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PARTIAL COMPOSITE ACTION IN SC COMPOSITE WALLS FO NUCLEAR STRUCTURES

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ABSTRACT

Steel-concrete composite (SC) walls are being used for the third generation nuclear power plants and being considered for small modular reactors (SMR). The steel faceplate thickness t_p, the yield stress F_y, the shear connector spacing s, stiffness k_s, and strength Q_n determine: (a) the development length of steel faceplates, (b) the level of composite action between the steel plates and the concrete infill, and (c) the local buckling of the steel faceplates. Thus, shear connectors have a significant influence on behavior of composite SC walls, and should be designed accordingly. This paper will present effects of shear connector design on the level of composite action and development length of steel faceplates in SC walls.

INTRODUCTION

Steel-plate composite (SC) walls typically consist of thick concrete walls with two exterior steel faceplates. The concrete core is sandwiched between the two exterior steel faceplates, and the steel faceplates are attached to the concrete core using shear connectors, for example, ASTM A108 steel headed shear studs. These steel-headed shear studs are the most commonly used shear connectors in SC walls and the focus of this paper. They are stud welded to the steel and embedded into the concrete core. The embedment length is typically equal to or greater than eight times the stud diameter because the concrete core is quite thick. Other shear connectors, for example, embedded steel shapes or tie rods etc. are not the focus of this paper because there can be significant variation in their performance depending on their attachment (welding or bolting) to the steel faceplates and embedment into the concrete infill and experimental data on their behavior is lacking.

Composite action is achieved between the steel faceplates and the concrete core by these steel headed shear studs. The shear studs and concrete core enhance the stability of steel plates, while the steel plates serve as permanent formwork for concrete casting. SC structures have gained popularity during recent decades, especially in the third generation of nuclear power facilities due to their structural efficiency, economy, safety, and construction speed.

PARTIAL COMPOSITE ACTION

The stiffness and spacing of the steel headed shear studs will cause partial composite action to occur between the steel faceplates and concrete infill of SC walls. The level of partial composite action will be influenced by the steel headed shear stud size (d), spacing (s), and plate slenderness (s/t_p) ratio among other parameters. The level of partial composite action could have an influence on structural behavior, such as section flexural stiffness (EI) of the SC wall section. This paper uses the finite element method to evaluate and investigate the level of partial composite action, the parameters influencing it (e.g., s/t_p ratio and steel faceplate reinforcement ratio).

