicates north or south end of a specimen, the second letter represents the elevation or position of the stain gauge, i.e. top, middle, or bottom, and the number denotes the distance from the centre line of loading to the stain gauge, i.e. the smaller the integer the closer to the loading point. NSP and SSP are the labels of strain gauges to measure maximum tensile strain in the bottom steel plate at north and south end, respectively.



(a) North end (b) South end

Figure 4. Strain gauges arrangement and label of Specimen SC1 (unit: inch)



(a) North end (b) South end

Figure 5. Typical strain gauges arrangement and label of Specimens SC2 to SC6 (unit: inch)

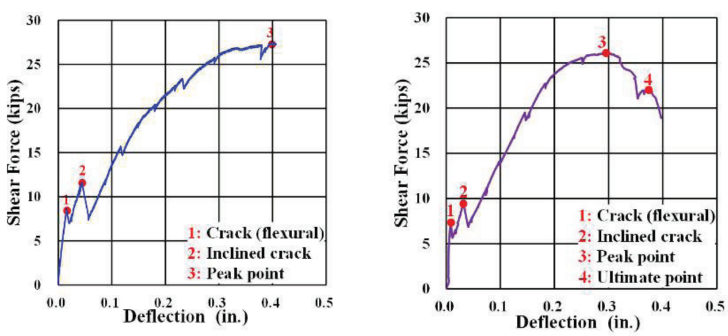
EXPERIMENTAL RESULTS AND DISCUSSIONS

Specimen SC1

Specimen SC1 was designed to have a minimum shear reinforcement ratio as per the recommendations of ACI 349 Code. The specimen was tested under four-point bending. The shear force-deflection curve of north and south ends are shown in Figure 6(a) and (b), respectively. It becomes evident from Figure 6 that neither cross ties nor bottom steel plate was yielded, and concrete was not crushed at the peak load. Specimen SC1 failed in a brittle way with no ductility due to de-bonding between the bottom steel plate and concrete.

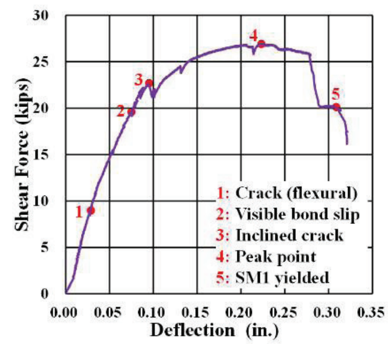
Specimen SC2

The shear reinforcement ratio of specimen SC2 is 25% more than specimen SC1. The shear force-deflection curve of the south end is shown in Figure 7. Specimen SC2 exhibited similar behaviour to specimen SC1; that is not yielding of cross ties and steel plate and no crushing of concrete at the peak load. Therefore, SC2 south had a brittle failure with no ductility.



(a) North end (b) South end

Figure 6. Shear force-deflection curves of Specimen SC1

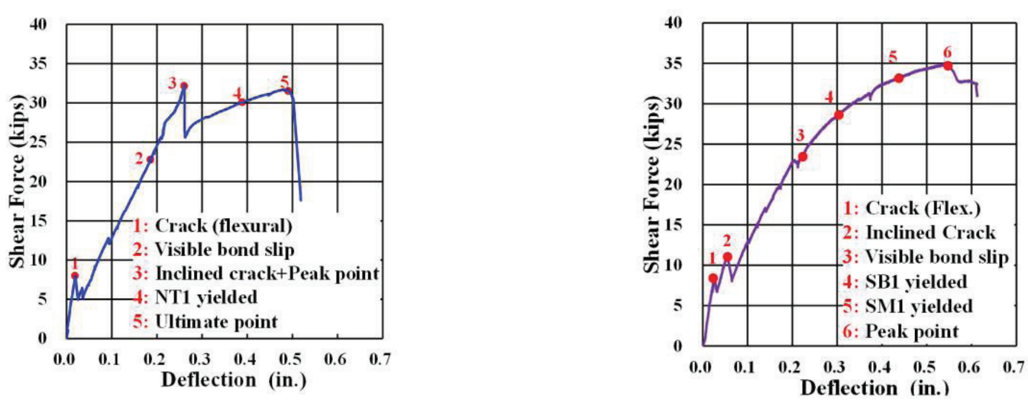


(c)

Figure 7. Shear force-deflection curve of Specimen SC2 south

Specimen SC3

The shear reinforcement ratio of SC3 is 45.0% more than SC1. The shear force-deflection curves of the north and south ends are shown in Figure 8(a) and (b), respectively. As shown in Figure 8(a), the load drops at the peak as an inclined crack occurs. However, F_{north} continues to increase and one of the cross ties is yielded before reaching the failure load which is very close to the peak load. Figure 8(b) shows that the south end exhibit a ductile behaviour in which cross ties were yielded prior to the peak and concrete was not crushed. Hence, this behaviour shows that specimen SC3 has just about the minimum amount of cross ties to prevent a brittle failure.

