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Effect of shear connectors on local buckling and composite action in steel concrete composite walls

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A B S T R A C T

Steel concrete composite (SC) walls are being used for the third generation nuclear power plants, and also being considered for small modular reactors. SC walls consist of thick concrete walls with exterior steel faceplates serving as reinforcement. These steel faceplates are anchored to the concrete infill using shear connectors, for example, headed steel studs. The steel faceplate thickness (t_p) and yield stress (F_y), and the shear connector spacing (s), stiffness (k_s), and strength (Q_n) determine: (a) the level of composite action between the steel plates and the concrete infill, (b) the development length of steel faceplates, and (c) the local buckling of the steel faceplates. Thus, the shear connectors have a significant influence on the behavior of composite SC walls, and should be designed accordingly. This paper presents the effects of shear connector design on the level of composite action and development length of steel faceplates in SC walls. The maximum steel plate slenderness, i.e., ratio of shear connector spacing-to-plate thickness (s/t_p) ratio to prevent local buckling before yielding is also developed based on the existing experimental database and additional numerical analysis.

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1. 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 plates according to AWS D1.1 (AWS, 2006) requirements and embedded into the concrete core. The embedment length is equal to or greater than eight times the stud diameter, which is possible 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 steel faceplates and embedment into concrete infill, and experimental data regarding their behavior is lacking.

Composite action is typically achieved between steel faceplates and concrete using 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.

Steel headed shear studs have been studied extensively to establish their: (a) shear force-interfacial slip behavior including interfacial shear strength, stiffness, and ductility, and (b) tension pullout behavior and strength. For example, in the US, Ollgaard et al. (1971) tested forty-eight pushout specimens with both normal weight and light weight concrete, and used the test results to develop equations for calculating the interfacial shear strength of shear studs, which was later adopted by the AISC Specification (AISC, 2010). These researchers also developed a shear force - interfacial slip model that can be used to define or model the interfacial shear-slip behavior of shear studs. Similarly, in Australia, Oehlers and Coughlan (1986) tested 116 pushout specimens in static and fatigue cyclic loading. They used the experimental results to develope equations for calculating the shear stud strength, interfacial shear stiffness and shear force-relative slip model. In Europe, Kruppa and Zhao (1995) also conducted extensive experimental investigations and characterized the shear force-interfacial slip behavior of steel headed shear studs at both ambient and elevated temperatures.

More recently, Pallares and Hajjar (2010) compiled and examined all existing test data on the interfacial shear and pullout tension behavior of steel headed shear studs. They compiled the results of 391 monotonic and cyclic pushout tests of steel headed shear studs subjected to interfacial shear force without the use of a metal deck. They performed statistical reliability analysis, and developed equations for calculating the interfacial shear strength of steel headed shear studs when steel shank failure is the governing failure mode. They also confirmed the reliability of ACI 349

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Appendix D equations for calculating the interfacial shear strength of studs when concrete breakout or pryout failure is the governing failure mode. The results and findings from Pallares and Hajjar (2010) have been used to improve the AISC Specifications (AISC, 2010) and to include a section on the design of steel studs for composite column applications.

All of these investigations have provided basic knowledge and information that can be used to design steel headed shear studs and to evaluate their influence on the level of composite action in the SC walls. In addition to developing composite action, shear studs serve another important function for composite SC walls, namely, prevention of steel faceplate local buckling before yielding in compression. SC walls in safety-related nuclear facilities typically have concrete thickness from about 24 in. to 60 in. to provide adequate radiation shielding. The steel faceplate reinforcement ratios, defined as $2t_p/T$ vary from about 1.5 to 5%, where t_p is the steel faceplate thickness and T is section thickness. The steel faceplate thicknesses can vary from about 0.25 to 1.50 in. These steel faceplates are anchored to the concrete core at the shear stud locations, but they can undergo local buckling between these shear stud locations. The steel faceplates can undergo local buckling when the SC wall section is subjected to axial compression. The plate slenderness is defined as the stud spacing s divided by the steel faceplate thickness t_p. This paper presents the development of a steel plate slenderness limit to prevent the occurrence of local buckling before yielding in compression, i.e., the slenderness criteria or requirement for non-slender steel faceplates in SC walls.

