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Out-of-plane Shear Strength of Steel Plate Concrete Walls Dependent on Bond Behavior

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1 ABSTRACT

This paper investigates out-of-plane shear behaviour of composite walls of steel plates (SC walls) and suggests a strength model based on the limit analysis in the framework of the plasticity theory. For speedy and modular construction, SC walls are fabricated by double steel plates with welded shear studs on steel plates and are filled with concrete between double steel surface plates. Review on current design formulas proposed by JEAG 4618 requires further understanding of shear behaviour dependent on bond stress relying on studs and taking into account of difference between ordinary reinforced concrete members. To this end an arch action dependent on bond action by shear studs is experimentally investigated with consideration of effectiveness factors for compressive strength of concrete of direct strut for arch action are proposed. The contribution of tensile strength and compressive strength of concrete to the shear strength due to arch action in short shear span ratio is investigated by assuming fan-shaped compression fields involving a strut in case of single curvature and double curvature types. Series of experimental programs have been prepared for verification of proposed shear strength models with test results. The test results, including those from JEAG, show good agreements with the proposed formula.

2 INTRODUCTION

The development of composite walls of steel plates (SC wall) as one of modular construction systems has provided a viable option in the construction industry, in particular, nuclear power plant facilities. It is well recognized that the proposed modular construction scheme has greater benefit in reducing the construction period, guaranteeing the economic profits from electric-power production upon completion. This combination of steel plates with concrete wall structures takes advantage of the improvement in the post-buckling behaviour of steel plate with inherent rigidity of concrete.

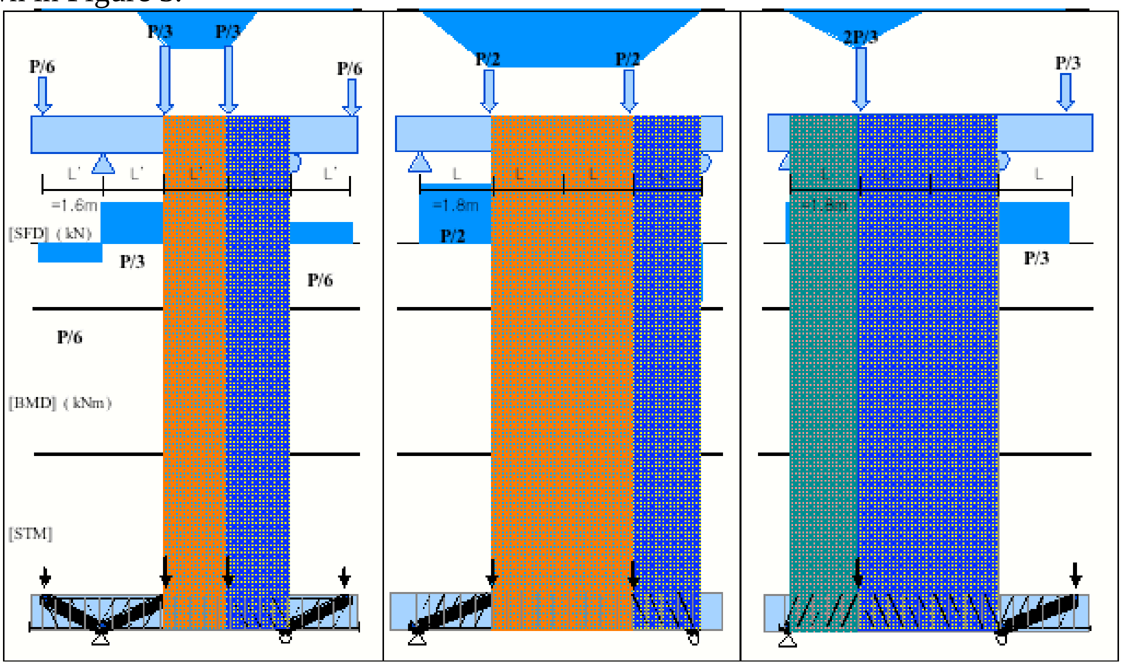
Bond transfer between steel plate and concrete in SC wall subject to out-of-plane shear is quite different with ordinary reinforced concrete structures. Bond stress in cracked concrete member provides increment in tension force, which can be a main factor producing shear flow around tension member. This adhesive stress between concrete and tension member in SC structure is provided primarily by studs welded in steel plate which is assumed to coalesce into concrete during concrete placing. Bond stress in RC members, in the meantime, is possible mainly by deformed steel bar between cracks in concrete, requiring complicated steel design in construction process such as splices and hooks at the end of anchorages. In SC wall, however, these connecting processes are conducted with simple and facile connecting method such as welding and bolting; so that the modular system can be possible.

