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Steel-plate composite walls: Experimental database and design for out-of-plane shear

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ABSTRACT

The seismic behavior and design of steel-plate composite (SC) walls in safety-related nuclear facilities is typically governed by their in-plane shear strength and ductility. However, the out-of plane shear (and flexure) behavior can govern the design near foundations and connections where SC walls interact with other structures. The out-of-plane shear behavior of SC walls is similar to that of reinforced concrete (RC) walls, and has been evaluated experimentally by conducting beam tests in one-way bending. The beam tests were conducted on specimens that were representative of strips taken in the longitudinal and transverse directions of full-scale SC walls. This paper includes a summary of the experimental database of SC beam shear tests conducted in Japan, S. Korea, China and the US. Different loading configurations were used to test the SC beam specimens. The parameters considered were the shear span-to-depth ratio, steel faceplate thickness (reinforcement ratio), stud anchor spacing, and the presence (or absence) of shear reinforcement. The out-of-plane shear strengths from the tests in the experimental database are summarized and compared with shear strength calculations based on applicable design code equations to estimate the lower bound design shear strength of SC walls. Reliability analysis is conducted to suggest associated strength reduction (ϕ) factors.

1. Introduction

Steel-plate composite (SC) walls are being used in the third generation of nuclear power plants and also being considered for future small modular reactor (SMR) plants. In general, SC walls are being considered for structures that were traditionally made using reinforced concrete (RC) or prestressed concrete. The motivation for using SC walls comes from modular construction techniques, which enable considerably faster erection and construction compared to traditional reinforced concrete construction. In addition to constructability advantages, SC walls have also demonstrated excellent performance under mechanical loading as presented in [1,2]. The excellent structural performance of SC walls is driven by the steel faceplates that serve as tension reinforcement in all planar directions regardless of the loading (membrane forces or out of plane moments) [3]. Both AP1000© [4] and US-APWR© [5] use SC walls extensively in the containment internal structures (CIS) to provide adequate strength and radiation shielding for design basis events like safe shutdown earthquake, accident thermal conditions, and internally generated missile impact. This paper focuses on the design of these SC walls for out-of-plane shear forces that are resisted primarily by the concrete infill and tie bars connecting the faceplates.

In reinforced concrete design of safety related nuclear facilities, steel reinforcing bars with large diameters and close spacing are typically required to provide adequate design strength to meet the design demands. Due to clear cover and minimum spacing requirements, these steel rebars are placed in separate layers in the vertical, horizontal, diagonal and transverse directions to resist the design force and moment demands. This can result in rebar congestion making it difficult to build reinforcement cages, and to place and compact concrete. The use of SC walls with steel faceplates on the exterior surfaces significantly reduces rebar congestion and assures efficient concrete placement particularly when self-consolidating concrete is used. Results from previous experimental programs [6,7] have demonstrated that SC walls provide more strength and ductility than conventional RC walls for blast and missile impact loading as well.

SC walls can be utilized in safety-related nuclear facilities as part of: (i) containment external structures such as shield buildings, and (ii) containment internal structures, such as steam generator compartments, pressurizer, etc. When designing these structures, large out-of-plane shear force demands occur at structural discontinuities, wall intersections, regions adjacent to large openings, and at the base of the structure anchored to the concrete basement. The loading conditions generating these out-of-plane shear forces are: (i) safe shutdown earthquake, and (ii) accident thermal loading causing large nonlinear temperature gradients through the wall thickness. These out-of-plane shear forces occur in the through thickness direction of the walls subjecting the concrete infill to significant stresses. The out-of-plane shear