Additionally, the paper includes the development of analytical and numerical models for investigating composite action in SC walls using the shear force-interfacial slip models for shear studs developed by Ollgaard et al. (1971). These models are used to evaluate the effects of shear stud spacing and strength on: (i) level of composite action in SC walls, (ii) development length of steel faceplates, and (iii) influence of partial composite action on the overall SC wall flexural stiffness. The results from the local buckling and partial composite action evaluations are used to propose design recommendations for shear connector size and spacing in composite SC walls for safety-related nuclear facilities.

2. Local buckling and plate slenderness limit

In SC walls, the steel faceplates serve both as reinforcement and permanent concrete formwork. The steel faceplates can undergo local buckling if axial compressive stresses are large. The deformations and locked-in stresses induced in the steel faceplates by the concrete casting process (i.e. hydrostatic pressure) can make it more vulnerable to local buckling. Research on the local buckling of steel faceplates of SC walls can be traced back to the 1980s when this type of construction was first used. SC construction in safety related facilities has renewed interest and attention on this issue of plate slenderness and local buckling.

2.1. Experimental database

Researchers in Japan and Korea (Sakamoto et al., 1985; Akiyama et al., 1991; Usami et al., 1995; Kanchi et al., 1996; Miyauchi et al., 1996; Choi and Han, 2009) have experimentally investigated the compressive behavior of SC walls. SC wall specimens were tested with steel faceplates having stud spacing-to-plate thickness (s/t_p) ratios ranging from 20 to 50. The steel faceplates of SC specimens buckled in the plastic, inelastic, and elastic ranges depending on plate s/t_p ratio. The steel faceplates buckled in between the shear stud rows. The critical buckling stress could be predicted using Euler's column equation with an effective length coefficient (K) of 0.7, which corresponds to the pinned-fixed end conditions.

More than 40 test results reported in the literature were examined. Most experiments used a load-unload-reload to failure loading scheme, however the loading cycle was found to have little effect on initial stiffness and ultimate load. The most relevant experimental results from all tests have been compiled and plotted in Fig. 1. The ordinate in the plot is the normalized strain, $\varepsilon_{cr}/\varepsilon_y$, where ε_{cr} is the measured critical buckling strain of the steel plate from compressive tests and ε_y is the nominal yield strain of the steel plates. The abscissa is the stud spacing-to-plate thickness (s/t_p) ratio normalized with respect to the square root of E/F_y, where E is the Young's modulus of steel. Euler's column buckling curve with effective length coefficient (K) equal to 0.7 is also plotted in the figure. It is observed that the test data points follow the trend of Euler's curve with K = 0.7. Another important observation is that there is no data that falls in the shadowed area where the normalized slenderness ratio is less than 1.0 and ε_{cr} is less than ε_y. This implies that when the normalized plate slenderness $[s/t_p x\sqrt{F_y/E}]$ ratio is less than 1.0, yielding (ε_y) occurs before local buckling (ε_{cr}).

2.2. Finite element analysis

The finite element method was used to expand the experimental database and to further evaluate the effect of s/t_p ratio on local buckling. Nonlinear finite element analyses were conducted using ABAQUS (SIMULIA, 2011). The finite element models and analysis approach were benchmarked using the experimental results reported by Kanchi et al. (1996).

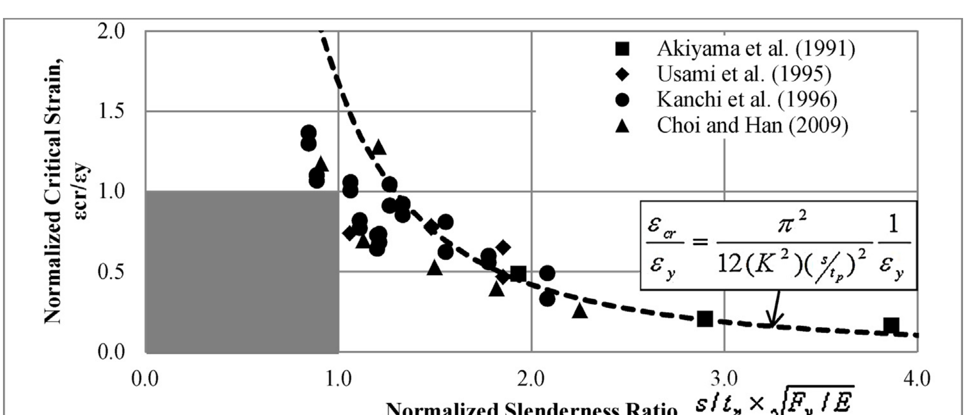

Fig. 1. Summary of local buckling experimental data.

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