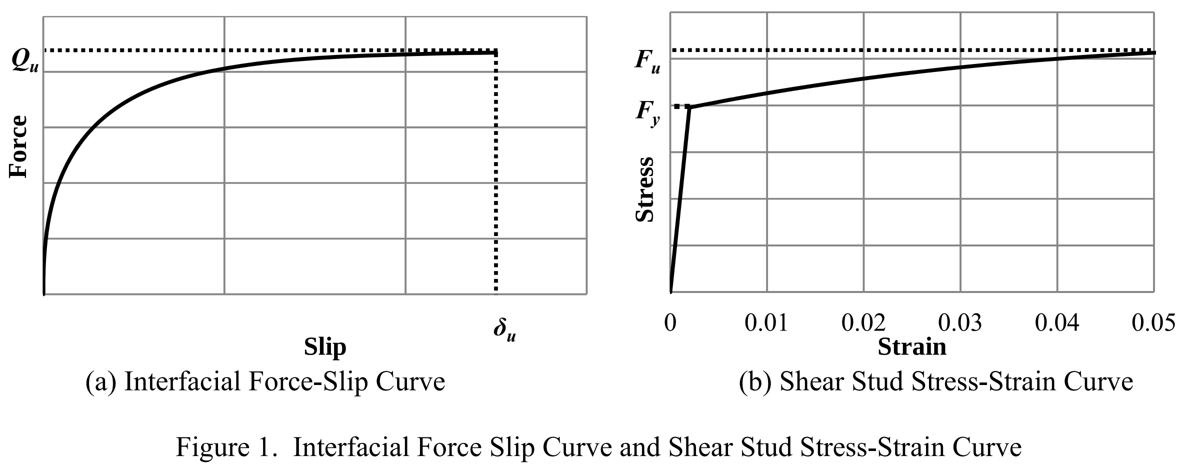
Previous Analytical Approach

Gallocher et al. (2011) has previously developed an analytical approach to investigate the relationship between the degree of partial composite action in the SC section and the interfacial shear stiffness at the steel-concrete interface. This approach had several assumptions and limitations. For example, the steel and concrete materials were assumed to be linear elastic with no cracking, and the interfacial shear connectors were modelled using elastic shear springs with smeared uniform stiffness (k_s). Gallocher et al. (2011) evaluated the system for different loading scenarios at the ends, i.e., (i) steel only loaded, and (ii) concrete only loaded. They defined composite action as the ratio of the longitudinal strains (ε_s and ε_c). 100% composite action implies strain compatibility between the steel faceplates and concrete infill, and lower percentages indicate relative slip between the steel and concrete. This is a slip or strain based definition of partial composite action instead of the conventional strength based definition of composite action typically used for steel-concrete composite beams in the AISC. The analytical results indicated that the degree of composite action was directly related to the interface stiffness (k_s) and the steel faceplate reinforcement ratio ($2t_p/T$). Composite action develops slowly with distance from the loaded end, and it is not possible to develop full composite action (defined as strain compatibility) unless the interface shear stiffness was very high. Inspite of the limitations, the analytical approach provided significant insights into composite action, and inspired additional research using the numerical approach presented here.

Finite Element Model (FEM)-Based Approach

3D finite element models were developed to model and investigate the development of partial composite action in SC wall sections. These models were benchmarked by using them to predict the interfacial shear force-relative slip behavior of pushout specimens tested and reported in the literature, for example, the test results reported by Anderson and Meinheit (2000) and Shim et al. (2004).

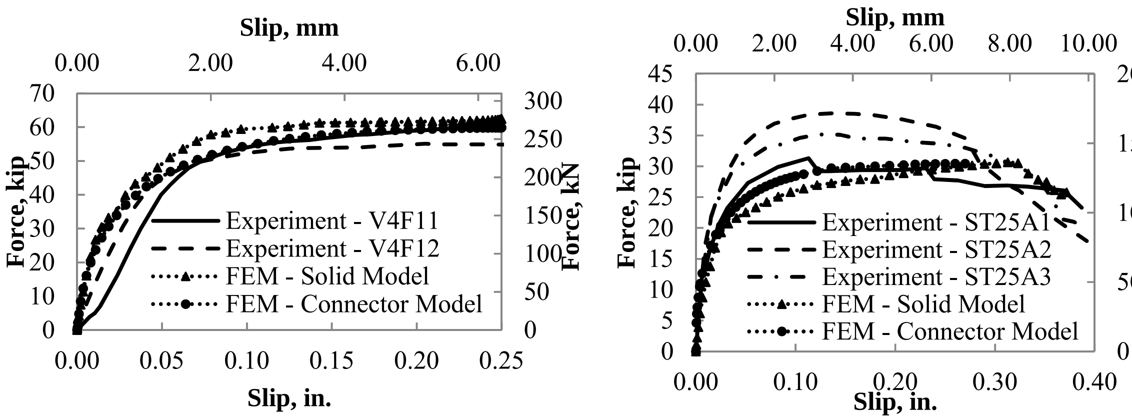
Two different types of finite element models were considered: (i) Using solid eight-node elements (C3D8R) for all the components including the steel faceplates, concrete infill, and the shear studs. General contact interaction was used between the shear studs and the concrete with hard frictionless contact behavior. (ii) Using four-node shell (S4R) elements for the steel faceplates, eight-node elements (C3D8R) for the concrete infill, and connector elements (CONN3D2) for the shear studs. Figure 1 (a) shows the interfacial shear force-relative slip behavior model developed by Ollgaard et al. (1971), and used for the connector elements. For both models, the concrete damaged plasticity (CDP) model in ABAQUS (SIMULIA, 2011) was used to model the concrete behavior, and the elastic-plastic model with Von Mises yielding was used for the steel faceplates. The steel studs of the solid model were modeled using elastic-plastic behavior with Von Mises yielding and the stress-strain behavior shown in Figure 1 (b).



(a) Interfacial Force-Slip Curve (b) Shear Stud Stress-Strain Curve

Figure 1. Interfacial Force Slip Curve and Shear Stud Stress-Strain Curve

Figures 2 (a) and (b) show comparisons of the pushout force-relative slip behavior predicted using both models with the experimental results reported by Anderson and Meinheit (2000) and Shim et al. (2004). As shown, both models predict the measured experimental behavior reasonably, and compare favorably with each other. The solid model was more realistic but computationally expensive. Alternatively, the model with connector elements for the shear studs simplifies the mesh, reduces the computation time, and directly implements the interfacial shear force-relative slip model developed by Ollgaard et al. (1971). Therefore, the simpler modeling approach with connector elements was selected for the additional work.