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Nomenclature

a	shear span
A_c	cross-section area of concrete
A_g	gross area of SC beam section
A_{sa}	cross-section area of stud shank
A_v	cross-section area of shear reinforcement (or ties) at spacing S
b_w	beam section width
d	beam section depth and wall thickness
d_{stud}	stud diameter
ε_c	longitudinal strain measurement in compression plate
ε_t	longitudinal strain measurement in tension plate
ε_v	longitudinal strain measurement in shear reinforcement plate
ε_y	strain corresponding to yield strength of steel plates
f_c'	compressive strength of concrete
f_y	yield strength of steel faceplate
f_{yt}	yield strength of the shear reinforcement (or ties)
I_{cr}	moment of inertia of the cracked transformed SC cross-section
L	specimen length
M_u	bending moment
M_u/V_ud	shear span-to-depth ratio
Q_{arch}	shear strength contribution from arch mechanism
Q_{bond}	shear strength contribution from truss mechanism
Q_n	shear strength of one stud anchor
Q_p	moment of area of the tension faceplate about the neutral axis of the cracked SC cross-section
Q_w	shear strength of cracked concrete
R_m/R_n	mean ratio of experimental shear strength-to-nominal shear strength
s	stud anchor spacing
s/t_p	steel faceplate slenderness
S	shear reinforcement (tie) spacing
t_p	steel faceplate thickness
v_u	normalized experimental shear strength
V_c	shear strength contribution of concrete
V_{ar}	shear strength contribution from arching mechanism
V_{cr}	shear strength contribution of cracked concrete
V_{exp}	shear strength from experiments including self-weight
V_F	coefficient of variation due to fabrication effects
V_M	coefficient of variation due to material effects
V_M^c	coefficient of variation due to material (concrete)
V_M^s	coefficient of variation due to material (steel reinforcement)
V_n	nominal shear strength calculated by design code equations
V_P	coefficient of variation reflecting uncertainties in design
V_r	required out-of-plane shear strength for the width of b_w
V_{ra}	required shear strength of a single stud anchor
V_R	coefficient of variation for resistance
V_s	shear strength contribution of steel shear reinforcement (or ties)
V_u	shear force at section
α	linearization approximation constant
β	reliability (safety) index
μ_{avg}	shear bonding strength of a stud anchor
ν_2	effectiveness factor
$\rho = 2t_p/d$	longitudinal reinforcement ratio (steel faceplates)
$\rho_w = t_p/d$	longitudinal tensile reinforcement ratio (steel faceplate)
$\rho_t = A_v/b_wS$	shear reinforcement ratio
ϕ	strength reduction factor
ϕ_r	ratio of the stud shear bonding strength to the concrete compressive strength
Ω	safety factor

strength of walls can be investigated by conducting beam tests on one-way beam strips taken from structural walls, as discussed by Ucciferro [8]. If the SC walls are straight or with very large radius (radius-to-thickness ratio greater than 20–25), then one way beam strips can be assumed to be straight for practical testing purposes.

The out-of-plane shear force resisting mechanisms for SC walls are similar to those for RC beams, but with some differences [9]. The main contributors to out-of-plane shear resistance are: (i) the concrete infill between the steel faceplates, and (ii) shear reinforcement or ties if provided. The steel faceplates have a minor influence on the out-of-plane resistance, but they have major influence on the out-of-plane failure mode (i.e., flexural or shear failure).

The through thickness shear force is resisted by the concrete by a combination of different load carrying mechanisms, such as; (i) shear resistance in the uncracked compression zone, (ii) aggregate interlock along the crack interface, and (iii) dowel action of steel faceplate. The presence of transverse shear reinforcement (ties) contributes directly to the shear strength when it crosses a shear crack, and also has an indirect influence on the load carrying mechanisms of concrete by potentially retarding crack opening.

The shear reinforcement type, size, and spacing vary based on the particular structure design. Some of the types of shear reinforcement or ties in practice include: (i) steel rebars or deformed bars, (ii) structural steel sections, and (iii) rectangular plates or bars welded to the steel faceplates. The interfacial shear between the steel faceplates and concrete infill is typically resisted by steel headed stud anchors (stud anchors) or other structural shapes (like angles or channels) welded to the steel faceplate and anchored into concrete. The out-of-plane shear reinforcement (or ties) can also contribute to resist the interfacial shear force between the steel faceplates and concrete. The design of shear connectors for SC walls is discussed in Zhang et al. [10], and not repeated here for brevity.

Experimental investigations of the out-of-plane shear behavior of SC walls have been conducted in Japan, S. Korea, China and the US. Tests have been conducted on SC beam specimens with and without shear reinforcement. The beam specimens typically had stud anchors between the steel faceplates and concrete. Some specimens also had stiffener sections (ribs) that were welded to steel faceplates and anchored into the concrete infill. The out-of-plane loading configurations varied slightly between tests. The major parameters included in these tests were; (i) the section depth, (ii) shear span-to-depth ratio, (iii) steel faceplate reinforcement ratio, (iv) concrete strength, and (v) stud anchor and tie bar reinforcement ratio.

This paper compiles the experimental database of out-of-plane shear tests conducted on SC beam specimens representative of designs for safety-related nuclear facilities. The experimental results for specimens with out-of-plane shear failure are compared with out-of-plane shear strength equations from relevant design codes in the US, Japan and S. Korea. The paper is structured to present the relevant design approaches first, followed by the experimental database and comparisons of experimental results with code equations. The effects of parameters such as the section depth, shear span-to-depth ratio are evaluated and discussed. The comparisons are used to recommend out-of-plane shear strength design equations for SC walls. Reliability analysis is conducted to suggest associated resistance (ϕ) factors.

2. Current design practice for out-of-plane shear strength

Current design codes include equations for calculating the shear strength of reinforced concrete beams. These equations are based on