Engineering Structures 141 (2017) 596–606

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Cyclic tests on slip resistance of squat heavyweight concrete shear walls with construction joints

Keun-Hyeok Yang [a,*], Ju-Hyun Mun [b], Yong-Ha Hwang [c], Jin-Kyu Song [d]

[a] Department of Plant·Architectural Engineering, Kyonggi University, Suwon, Kyonggi-do, Republic of Korea
[b] Technical Research Center, GL Construction Co., Ltd., Gwangju, Jeonnam, Republic of Korea
[c] Department of Architectural Engineering, Kyonggi University Graduate School, Seoul, Kyonggi-do, Republic of Korea
[d] Department of Architectural Engineering, Chonnam National University, Gwangju, Jeonnam, Republic of Korea

ARTICLE INFO

Article history:
Received 19 September 2016
Revised 26 March 2017
Accepted 27 March 2017
Available online 3 April 2017

Keywords:
Squat shear wall
Heavy-weight concrete
Sliding shear
Construction joint
Slip resistance

ABSTRACT

The objective of this study was to examine the effectiveness of different slip-resistance bars (X-, W-, and Ω-shaped bars) on reducing sliding shear displacement at the base interface of squat heavyweight concrete (HWC) shear walls with construction joints. In addition, the structural applicability of welded wire fabric (WWF) reinforcement was investigated as an alternative to the individual deformed bars conventionally used for the shear reinforcement of shear walls. All the wall specimens had the same concrete dry density of 3380 kg/m^3, geometrical dimensions with barbell-shaped cross-sections, and shear ratio of 1.0. The ultimate failure of the walls subjected to under constant axial loads and reversed cyclic lateral loads was associated with a kinking in the longitudinal and vertical shear bars and splitting of the surrounding concrete at the base interface due to the dowel resistance of the bars. The slip-resistance bars were effective in reducing the shear slip displacement at the base interface after the peak load of the walls was reached. The WWF reinforcement performed comparably to the conventional shear reinforcements in enhancing the shear strength of the squat shear walls and preventing a rapid decrease in the applied loading after the peak strength. The shear strength of the squat HWC shear walls can be conservatively estimated using equations proposed by EC8 for earthquake resistance, even for avoiding sliding shear failure at high wall drift ratios.

1. Introduction

As high-density materials are known to be effective in attenuating and absorbing high-energy X-rays, gamma rays, and neutrons, heavyweight concrete (HWC) is used for shielding against radioactive rays in the walls and roofs of building structures requiring impenetrability such as nuclear power plants, medical units, and accelerator laboratories [1,2]. Experimental data [3,4] have indicated that HWC is beneficial for enhancing the modulus of elasticity and shear strength. However, it is not easy to find data that verify the structural advantages of HWC elements, although thorough evaluation of the structural performance including serviceability, strength, and ductility is essential for the rational design of concrete members.

Reinforced concrete squat shear walls with a shear ratio below 2.0 are frequently applied to provide seismic resistance to low-rise buildings and safety-related nuclear structures. In particular, nuclear structures are likely to be subjected to multiple cycles of loading to peak strength in safe shutdown earthquake shaking. The predominant performance of squat shear walls is shear rather than flexure because most of the applied lateral loads are transferred through the concrete strut action at the wall web to the base. Furthermore, sliding displacement along the interface between the wall and base becomes more important at a high level of inelasticity after the ultimate strength of the squat walls is reached [5]. Hence, sufficient experimental data on the shear strength and slip resistance of squat HWC shear walls should be accumulated for the reliable design of HWC shielding structures. However, available studies [6,7] on the cyclic shear behavior and sliding resistance of squat shear walls are very rare, even for normal-weight concrete (NWC). The ACI 318-14 guideline [8] for the shear strength of squat shear walls is based on empirical expressions for the shear transfer capacities of concrete and shear reinforcements originally established for slender beam tests [9]. The shear transfer capacity of horizontal shear reinforcement is formulated using the 45° truss analogy derived from the lower

---

[*] Corresponding author.

E-mail addresses: yangkh@kyonggi.ac.kr (K.-H. Yang), mjh352002@nate.com (J.-H. Mun), hyongha89@gmail.com (Y.-H. Hwang), jgsong@jnu.ac.kr (J.-K. Song).