(a) Anderson and Meinheit (2000) (b) Shim et al. (2004)

Figure 2. Finite Element Analysis of Push-out Experiments

EFFECTS OF PLATE SLENDERNESS RATIO AND REINFORCEMENT RATIO

Several 3D finite element models were developed to conduct analytical parametric studies, and investigate the effects of various geometric and material parameters on the level of composite action in SC walls. These models were developed using the simpler modeling approach presented earlier, i.e., using connector elements for the shear studs, shell elements for the steel faceplates, and solid elements for the concrete infill. The model lengths were equal to eight times of the SC wall thickness (T), and subjected to axial compressive loading over the concrete infill only at the ends. The applied axial loads were transferred gradually to the steel faceplate by the shear studs. The amount of force transfer increased gradually with the distance from the ends (with only concrete loaded). The percentage (%) composite action was calculated as the ratio of the longitudinal strain in the steel faceplates (ε_s) to the strain in the concrete infill (ε_c). This ratio is equal to zero at the ends because the steel faceplates were not loaded at the ends, and it increases gradually as composite action develops in the SC wall. The distance over which maximum composite action develops between the steel faceplates and concrete is of significant interest, and it is expressed in terms of the section thicknesses (T) measured from the end.

For example, Figure 3 shows how the level of composite action develops as a function of the distance from the member end expressed in terms of the SC wall thickness (T). For a steel faceplate reinforcement ratio of 2%, the level of composite action depends on the stud spacing (expressed as the plate slenderness ratio). For s/t_p ratio of 20, the level of composite action at a distance of two times the section thickness from wall end is equal to only 60%. The corresponding % composite actions for SC walls with s/tp ratios of 16 and 10 were equal to 70% and 85%, respectively. Thus, as expected the level of composite action increases with a decrease in the stud spacing and the s/t_p ratio. However, full composite action does not develop for any of the s/t_p ratios in Figure 3. Additionally, when the number of studs is quadrupled (going from s/t_p of 20 to s/t_p of 10), the partial composite action increased from 60% to only 70%, which is neither economical nor structural efficient.

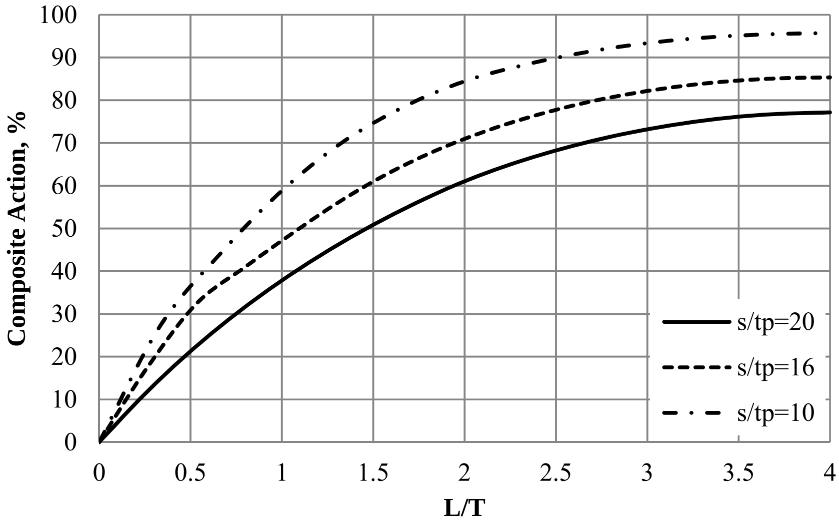


Figure 3. Effect of Plate Slenderness Ratio (Reinforcement Ratio = 2%)

Figure 4 shows the development of partial composite action with distance from the member end for SC walls with s/t_p ratio of 20, and increasing steel faceplate reinforcement ratios of 1.5%, 2.0%, 3.3%, and 4.2%. For the reinforcement ratio of 1.5%, the level of composite action at a distance of two times the section thickness from the wall end is equal to 90%. The corresponding % composite actions for SC walls with reinforcement ratios of 2.5%, 3.3, and 4.2% were equal to 75%, 60%, and 52%, respectively. As shown in Figure 4, SC wall sections with lower reinforcement ratios develop composite action more rapidly. SC wall sections with very high reinforcement ratios can have very low levels of % composite section.