The previous experimental observation showed crack in SC walls subject to out-of-plane shear was different from those in ordinary reinforced concrete beams. The main reasons are due to confinement from the plates and different bond transfer by studs which creates stable bond transfer in the interface between concrete and steel plates [1]. This paper proposes a shear strength model regarding bond effect on arch action as well as the diagonal stress field between plates. The proposed model focuses on reduced strength of arch action as a primary out-of-plane shear transfer in SC walls of short *a/d* ratios due to reduced effective compressive strength of strut. Also truss action requires us to consider reduced effective compressive strength of the diagonal stress field.

3 EXPERIMENTAL PROGRAM

3.1 Specimens and Load Configuration

A series of experimental program [2] were prepared for the investigation of characteristics of shear behaviour in SC walls and for verification of shear strength formula to be proposed later. Two different types of SC walls were fabricated: specimens without ribs and specimens with ribs. In the first year experimental program, tests for non-ribbed SC wall were performed focusing on three important parameters: shear span ratio, plate thickness, and shear reinforcement ratio. Consequently two different loading patterns were applied: single curvature systems within shear span as illustrated in Figure 1 a) and double curvature system as in Figure 1 c). In the single curvature loading experimental program, the flexural and shear behaviour of SC walls with ribs were investigated where H-100×100×6×8 ribs were welded along outside of shear bars. The shear bar of 16 mm diameter was intended for spacing between two steel plates before concrete was placed, as shown in Figure 3.



a) Symmetric double curvature b) single curvature c) Anti-symmetric double curvature

Figure 1. Loading condition for shear transfer

In the first phase experimental program as in Figure 2, NRC-0R-4S400-4ST involved couplers to connect top and bottom shear bars for easy fabrication. Shear span ratios of 3.2 and 4 were prepared by changing loading points. To investigate the effect of steel ratio on failure mode, NRT-0R-3S400-4ST of 4.5 mm steel plate was compared with those of 9 mm thickness.

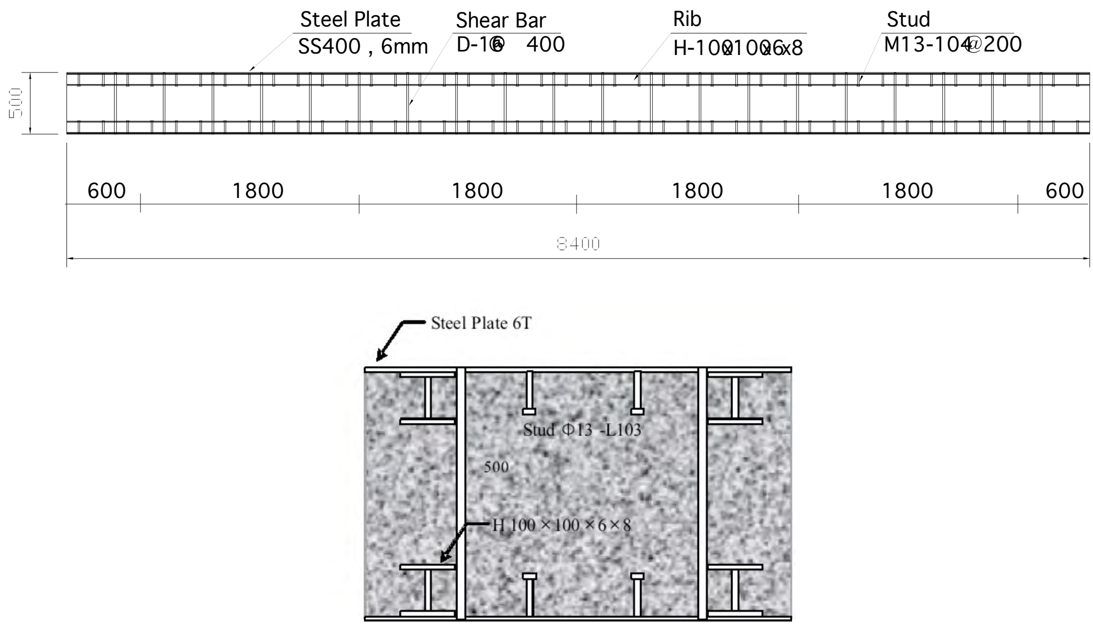


Figure 2. Detail of standard specimen (top), Section detail (bottom)

As mentioned earlier the second phase experimental program for single curvature loading system intended to investigate the effect of ribs on shear behaviour of SC walls. A basic specimen S-4R-2S400-4ST and the specimen B-4R-2S400-4ST are illustrated Figure including a typical section with ribs, shear bars, and shear studs. The other specimens S-0R-2S400-4ST, S-4R-0S-4ST, and S-4R-2S400-0ST were prepared to investigate effects of such components on shear behaviour. Table 1 shows properties of test specimens, and material properties are listed in Table 2.

