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Partial interaction theory to analyze composite (steel–concrete) shear wall systems under pure out-of-plane loadings

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ABSTRACT

This paper presents a closed form solution for the analysis and design of composite steel concrete (SC) shear wall systems subjected to pure out-of-plane loads with partial interaction theory. This method takes into account the flexibility of connection between plate and concrete. SC walls under out-of-plane loads can be considered a slab under distributed loads; therefore, for obtaining the formulation of these systems, a strip beam-slab is considered. These walls are subjected to soil pressure when used in deep excavations water hydraulic pressure when used as marine structures, and ice moving pressure when used in offshore structures etc. For providing the interaction between steel and concrete, shear connectors and, for calculating the out-of-plane loadings, classic methods are utilized. The existence of concrete in composite shear walls not only prevents the steel plate from buckling, but also plays an important role in out-of-plane resistance. To investigate the effect of concrete on the behavior of these SC shear walls, two cases are considered in this study: shear walls with and without concrete. To validate the accuracy of the proposed method, a number of shear walls were modeled and analyzed by ABAQUS software and compared with the results from theoretical formulations. Results indicate that the proposed interaction theory is well capable of predicting the deformation and stress distribution of the composite shear walls.

1. Introduction

Steel plate shear wall (SPSWs) is an effective lateral resistance system against earthquake and wind loads. When lateral loads are applied to this wall, the thin infill plate buckles in shear while developing the diagonal tension field action that resists the lateral forces. Low weight, low construction costs, high construction speed, high stiffness, and high capacity to dissipate the energy are the advantages of these systems. For in-plane loading, many studies have been done in the past decades: the earliest study was done by Thorburn et al. [1] that introduced replacing the plate with the simple strip model to represent the behavior of the unstiffened SPSW system under in-plane loads. Roberts and Sabouri-Ghomi [2] applied quasi-static loads to unstiffened steel plate shear walls with an opening at the center of the plate. Driver and Grondin [3], Lubell et al. [4], Romero [5], Seilie and Hooper [6], Sabelli and Bruneau [7], and Bhowmick [8] have studied the seismic behavior of steel plate shear walls. In another study, Sabouri-Ghomi and Sajjadi [9] studied the behavior of SPSW systems with and without stiffeners.

In the past decades, composite structural wall systems are used in seismic zones as the primary lateral resistance system for building structures. Composite constructions utilize exterior steel plate, infill concrete, shear connector, and network of steel reinforcement. Optimum performance of the composite system depends on transfer of stresses between concrete and steel. This transfer is provided by shear connectors. SC composite walls combine benefits of both reinforced concrete and steel plate shear walls: reinforced concrete is inexpensive, massive, and stiff, while steel walls are strong, lightweight, and easy to assemble. The optimal combination of the properties of the two materials, steel and concrete, makes the structures safe and economical and the steel can improve the concrete behavior in tension. Saari et al. [10] studied the behavior of the shear stud in composite shear walls under seismic loads. Link and Elwi [11] presented the capacity of composite walls under the transverse and longitudinal loads due to moving ices in the offshore structures. Hajjar [12] summarized

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Nomenclature

γ	slip between the layers
Q	load on one shear connector
q	shear flow
s	space between shear connectors
n	number of shear connectors
k	stiffness of shear connectors
K	the factor to control the slope of the concrete stress–strain curve
F	force between layers
ε_{ct}	concrete strain in tension region
ε_{pc}	steel plate strain in compression region
M	bending moment; subscripts c for concrete and p for steel plate
E	modules of elasticity; subscripts c for concrete and p for steel
I	second moment of area, subscripts c for concrete and p for steel plate
A	area; subscripts c for concrete and p for steel plate
t	thickness; subscripts c for concrete and p for steel plate
h_t	total depth of beam section
W	distributed load on beam per unit length
y	vertical deflection of the beam
σ'_{cu}	ultimate strength of the concrete in compression
σ'_{tu}	ultimate strength of the concrete in tension
σ'_{el}	elastic limit of the concrete
σ_c	strength of the concrete in compression
σ_{cc}	existing stresses in the concrete in compression region
σ_{ct}	existing stresses in the concrete in tension region
σ_p	existing stresses in the steel plate
b	length of the composite wall
h	width of the composite wall (span of beam)
d_{ss}	shear connector diameter