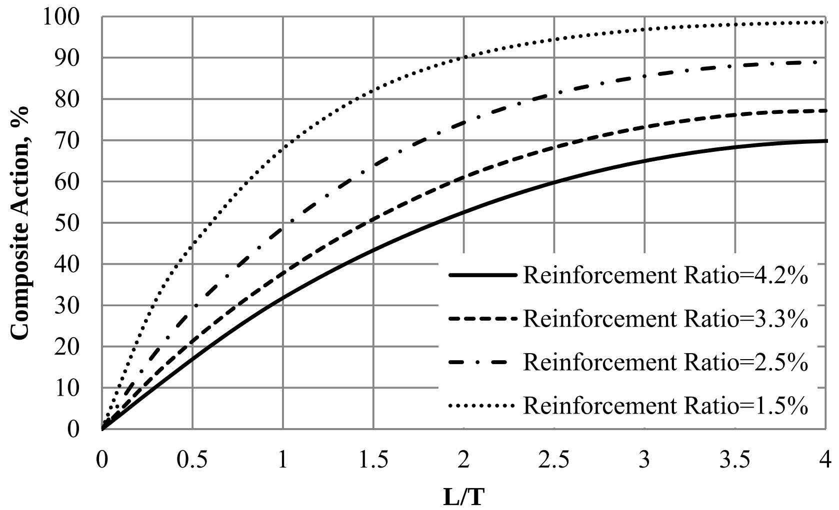


Figure 4. Effect of Reinforcement Ratio (s/t_p ratio = 20)

STUD SPACING DESIGN

Development Length

In SC composite walls, the development length can be defined as the length (L_d) over which the steel faceplate can develop its yield strength in axial tension. This is comparable to the concept of rebar development length in reinforced concrete (RC) structures. The development length reflects the degree of composite action that can be gained in an SC wall. A shorter development length requires closer stud spacing; thus, more interfacial shear can be transferred in order to obtain better composite action. A schematic representation of development length is shown in Figure 5.

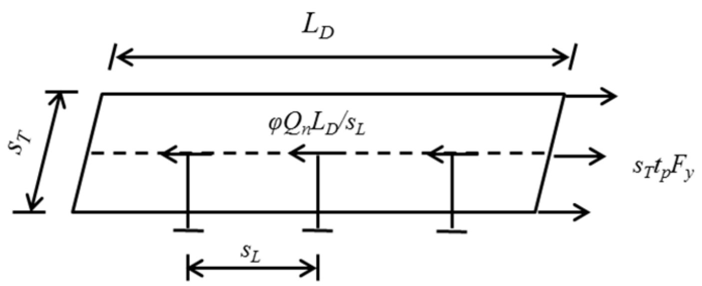


Figure 5. Schematic Representation of Development Length

The development length concept is derived based on the assumption that the shear studs are ductile, and the shear force being transferred along the interface is shared evenly by all studs. As shown in Figure 8, the summation of the shear stud capacities over the development length should be greater than the faceplate yield strength over the tributary area defined by the line connecting shear studs. If the transverse spacing of shear studs is equal to the longitudinal spacing, which is typical in SC composite wall design, the equation used to define the development length can be derived as shown in Equation (1). The capacity of a single shear stud Q_n can be calculated by the equation provided in the AISC Specifications (AISC, 2010). The reduction factor φ is suggested by Pallares and Hajjar (2010) and is taken as 0.65 for studs used in SC walls.

$$\phi \cdot Q_n \cdot \frac{L_D}{s} \geq s \cdot t_p \cdot F_y \tag{1}$$

Similar to the rebar of reinforced concrete (RC) walls, the development length of SC walls should be designed to be approximately two-to-three times the wall thickness. By rearranging the equation, the stud spacing requirements based on development length is derived in Equation (2), where L_d is the development length.

$$s \leq \sqrt{\frac{\phi \cdot Q_n \cdot L_d}{t_p \cdot F_y}} \tag{2}$$

Design Criteria

Steel headed shear stud spacing is not only crucial to define the faceplate slenderness ratio, but it is also a key factor for the SC wall to develop composite action between the steel and concrete and adequate development length. Therefore, shear stud spacing must be designed to achieve good composite action while maintaining a non-compact categorization of the faceplate. Varma et al. (2012) proposed the following equation as non-compactness limit for steel faceplates. Equations (2) and (3) should both be considered to identify the governing condition in the design process.