Table 1. Specimen

a/d	Steel plate thickness (mm)	Stud			Shear bar			Rib	Specimen Designation
		No. of row	Spacing	diameter (mm)	No. of row	spacing	diameter (mm)	No. of row	
3.2	9	4	@200	16	3	@400	D16	-	NR-0R-3S400-4ST
3.2	9	4	@200	16	4	@400	D16	-	NRC-0R-4S400-4ST
4	9	4	@200	16	3	@200	D16	-	NR-0R-3S200-4ST
4	4.5	4	@200	16	3	@400	D16	-	NRT-0R-3S400-4ST
3.6	6	4	@200	13	2	@400	D16	4	B-4R-2S400-4ST
7.2	6	4	@200	13	2	@400	D16	4	S-4R-2S400-4ST
7.2	6	4	@200	13	2	@400	D16	-	S-0R-2S400-4S
7.2	6	4	@200	13	-	-	-	4	S-4R-0S-4ST
7.2	6	-	-	-	2	@400	D16	4	S-4R-2S400-0ST

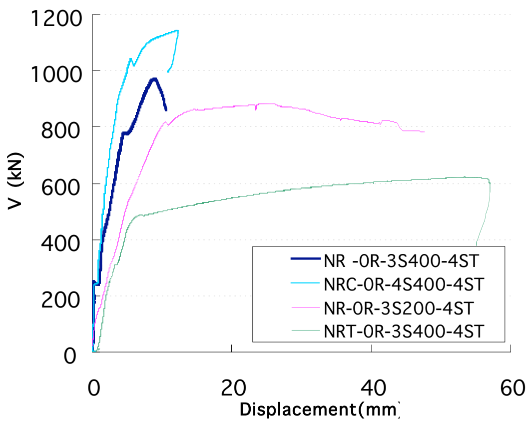
- NR: no rib - B: flexure test - S: shear test - R: rib - S: shear bar - ST: stud

Table 2. Material properties of concrete, plates, and studs

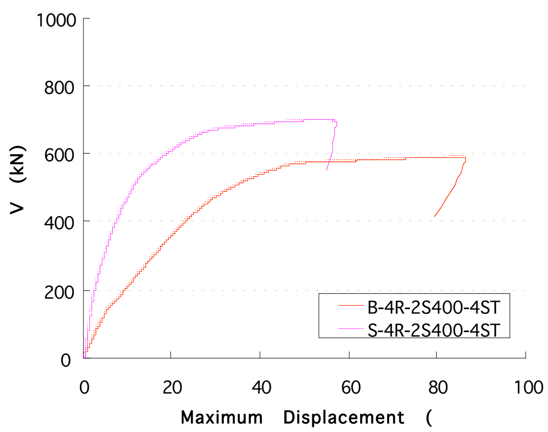
Specified compressive strength of Concrete (MPa)	Ultimate tensile strength of Plate (MPa)	Yield tensile strength of Plate (MPa)	Ultimate tensile strength of Stud (MPa)	Yield tensile strength of Bar (MPa)
38	428	303	450	361

3.2 Load-deflection curves

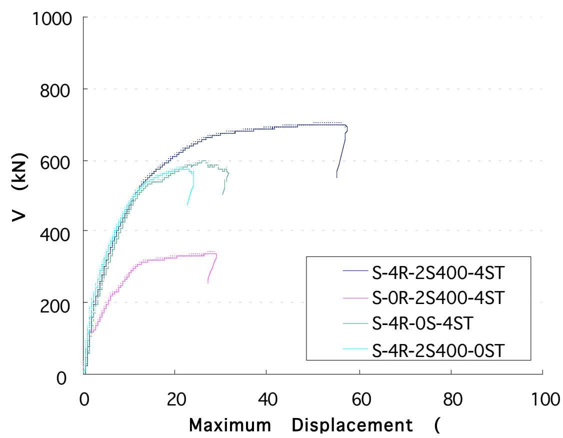
As *a/d* ratio of specimen increases, observed failure modes are expected to change from shear failure to flexural failure. Figure 3 a), b), and c) show the vertical load vs. deflection curve. The specimens of short shear span ratio of 3.2 showed shear failure modes while the other specimens of longer shear span ratio of 4.0 finalized by flexure failure modes. In the flexural failure modes load-deflection curves showed slightly ascending slopes of curve after the first yielding point, as shown in Figure 3 a). The specimens of shear span ratio of 3.7 showed brittle shear failure modes. Shear strength of specimen NR-0R-3S400-4ST which has three shear bars is reduced by approximately 17% in comparison with that of specimen NRC-0R-4S400-4ST which has four shear bars. The specimen of 4.5 mm thickness plates showed 31% strength reduction compared to the specimen of 9 mm plates but larger ductility.