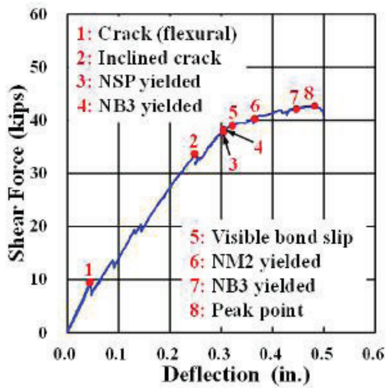


(a) North end (b) South end

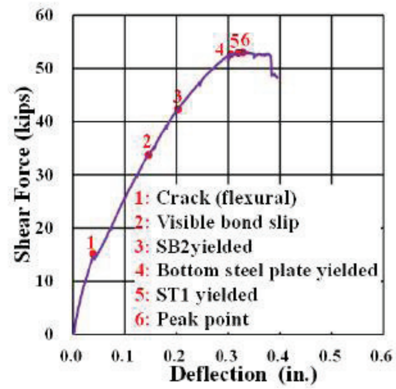
Figure 8. Shear force-deflection curves of Specimen SC3

Specimen SC4

The shear reinforcement ratios of the north and south ends of specimen SC4 are 54% and 93% more than that of specimen SC1, respectively. Figure 9 shows the shear force-deflection for the north and south ends. The north and south ends were tested one end at a time. The north end was tested first. Figure 9(a) illustrates that the bottom steel plate and the cross ties close to shear crack yielded before the peak load was reached. The inclined shear crack occurred at approximately 45 degrees, as shown in Figure 10(a). The bond slip between the bottom steel plate and concrete was monitored during the test. At post peak load stage, the bottom steel plate slipped about 0.75 in. (19.1 mm), as shown in Figure 10(b).



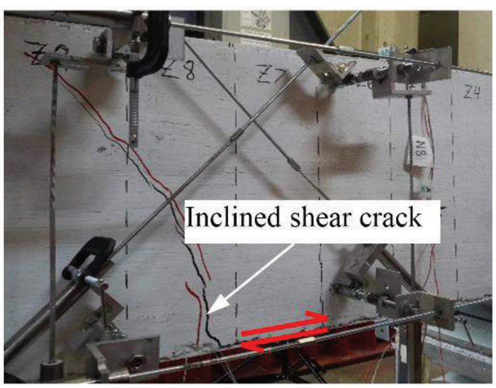
(a) North end



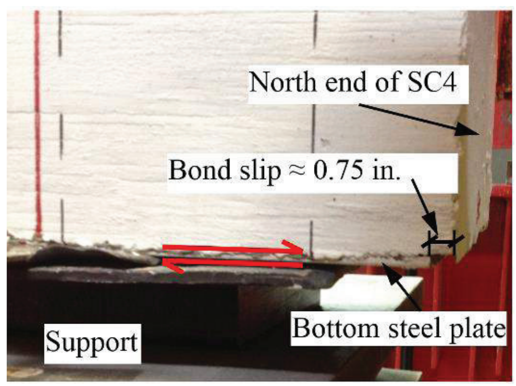
(b) South end

Figure 9 Shear force-deflection curves of SC4

The south end of SC4 was tested after the north end was unloaded. To eliminate the influence of the damage at the north end, the north support was moved to the nearest un-cracked section. The shear force-deflection curve of the south end is shown in Figure 9(b). The cross ties close to shear crack (SB2) yielded after a visible bond slip was observed. Also, the bottom steel plate and cross ties near the top steel plate were yielded in succession. At the post peak stage, the cross ties were sheared off and bottom steel plate slipped up to 0.50 in. (12.7 mm).