$$\frac{s}{t_p} \leq 1.0\sqrt{\frac{E}{F_y}} \tag{3}$$

Stud spacing is dependent upon whether the design is targeting a development length (L_d as a function of thickness T) or only to preclude local buckling before yielding. In some scenarios, stud spacing based on local buckling criterion alone can ensure very good composite action. However, the governing condition may change from local buckling to the required or selected development length. For example, for SC walls with a 0.5 inch (12.7 mm) thick steel faceplate with F_y=50 ksi (345 MPa), the stud spacing (s/t_p) required for different steel faceplate reinforcement ratios (1% - 5%), different development lengths (L_d = T to 4T), and to prevent local buckling before yielding (using Equation 3) are summarized in Tables 1 – 3. These Tables are for ASTM A108 stud diameters equal to 1.0, 1.5., and 2.0 times the steel faceplate thickness (t_p). If the governing stud spacing (s/t_p) is for the development length requirement, then it is shaded with grey. If not shaded, then the local buckling (non-compactness) requirement governs the required s/t_p ratio. As shown in Table 1, if the stud diameter is equal to the steel plate thickness, then the development length requirement governs the design for all reinforcement ratios and target development lengths. As shown in Table 2, if the stud diameter is equal to 1.5 times the plate thickness, then the local buckling criterion governs for low reinforcement ratios (1-2%) and large development lengths (L_d = 2T or more). As shown in Table 3, if the stud diameter is equal to 2.0 times the plate thickness, then the local buckling criterion governs for most cases with larger development length (L_d = 2T or more).

Table 1. Plate slenderness ratio design when $d/t_p = 1$

$d/t_p = 1$					
ρ, $(2t_p/T)$	s/t_p				
	L_d=T	L_d=2T	L_d=3T	L_d=4T	LB
1.0%	12	17	21	24	24
1.5%	10	14	17	20	24
2.0%	8	12	15	17	24
2.5%	8	11	13	15	24
3.0%	7	10	12	14	24
4.0%	6	8	10	12	24
5.0%	5	8	9	11	24

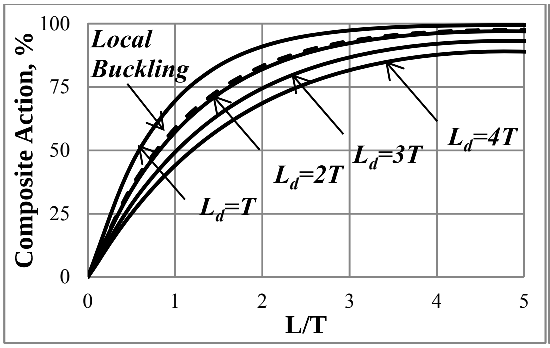
Table 2. Plate slenderness ratio design when $d/t_p = 1.5$

$d/t_p = 1.5$					
ρ, $(2t_p/T)$	s/t_p				
	L_d=T	L_d=2T	L_d=3T	L_d=4T	LB
1.0%	18	25	31	36	24
1.5%	15	21	25	29	24
2.0%	13	18	22	25	24
2.5%	11	16	20	23	24
3.0%	10	15	18	21	24
4.0%	9	13	16	18	24
5.0%	8	11	14	16	24

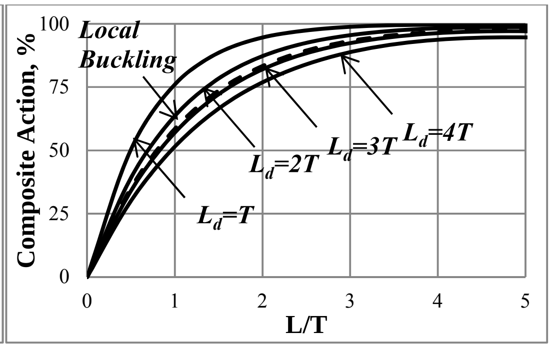
Table 3. Plate slenderness ratio design when d/t_p = 2

d/t_p = 2					
ρ, ($2t_p/T$)	s/t_p				
	L_d=T	L_d=2T	L_d=3T	L_d=4T	LB
1.0%	24	34	41	48	24
1.5%	20	28	34	39	24
2.0%	17	24	29	34	24
2.5%	15	21	26	30	24
3.0%	14	20	24	28	24
4.0%	12	17	21	24	24
5.0%	11	15	19	21	24