a) Deflection curve of specimen without ribs



b) Single curvature test



c) Double curvature test

Figure 3. Load –Deflection Curves

The second phase program for the investigation of the effect of ribs on flexural and shear strengths were performed. More than half of specimens showed flexure failure modes which had long shear span ratio. It was observed that the contribution of ribs to the flexural capacity was more than that expected. The effect of single and double curvature on shear strength was examined by the comparison between S-4R-2S400-4ST and B-4R-2S400-4ST illustrated in Figure 3 b), respectively. The specimen subjected to out-of-plane shear in single curvature showed flexural crack in concrete in tension along span between supports.

As illustrated in Figure 3 c) specimens S-4R-0S-4ST and S-4R-2S400-0ST without shear bars and studs experienced shear failure mode and a steep decline in loading capacity after first yielding. These two components contribute to the shear strength and did not show any difference in their initial stiffness. However, addition of shear studs made the specimen more ductile due to stable bond generated by studs.

3.3 Crack pattern and Stress distributions

Distributed crack along the interfaces between steel plates and concrete as shown Figure 4 indicates some evidence of stable bond resistance. In contrast, the specimen, S-4R-2S400-0ST with shear studs only developed a few number of major diagonal crack in the direction from the loading points to the supports while cracks the interface between concrete and plates were rarely observed.

The rib effects on the flexure capacity of SC wall are examined by strength comparison of S-0R-2S400-4ST without ribs. The flexure strength was reduced by 51%. Specimens in shear failure showed similar strength reduction compared with SC wall without ribs.

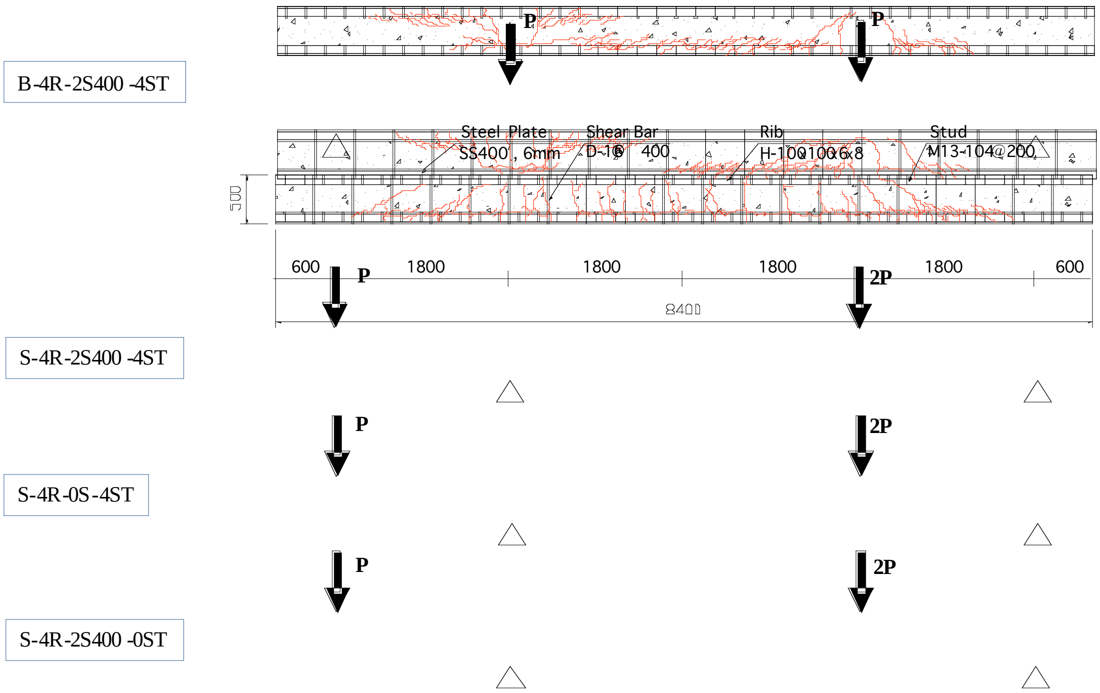


Figure 4. Crack patterns of single curvature test and double curvature test

As illustrated in Figure 4 c) specimen S-4R-0S-4ST and S-4R-2S400-0ST without shear bars and studs experienced shear failure with a large degradation after first yielding. Two of these components increase shear strength but do not increase their initial stiffness. Shear studs made the specimen more ductile due to stable bond resistance. Distributed crack along the interface as shown Figure 4 shows some evidence of stable bond resistance. In contrast, the specimen, S-4R-2S400-0ST without shear studs only showed a few number of major diagonal crack in the direction from the loading points to the supports and the range of cracks the interface between concrete and plates were limited.