(a) At the peak load stage



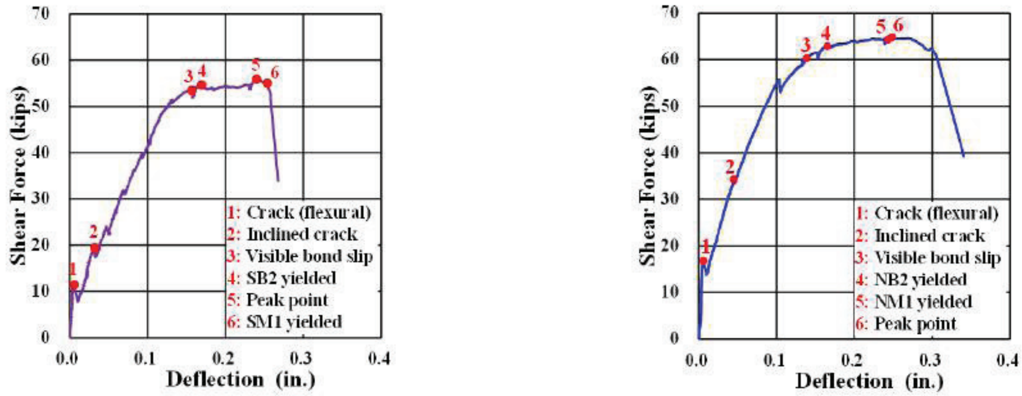
(b) At the post peak stage

Figure 10 Critical shear crack and bond slip of Specimen SC4 north

Specimen SC5

The shear reinforcement ratios of the north and south ends of specimen SC5 are 25% and 49% more than that of specimen SC1, respectively. Figure 11(a) shows the shear force-deflection curve of the south end. Bond slip and yielding of cross ties were observed prior to the peak. Concrete was not crushed in the south end and steel plate was not yielded.

Figure 11(b) shows the shear force-deflection curve of the north end. The bond slip and yielding of cross ties occurred prior to the peak. Concrete was not crushed in the north end and the bottom steel plate was not yielded.



(a) South end (b) North end

Figure 11. Shear force-deflection curves of Specimen SC5

Specimen SC6

Specimen SC6 was tested under a shear span-to-depth ratio (a/d) of 5.15. The spacing of cross ties in specimen SC6 is 6.00 in. (152.4 mm), giving a shear reinforcement ratio of 25% more than the minimum amount provided in specimen SC1. As compared with specimens SC1 to SC5, more flexural cracks were developed in specimen SC6, which significantly reduced the stiffness (Figure 12). The cross ties yielded just after the yielding of the bottom steel plate. Specimen SC6 had the most ductile behaviour amongst all the tested beams.

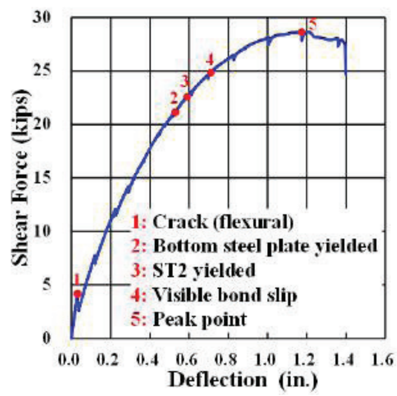


Figure 12. Shear force-deflection curve of SC6

MINIMUM CROSS TIE RATIO OF SC BEAMS

The minimum cross tie ratio of SC structures subjected to out-of-plane shear is proposed based on test results of specimens SC1 to SC6. Specimens SC1 and SC2 failed prematurely due to insufficient amount of cross ties. Specimens SC4 north and south ends, and specimen SC3 were tested under the same shear span-to-depth ratio (a/d) of 2.5 with different cross tie ratios (ρ_{test}). To compare the test results of these specimens, the normalized shear force-deflection curves are plotted in Figure 13. The shear force was normalized with $\sqrt{f_c'}b_w d$, and the deflection was normalized with $\Delta_{peak.}$ (deflection corresponding to peak shear force). Figure 13 shows that the capacity and ductility of SC beams increase as the amount of cross ties are increased. Specimens SC3 north and south ends which were tested simultaneously, exhibited different behaviours. Specimen SC3 north had a sudden load drop due to shear crack right after it reached the peak load. The north end, however, was still able to resist load, but its stiffness had reduced significantly. Cross ties in Specimen SC3 north were yielded before the second peak value was reached. The ductility of SC3 north was calculated to be 1.17. On the other hand, specimen SC3 south behaved in a ductile manner and its ductility was found to be 1.79. Specimen SC3 north and south ends, just had adequate cross tie ratio for the SC beam to preserve a certain ductility. For specimen SC4, both north and south ends, showed ductile behaviour and higher ultimate shear strength than those of specimen SC3. The ductility of north and south ends of specimens SC4 were calculated as 1.58 and 1.65, respectively. The peak shear strength of specimens SC4 south and north was 35% and 67% more than the peak shear strength of specimen SC3 north, respectively. This trend further confirms that SC beams could have ductile behaviour if sufficient cross ties is provided.