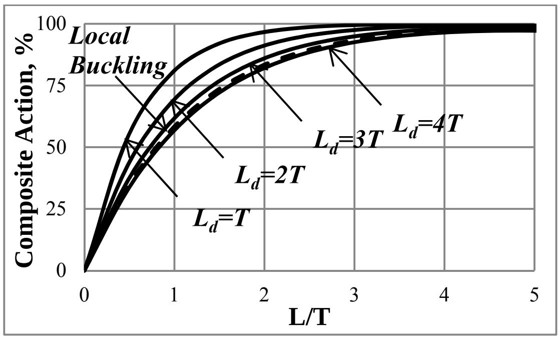
The results from Table 2 (d/t_p = 1.5) are shown in more detail in Figures 6 (a) – (e), which show the development of partial composite action (in %) along the length of the wall for the stud designs with different target development lengths (L_d = T, 2T, 3T, and 4T) and for the design with local buckling (non-compactness) requirement governing. The higher curve always governs. So, if the local buckling governed curve is higher, then it governs over the curves with target development length (L_d) below it. As shown in Figure 6 (a), for reinforcement ratio of 1%, the local buckling (non-compactness) requirement governs over all cases with target L_d greater than 2T. The level of composite action at a distance of 2T from the member ends is equal to 90% and 80% respectively. As shown in Figures 6 (b) – 6 (f), the local buckling (non-compactness) requirement governs for some cases with reinforcement ratios less than 2.5%. The development length requirement governs for most cases with reinforcement ratios greater than 2.5%. For all stud spacing designs with target development length L_d less than or equal to 3T, the percent composite action at a distance of 2T from the member end is between 75-90%, which is very good.



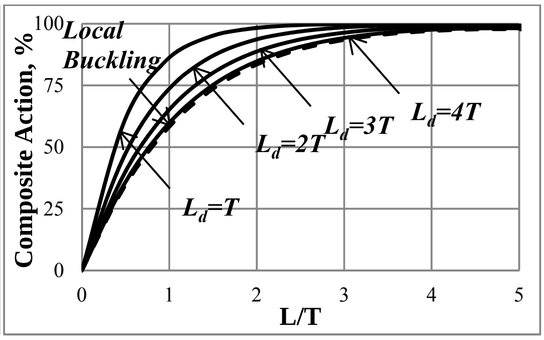
(a) $2t_p/T$=1%



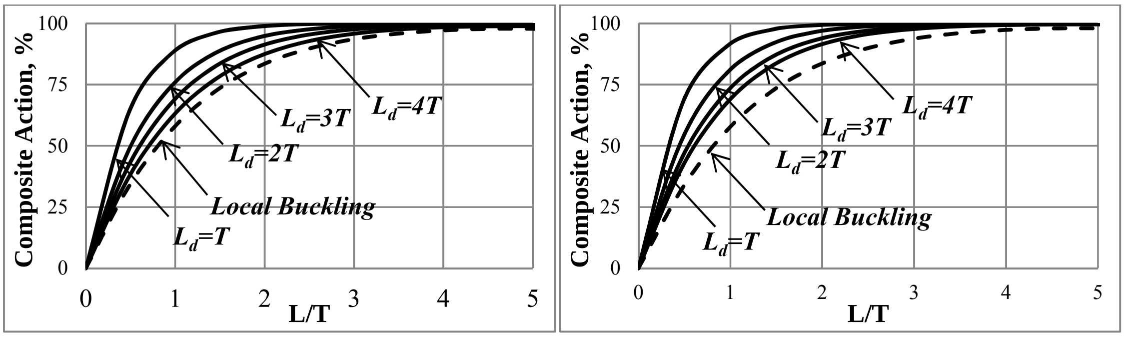
(b) $2t_p/T$=1.5%



(c) $2t_p/T$=2.0%



(d) $2t_p/T$=2.5%



(e) $2t_p/T$=3% (f) $2t_p/T$=4%

Figure 6. Partial Composite Action vs. Distance from Member End for Different Stud Spacing Design (d/t_p=1.5)

CONCLUSIONS

Steel headed shear studs are used to prevent local buckling and provide composite action in SC walls. The stud spacing should be properly designed to avoid local buckling and to ensure good composite action in SC walls. Equations (2) and (3) have provided the criteria considering both conditions, and a 75% to 90% composite action can be expected if the stud spacing is designed accordingly to achieve target development lengths of three times the wall thickness (T) or less. .

Partial composite action exists in SC walls. The degree of composite action is affected by the reinforcement ratio and the plate slenderness ratio (s/t_p). High (75-90%) composite action can be developed in SC wall sections with lower reinforcement ratio and with smaller stud spacing (lower s/t_p ratios). Finally, using more shear studs to increase composite action can be structurally or economically inefficient.

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