The contribution of ribs to the flexure capacity of SC wall is examined by comparing with the result of S-0R-2S400-4ST without ribs in which the flexure strength was reduced by 51%. Specimens in shear failure showed similar strength reduction compared with SC wall without ribs.

In the specimen S-4R-2S400-0ST, the shear bars near the loading point and supports reached yielding point first. The shear bars tended to restrain the opening of diagonal concrete cracking with the shear resistance in vertical direction. Strain distributions in ribs and steel plates of S-4R-0S-4ST are shown in Figures 5 and 6. Due to the inflection point in the middle of the specimen, tension and compression strain distributions in the top and bottom plates are expected in a linear shape denoted by blue line. However, most strains indicated positive values due to shear force.

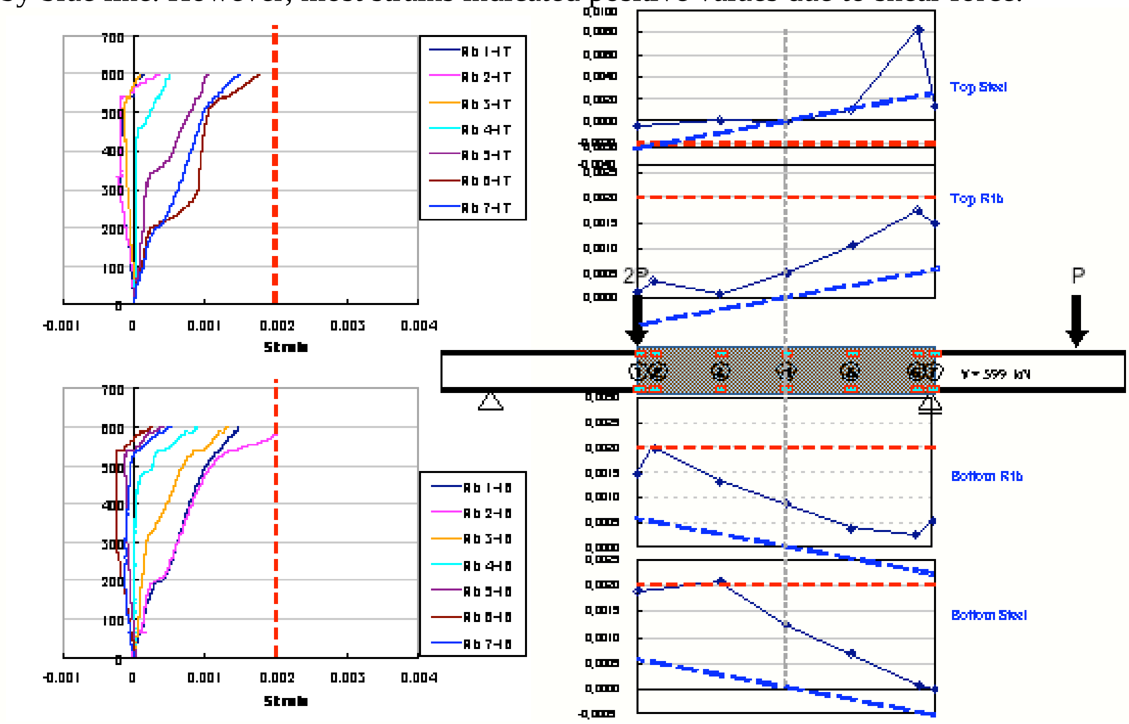


Figure 5. Strain distribution in ribs (S-4R-0S-4ST)

