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Improvement of shear stud spacing in steel-concrete-steel sandwich composite structures

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ABSTRACT

The application of modularized steel-concrete-steel sandwich composite structure (SCP) to the storage tanks installed at the polar or coastal regions is being considered because of their short construction time. However, design of SCP must be based on the application of existing design guidelines which require very close arrangement of shear studs. Densely arranged studs cause difficulty in pouring concrete during the manufacturing process and increase of production cost. This paper proposes an improved ratio of the stud spacing to the thickness of steel plate on the basis of numerous parametric studies to evaluate the relative influence of the stud spacing on the stability of the SCP.

1. INTRODUCTION

Steel-Concrete Plate composite (SCP) is a modularized construction member that saves construction time and cost. Since a modularized structure made of SCP does not require formworks or curing of concrete at the construction site, it can be constructed regardless of climate or locational conditions. Therefore, applying SCP to tank structures such as the containment structures of nuclear power plants and LNG storage tanks installed in harsh environments has been widely considered. SCP consists of a concrete block with two steel plates attached at both sides of the concrete matrix and connected by studs, and the studs are welded to a steel plate and embedded into the concrete. Accordingly, it is important for the studs to resist shear stress and to prevent separation between concrete and the steel plate. In particular, SCP develops structural instability due to the yielding or local buckling of steel plates when it is subjected to large external loads, and thus the determination of stud spacing and thickness of steel plate has been the main issue in the design of SCP.

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The behavior of SCP has been extensively investigated though experiments and numerical analyses by many researchers. Oduyemi and Wright (1989) suggested that the stable ratio of stud spacing to plate thickness is about 30, extensive research related to the stud spacing has also been performed. Zhang et al. (2014) investigated the effect of studs on the level of composite action and development length of the steel plate in SCP and determined the maximum spacing to plate thickness ratio to prevent local buckling before yielding.

Generally, design codes and guidances such as the Euro code, AISC design code, AASHTO LRFD design code and DNV INCA guidance have introduced regulations for the stud spacing to enhance the composite action between steel and concrete and to prevent local buckling in the steel plate. However, these regulations are very simple and conservative and hence there is some limitation in achieving more reasonable and efficient design. An improved design guideline to determine the stud spacing accordingly should be introduced. On the basis of numerous parametric studies to evaluate the relative influence of stud spacing on the stability of SCP, an improved ratio of the stud spacing to the thickness of the steel plate to be used in the design of a containment vessel subjected to compressive loading is proposed.

2. STABILITY OF SCP STRUCTURES

All design codes and design guidances describe the provision for the stud spacing. Table 1 shows the design criteria in the representative design codes that can be applied to the design of SCP. When the given criteria are satisfied, the steel plate will not develop local buckling before reaching the yielding state. Since the DNV INCA guidance is not only a design guidance specific to SCP structures but also gives the most conservative results, the final stud spacing is been usually determined from this guidance.

Table 1. Design codes and guidances for stud spacing

Design criteria	Euro † code	AISC	AASHTO LRFD	DNV INCA Guidance
stud spacing (s)	$\geq 5\mathrm{d}$ $\leq 800\mathrm{mm}$ $\leq 6t_{slab}$	$\geq 6\mathrm{d}$ $\leq 8t_{slab}$ $\leq 900\mathrm{mm}$	$\geq 6\mathrm{d}$ $\leq 600\mathrm{mm}$	$\leq 0.75 \times (t_c + 2 \times t_s)$ (1) $\leq 22 \times t_s \times \sqrt{235/f_{yk-p}}$ (2)
maximum stud spacing (s*)	800mm	900mm	600mm	150mm (1) 94.35mm (2)

h= overall stud height (mm), t_{slab} = slab thickness by $t_c + 2t_s$ (mm), d= diameter of stud (mm), t_c= concrete thickness (mm), t_s= steel thickness (mm), f_{yk-p}= characteristic yield stress of steel plate (MPa), s*= stud spacing calculated when $t_c = 188\mathrm{mm}$, $t_s = 6\mathrm{mm}$, $d = 13\mathrm{mm}$ and $f_{yk-p} = 460MPa$, † In the Eurocode, if the slab is in contact over the full length with a steel compression flange, the Eq.(2) of the DNV INCA Guidance should be additionally considered.

As shown in Table 1, INCA Guidance proposes two criteria, wherein Eqs. (1) and (2) are related to the shear cracking of an interior concrete block and the local buckling of steel plate, respectively, and generally Eq.(2) governs the stud spacing in the case of SCP used for storage tank structures. When a SCP storage tank is being constructed, concrete is poured within two steel skin plates, but the dense placement of steel studs makes the pouring of concrete difficult. Increasing the stud spacing is thus strongly required to facilitate pouring of concrete and to achieve design improvement as well.

Upon this background, a review of Eq. (2) was first carried out. As shown in Eq. (2), the stud spacing s can be expressed by the relation $s = \alpha \cdot t_s\sqrt{235/f_{yk-p}}$. Elastic buckling analysis of a simply supported square plate uniformly compressed in one direction produces the critical load of $\sigma_{cr} = 4\pi E_s/(12(1-\nu^2)(s/t_s)^2)$, and the prevention of buckling at the plate makes it possible to replace σ_{cr} with the yield strength f_y. Accordingly, $^s/_{t_s} = \sqrt{4\pi E_s/12(1-\nu^2)f_y} = 56.8\sqrt{235/f_y}$ (if the elastic modulus of steel $E_s = 210\,\mathrm{GPa}$ and Poisson's ratio $\nu = 0.30$ are assumed.), which means that the proportional constant α will be 56.8.