http://dx.doi.org/10.1016/j.engstruct.2017.03.054
0141-0296/

Notations

A_g	cross-sectional area of walls
A_s	area of longitudinal reinforcement at the boundary elements
A_{s1}	net area of reinforcing bars
$A_{s,i}$	area of diagonal bars crossed with the base interface
A_v	area of vertical shear reinforcement at the wall web
b_w	thickness of the wall web
d_r	drift ratio of walls
E_s	modulus of elasticity of reinforcing bars
f'_c	compressive strength of concrete
f_y	yield strength of longitudinal reinforcement
f_{yh}	yield strength of shear reinforcement
$f_{yh,i}$	yield strength of diagonal bars crossed with the base interface
f_{su}	tensile strength of longitudinal reinforcement
h_l	distance from the base interface of the wall to the lateral load line
h_w	height of walls
l_i	distance between the centers of the axes of diagonal reinforcement at the wall base
l_w	length of walls
M_{cr}	initial flexural cracking moment
M_n	nominal momment capacity of walls,
N_u	applied axial load
T_{cfr}	concrete friction resistance predicted by Salonikios
T_d	dowel action resistance of longitudinal reinforcement predicted by Salonikios
V_{cd}	shear transfer capacity of concrete
V_{cr}	initial shear cracking strength of walls
V_{fl}	flexural strength of walls
V_{fr}	shear friction strength at the base interface
V_n	shear strength of walls
V_{Rd3}	diagonal shear tension strength of walls predicted by EC8
V_{Rd2}	diagonal shear compression strength of walls predicted by EC8
$V_{Rd,s}$	sliding shear strength of walls predicted by EC8
W_c	work damage indicators calculated up to the failure of walls
z	lever arm between tensile reinforcement and the center of compression zone
α_s	shear ratio of walls
Δ	lateral displacement measured at the line of action of the lateral load
ε_y	yield strain of reinforcing bars
θ	angle between the concrete compression strut and the axis perpendicular to the shear force
μ	friction coefficient of concrete
v_1	strength reduction factor for concrete cracked in shear
ξ	normalised neutral axis depth.
ρ_h	horizontal shear reinforcement ratio
ρ_l	longitudinal reinforcement ratio
ρ_v	vertical shear reinforcement ratio
φ_d	nominal diameter of reinforcing bars
φ	inclination of diagonal bars crossed with the base interface

bound theorem of concrete plasticity, whereas no specific comments on the shear transfer capacity of vertical shear reinforcement (longitudinal bars in the wall web). Furthermore, the shear friction design equations specified in ACI 318-14 ignore concrete cohesion and assume that the applied shear force is entirely transferred by the friction action of transverse reinforcement. The shear friction equations of ACI 318-14 are derived from the regression analysis using test data subjected to pure shear stresses. Overall, sliding resistance at the base interface of squat walls simultaneously subjected to moment, shear, and axial force are still ambiguous in the design specification. Against sliding shear failure of squat walls, EC8 [10] requires a definite calculation of the slip resistance, for which the mechanism includes the dowel action of vertical and diagonal bars and frictional action of concrete at the base interface. Previous studies [5,6] also indicate that diagonal shear reinforcement is effective in improving the seismic response of squat shear walls but is insufficient for preventing a large slip displacement at the base interface.

Walls commonly have construction joints at the base interface because of the separate placement of concrete between the wall and foundation at different ages. Based on push-off tests, Yang et al. [11] demonstrated that the failure mechanism in construction interfaces is similar to that in monolithic ones, whereas the sliding resistance of smooth construction interfaces decreased considerably because of the absence of aggregate interlock and the reduced concrete cohesion along the interface. This finding implies that the contribution of slip to the lateral displacement of squat shear walls would be greater for walls with construction interfaces than for monolithic walls, particularly at a high inelasticity state of the wall. However, most of the specimens [12–14] prepared to examine the cyclic shear performance of squat walls were manufactured monolithically with foundation, and insignificant examination of the slip shear displacement along the base interface was performed. Furthermore, few tests [5,6] on the shear sliding resistance of squat shear walls were conducted using monolithic specimens. Experimental work on squat shear walls with construction joints remains insufficient, particularly where a shear and/or sliding shear mode dominates, even for NWC shear walls.

This study tested six HWC squat shear walls with construction joints to examine the effectiveness of different slip-resistance bars on reducing sliding shear displacement at the base interface under a high inelastic state of walls. To prepare HWC squat shear wall specimens with unit weights of 3380 kg/m^3, magnetite particles were used for the concrete aggregates, and the shear ratio of the wall was fixed at 1.0. The contribution of the sliding shear displacement component to the lateral displacement of the walls was determined at each lateral displacement increment of the walls. The measured shear strength was compared with predictions obtained using the empirical equations of Salonikios [5] and EC8 [10], which were proposed to avoid sliding shear failure at a high wall inelasticity level.

2. Experimental test program

2.1. Details of wall specimens

Table 1 provides a summary of the test parameters selected for the squat HWC shear walls in this study. The dimensional details and configuration of the reinforcing bars in the boundary elements and web of the wall specimens are also shown in Fig. 1. The main parameters investigated were the details of the slip-resistance bars at the interface between the wall and bottom stub. Specimen C had no slip-resistance bars in the base interface. Specimens X, W, and O were designed to examine the effect of the configuration of the