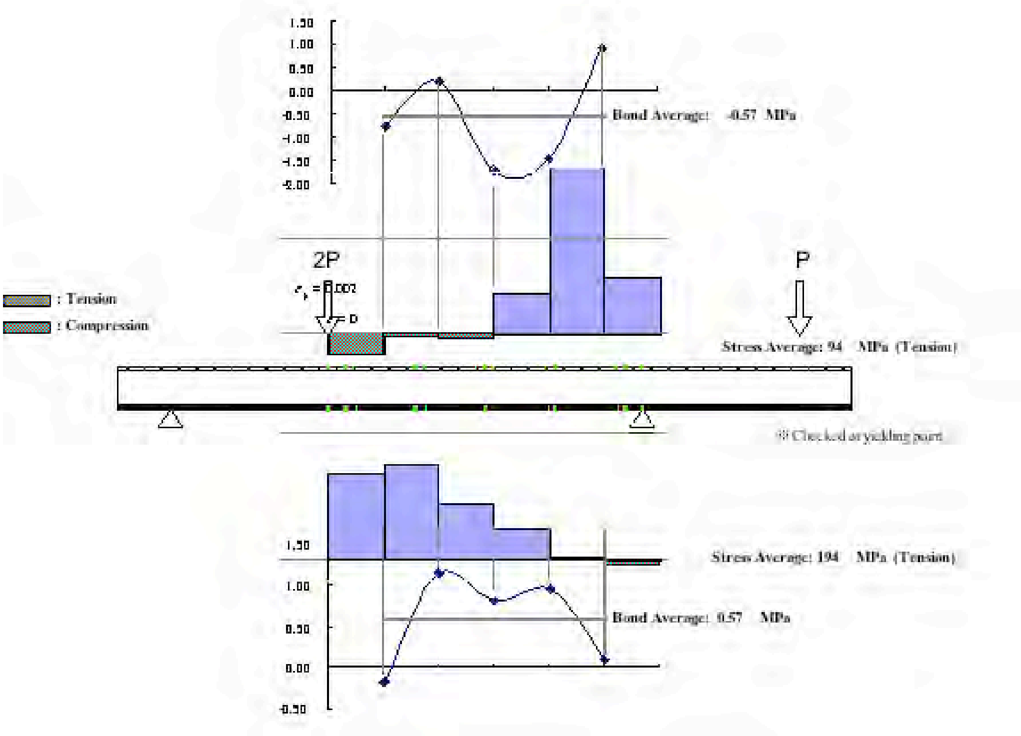


Figure 6. Average bond stress in shear span (S-4R-0S-4ST)

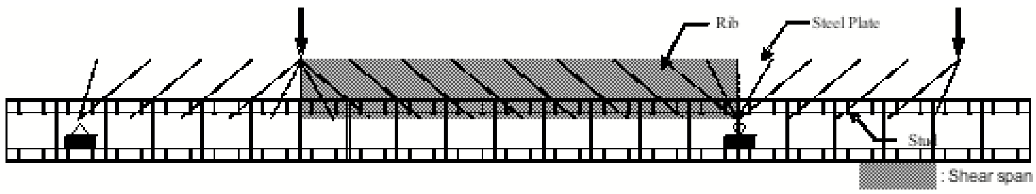
Measurement of strain distribution in plates provide failure mode identification and calculation of the bond stress, μ_{avg} , equal to the change tension force in the plates. Difference in tension force in the plate of length *dx* is expressed by bond per unit length. In the case of S-4R-0S-4ST, their strain distribution in the bottom plate in shear span rarely reached the yield point, 0.002. The calculated average bond stress equal to 0.57 based on the measurement at yielding is similar to 0.55 by the design equation [3].

4 SHEAR STRENGTH MODEL

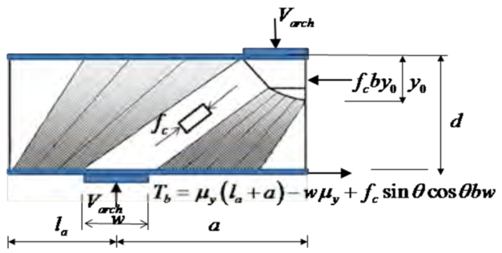
4.1 Bond effect on Shear

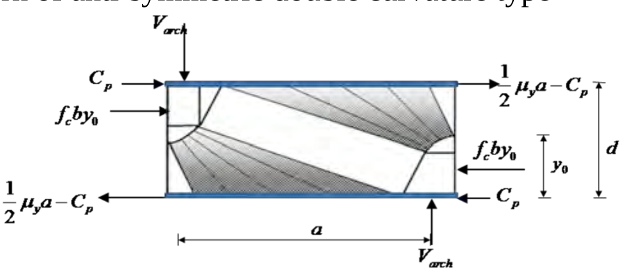
Consider a simply supported SC wall specimen resulting double curvature type shear as shown Figure 7. The top and bottom steel plates of SC wall is assumed to play a role of top and bottom chords as those of flexural reinforcing bars in reinforced concrete beams. Considering equilibrium conditions at interface between plate and concrete the magnitude of shear force transfer relying on bond forces by shear studs are determined by the magnitude of vertical component of tension including the pull-out strength of studs, tensile strength of concrete, and vertical shear reinforcement.