When a simply supported square plate with a span length of s is subjected to the action of uniformly distributed compressive forces in two perpendicular directions, the elastic stability analysis of the plate gives a decrease of the proportional constant down to $\alpha = 40.0$, and an additional change of the boundary condition from the simply supported to the pin-supported condition reduces the proportional constant to $\alpha = 24.0$. This means that Eq. (2) is conservative in determining the stud spacing because the determined spacing is smaller than that obtained from the pin-supported boundary condition which ignores the restraint for the deformation by the adjacent plates.

3. APPLICATIONS

Experiments for SCP members have also been carried out by many researchers (Akiyama et al. (1991), Usami et al. (1995) and Choi and Han (2009)]. More than forty SCP members with the stud spacing to plate thickness ratio (s/t_s) ranging from 20 to 50 were tested and Zhang et al. (2014) suggested using the Euler's column buckling curve with an effective length coefficient k equal to 0.7 to represent the critical stress of SCP panels, $\sigma_{cr} = \pi^2 E_s/(12k^2(s/t_s)^2) = 1.6785E_s/(s/t_s)^2$. In advance, the critical buckling stress gives a limiting ratio of $s/t_s = 1.3\sqrt{E_s/f_y}$ when $\sigma_{cr} = f_y$ and produces the proportional constant of $\alpha = 38.86$ in the expression for the stud spacing of $\mathrm{s} = \alpha \cdot t_s\sqrt{235/f_y}$ (see Fig. 1). This means that the channels installed in the specimens to keep concrete within both skin plates while pouring concrete develops a restraint effect equivalent to the simply supported boundary condition.

However, the accuracy of the critical stress may depend on the exactness of the test setup. Because of the initial imperfection of the specimen, the bond-slip along the steel-concrete interface and the instability of the boundary condition, the experimentally determined buckling stress has been decreased and a few researchers (Zhang et al.

(2014), Cho et al. (2014)) proposed the critical s/t_s ratio as $s/t_s = 1.0\sqrt{E_s/f_y}$, which corresponds to k= 0.91 and $\alpha = 29.89$.

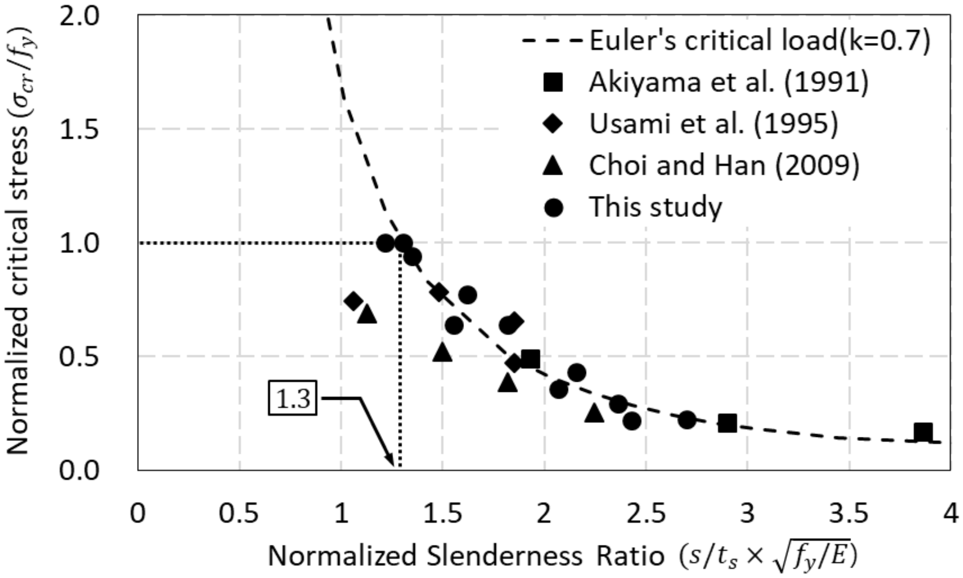

Fig. 1 Comparison of numerical results with experimental data

Upon this background, elastic stability analyses were performed to investigate the influence of the channel, which is placed along the end face of the skin plates on the stud spacing. Three different boundary conditions that describe the connection situations between the adjacent SCP members were considered. First, the simply supported boundary condition means restraint for the displacement in the lateral direction along the end faces of the SCP member, and uncovering and covering conditions of the stud represent additional placement of a channel with a flange shorter and longer than the distance to the first steel stud arrangement along the end faces of the SCP member, respectively.

4. CONCLUSION

One of the key issues in the design and construction of SCP members is to determine a reasonable shear stud spacing, because the shear stud provides composite action between exterior steel faceplates and the interior concrete matrix and prevents local buckling of the steel plate before yielding as well. Since current design codes produce very conservative results in the stud spacing, this paper introduces an improved guideline for the stud spacing through parametric studies for SCP subjected to the uniaxial and/or biaxial compressive forces.

The obtained numerical results show that the proportional constant $\alpha = s/t_s\sqrt{f_y/E_s}$ can be increased at least to $\alpha = 33.0$. from $\alpha = 22.0$ considered in the current design practice. In advance, the placement of the outmost steel studs within the channel height will increase the value of the proportional constant up to $\alpha = 61.88$, which gives 281% larger stud spacing than the current reference. This means that an increase of the stud spacing with placement of the outmost stud within the channel height should be considered for more rational design and placement of the steel shear studs.

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