the recent research on a composite lateral resistance system. Shanmugam et al. [13] investigated the ultimate load behavior of double skin composite (DSC) slabs. Some experimental tests were done and compared with finite element results. In the other study, Tong et al. [14] presented an experimental study of the cyclic behavior of a composite structural system; the one-bay, two-storey test specimen was built in the one-third scale. Zhao and Astaneh-Asl [15] used a concrete cover on the steel plate to increase the stiffness and enhance the buckling behavior of the plate. Vasdravellis et al. [16] investigated the behavior of steel–concrete composite beams subjected to the combined effects of negative bending and axial compression. Rafiei et al. [17] presented the development of experimental and finite element models to simulate the behavior of a novel composite shear wall system consisting of two skins of steel and an infill of concrete under in-plane loadings. Varma et al. [18] presented the finite element model for predicting the behavior and failure of composite walls subjected to a combination of in-plane forces and moments. Sener and Varma [19] found the out-of-plane shear strength of composite walls. They indicated that the steel faceplates had a minor influence on the out-of-plane resistance, but they had a major influence on the out-of-plane failure mode. Zhang et al. [20] found the effects of shear connectors on local buckling and level of composite action in steel concrete composite walls. The results based on experimental and numerical database indicated that when the normalized shear connector spacing-to-plate thickness ratio, $(s/t_p \times \sqrt{F_y/E})$ is less than 1.0, yielding in steel plate occurs before local buckling.

It has been observed that most of the past studies on SPSWs and composite shear walls focused mainly on in-plane loads. The objective of the present work is to present the out-of-plane resistance of SC composite shear wall systems. A closed form solution to analyze and design simply supported composite steel-concrete (SC) shear wall systems subjected to out-of-plane loads is presented by considering the partial interaction theory. The out-of-plane loads considered in this study are water hydraulic pressure, soil pressure, and ice pressure on offshore structures that could act on a structure as a static load. Under these loads, the walls are bent and deformation occurred in plates. For limiting this deformation, composite shear walls are used. Wright et al. [21–23] conducted experimental studies of simply supported double skin composite beams and also presented a closed form solution for analysis of these composite beams. Dogan and Roberts [24] compared experimental deformations of steel-concrete-steel sandwich beams with full and partial interaction theories. Xie et al. [25] presented experimental and numerical studies on the static behavior of the friction-welded connections with the bar loaded in shear. In the other study, Xie et al. [26] presented an experimental investigation on the static behavior of steel-concrete-steel beams.

The objective of this study is to develop theoretical formulations for analysis and design of SC composite shear walls under out-of-plane loading. This formulation obtained by the partial interaction theory considered flexibility between plate and concrete. To validate the proposed theoretical formulation, finite element models were developed and results from FE analyses were compared with the theoretical relations.

2. General theory

In this section a closed form solution for analysis and design of steel-concrete (SC) composite shear wall systems subjected to out-of-plane loads is presented. In the first step, theoretical formulations are obtained from simple bending and partial interaction theory and, then in the second step, the results are compared with those from finite element analyses. Fig. 1 presents the general form of the problem, to which out-of-plane loads are applied. This type of loads is applied from soil pressure in deep excavations in high-rise buildings, water hydraulic pressure on marine structures, ice moving pressure in offshore structures, etc. In the deep excavations, structural walls are subjected to the soil pressure; therefore, these systems must be designed for these kinds of loads. For calculating the static and dynamic pressures of the soil, Coulomb [27] and Mononobe-Okabe [28,29] methods are utilized respectively. Furthermore, ice actions on offshore structures are among the main concerns for engineering activities in cold areas with ice-infested waters and can be categorized as out-of-plane loads. Løset et al. [30–32] studied the effect of these kinds of load on the offshore structures.

In the present study, because of rigid diaphragms, the beams are not considered and simple supports are assumed for considering the critical situations; then, the walls act as a one-way slab with cylindrical deformation.

2.1. Partial interaction theory to design the composite shear walls

For this study, for modeling of the interactions in the interface of the layers of SC composite shear walls, partial interaction theory is utilized. In this method, theoretical relations are obtained by