According to current shear strength models out-of shear strength of SC walls includes arch action V_{arch}, bond strength V_{bond}, concrete tensile cracking strength V_c, and shear resistance V_s, by stirrups. They suggest that, as a main factor to arch action, shear span ratio (a/d) contributes to the magnitude of arch action; bond stress on the interface between steel panels and concrete as an average resistance generated by mechanical friction with shear studs; and diagonal concrete strength relying of tensile strength of concrete V_c independent of other shear transferring components. An existing shear strength relying on arch action [4] has been explained in terms of *a/d* ratio and the crushing strength of strut with the dimension of nodal zone determined by magnitude of tie forces. The shear strength of arch action combined with truss action is increased by addition of tensile strength of concrete and stirrup strengths. A concentrated shear force is assumed to transfer by a single strut with distributed shear by bond. The tension forces in the steel plates are developed by bond on the interface between concrete and steel plates. Studs welded on the surface of steel plate provide the mechanical bond stress, τ_{bond} along the interface withholding the separation of between the materials.



a) Loading pattern of anti-symmetric double curvature type





b) Arch action with simple support c) Arch action for anti-symmetric double curvature type

Figure 7. Arch action with bond stress in SC wall

4.2 Shear strength by arch action

Consider shear transfer for single curvature type with simple supports as shown in Figure 7 b) and another one for double curvature types for arch action as shown in Figure 7 c). The width of strut is determined by the dimension of nodal zones beneath the loading point and on the support. First consider the single curvature type arch action as in a simply supported deep beam. When the stress in the steel plate is determined by bond stresses, the equilibrium condition in the horizontal direction for arch action and fan action requires

$$f_c by = T_b \tag{1}$$

We may assume that the bond distribution along the fan is a uniform or linearly distributed from the maximum bond strength to zero at the support and the tensile force in the steel plate has different values. Moment equilibrium condition with the equation (1) results in the following equation in terms of unknown y_0 for the uniform bond stress distribution.

$$\left(1-\frac{f_c b}{\mu_y}\frac{a}{d}\sin^2\theta\right)y_0^2 - 2d\,y_0 + 2\left(l_a + a\right)a\sin^2\theta = 0 \tag{2}$$

For a linear distribution of bond along the fan we have the following equation

$$\left(\frac{3}{8}-\frac{f_c b}{\mu_y}\frac{a}{d}\sin^2\theta\right)y_0^2 - \frac{3}{4}d\,y_0 + 2\left(l_a + a\right)a\sin^2\theta = 0 \tag{3}$$

where $\sin^2\theta = \frac{d}{\sqrt{a^2+d^2}}$ and l_a is the additional length of plate beyond the simple support.

Solving y_0 from equation (2) or (3) and substitution into equation (4) yields the shear strength

$$V_{arch} = \frac{f_c by}{a}(d - y_0/2) \tag{4}$$

The tensile strength of concrete is considered, the shear strength becomes

$$V_{arch+tension} = \frac{f_c by}{a}(d - y_0/2) + \frac{\sqrt{f_c}}{6}bd\frac{a}{d} \tag{5}$$

Now we consider the double curvature shear transfer as shown in Figure 8(c).

$$V_{arch+bond} = \frac{f_c bd}{4}\frac{d}{a} + \mu_y d + C_p\frac{d}{a} \tag{6}$$

When the compression forces in steels are neglected, the shear strength consists of arch action, bond strength contribution, and tensile strength of concrete.

$$V_n = \frac{f_c bd}{4}\frac{d}{a} + u_y d + \frac{\sqrt{f_c}}{6}bd\frac{a}{d} \tag{7}$$

4.3 Shear strength by truss action

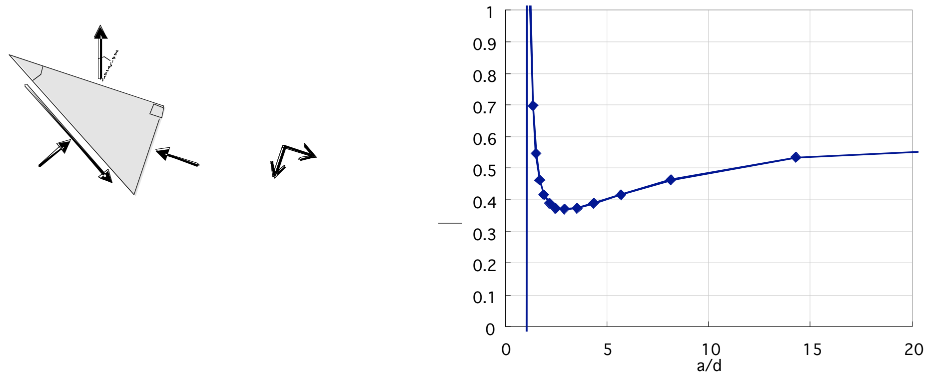
In case of long *a/d* ratios, the shear strength is determined by diagonal compression field.