Specimens SC3, SC5 south and SC6 which had the same cross tie ratio 0.137%, were tested under three different shear-span to depth ratios (a/d). The shear force vs. deflection curves of these specimens are presented in Figure 14. It is obvious that the capacity and stiffness increase as a/d decreases. For instance, specimen SC5 South, with the smallest a/d of 1.5, had the highest capacity and stiffness. It is also obvious that the deflection increases as a/d increases, i.e. specimen SC6, with the largest a/d 5.2, had the largest deflection. Furthermore, specimens SC3 south, SC3 north, SC5 south and SC6 had a ductility of 1.17, 1.79, 1.43 and 1.99, respectively. As compared to the minimum shear reinforcement ratio specified by ACI 349 Code, i.e. Eq. 2, the shear reinforcement ratio ($\rho_{t,test}$) of specimens SC3 south and north was 45% more, and the shear reinforcement ratio ($\rho_{t,test}$) of specimens SC5 south and SC6 was 25% more.

An interesting phenomenon could be found from the test results. It was observed that more cross ties (relative to the minimum required by ACI 349 Code) are required for SC beams tested under a/d of 2.5 than that of SC beams tested under a/d of 1.5 or 5.2. Similar trend can also be found in reinforced concrete members (Kuo et al., 2014) and prestressed concrete members (Laskar et al., 2010). Thus, the proposed minimum cross tie ratio ($\rho_{t,\min}$) for SC beams is

$$\rho_{t,min} = 1.45 \times \rho_{t,ACI} \text{ for } 2.0 < a/d < 4.0, \text{ or} \quad (3)$$

$$\rho_{t,min} = 1.25 \times \rho_{t,ACI} \text{ for } a/d \leq 2.0 \text{ and } a/d \geq 4.0. \quad (4)$$

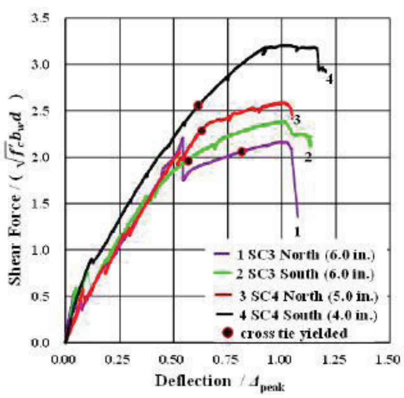


Figure 13. Specimens with the same shear span-to-depth ratio of 2.5

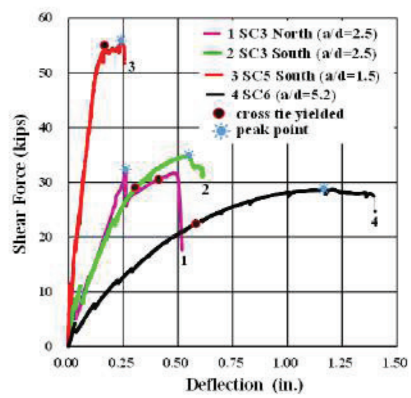


Figure 14. Specimens with cross tie spacing of 6.00 in.

CONCLUSIONS

Six SC beams with different shear reinforcement ratios (ρ_t) were tested under different shear span-to-depth ratios (a/d). Based on the test results, the minimum shear reinforcement ratio ($\rho_{t,\min}$) is recommended to ensure ductile behavior of SC beams. For SC beams with a/d in the range of 2.0 to 4.0, the minimum shear reinforcement ratio ($\rho_{t,\min}$) of 45% more than the minimum required by ACI 349 code ($\rho_{t,\mathrm{ACI}}$) is recommended. For SC beams with a/d less than 2.0 or more than 4.0, the minimum shear reinforcement ratio ($\rho_{t,\min}$) of 25% more than the minimum required by ACI 349 code ($\rho_{t,\mathrm{ACI}}$) is recommended.

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NOMENCLATURE

a	shear span (distance between center line of loading and support)
A_v	area of shear reinforcement at spacing s
b_w	web width of beam
d	effective depth of beam
$f_c^{'}$	specified concrete compressive strength
F_{peak}	peak shear capacity
s	center-to-center spacing of transverse steel
s_{tie}	spacing of cross ties
V_n	nominal shear strength of beam
V_c	shear strength contributed by concrete
V_s	shear strength contributed by transverse steel
$\rho_{t,ACI}$	minimum shear reinforcement ratio of SC beams specified by ACI 349 code
$\rho_{t,test}$	cross tie ratio of tested SC beams
$\rho_{t,\min}$	minimum shear reinforcement ratio recommended for SC beams

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