$$V_{truss} = \frac{\sqrt{f_c}}{6}bd\cot\theta + p_w d\cot\theta \tag{8}$$

where $\cot\theta = \frac{\mu_y s}{A_{sv} f_y}$

4.4 Effective compressive strength of concrete and Discussion

In this study an effectiveness factor is derived based on stress field developed by truss action. Due to bond and concrete in tension, the inclination angle of compression field is determined by pure shear condition developed by bond stress, which usually gives 45°. The single strut for arch action is in cracked state and provides a path for direct shear transfer. For given angle of truss action (β) maintaining constant value, strut angle (α) varies as aspect ratio changes according to the variation of shear span ratio. To investigate effective concrete strength, if we assume that trajectories by bond stress is initial cracks and set the conditions preventing reduction in compressive strength by sliding, the stress field of an infinitesimal element in strut under the effects of truss action and strut action is like as Figure 8 a), here the parameter c', μ' are the cohesion and the coefficient of friction, respectively. This approach accounts for the tendency of increase in effectiveness factor in concrete corresponding to shear span ratio (a/d), as shown in Figure 8 b).



a) Stress field in strut b) Effectiveness factor vs. a/d ratio

Figure 8. Evaluation of effectiveness factor in concrete

The results of shear strength formula show an approximately good agreement with test program's results, excluding specimens #3, #9 in relatively short shear span ratio, as shown Figure 9. However, considering the several inherent environmental conditions of test, the formulas seem to suggest good shear strength criteria of SC wall.

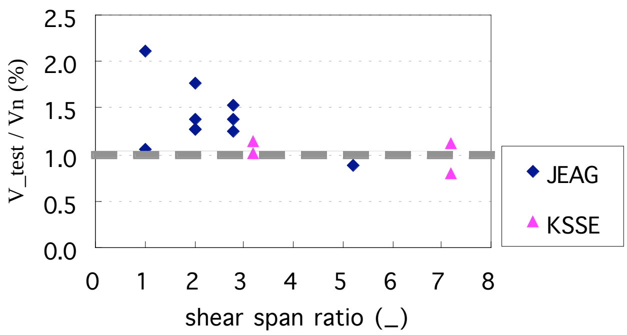


Figure 9. Comparison of theoretical model and test results

5 CONCLUSION

The following conclusions can be drawn based the proposed shear strength models with observation of experimental programs for SC walls subjected to out-of shear.

a) With consideration of bond and its effect on strut strength for arch action the proposed shear strength model is able to predict shear strength of SC walls. The strength models consider effects of bond strength on the interface between concrete and plates to determine the width of strut and effectiveness factor for strut in biaxial stress state.

b) Shear span ratio simply represents the slope of diagonal strut for arch action irrespective of single or double curvature. Increase in flexural capacity by ribs needs increase of shear strength for ductile failure.

c) Experimental data, strain distribution in plates, indicate that average bond stress, μ_{avg}, in the proposed model have been shown to accurately be close to the measured bond stress well. Strain distribution in shear bar and rib also reflects basic assumptions in shear strength model well.

d) More shear failure modes in test are intended in the next experimental program to validate the proposed design strength.

Acknowledgements
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Symbols

A_s : Area of steel plate
A_{sv} : Area of shear reinforcement
a : Shear span
a/d : Shear span ratio
b : Width of SC wall
d : Depth of SC wall
$f_c = v_2 f_c^{'}$: Effective concrete compressive strength
f_{yl} : Yield stress of steel plate
f_y : Yield stress of reinforcing bar
p_w : Shear reinforcement ratio ($= A_v / (sb)$, s : stirrup space)
t : Thickness of steel plate
T_b : Tensile force by bond stress along steel plate
V_{arch} : Strength contributed by arch action
V_{truss} : Shear strength by truss action
V_c : Strength contributed by concrete
V_s : Strength contributed by shear bar
y_0 : Depth of node by single strut in y-dir
w : Width of support
λ : Shear span ratio
μ_{avg} : Average bond stress induced by stud
v_2 : Coefficient of effective concrete strength
τ_{bond} : Bond stress on the interface between concrete and plate

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