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Shear behavior of strain-hardening cement composite walls under quasi-static cyclic loading

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ABSTRACT

In this study, strain-hardening cement composites (SHCCs) made of micro fibers only were manufactured and applied to fabricate four 1/3-scale shear walls for cyclic loading tests. A reinforced concrete (RC) wall also was fabricated to be used as a control specimen. The experimental results show that the SHCC walls exhibited significantly higher shear strength than the RC wall. A large number of fine cracks were observed in the SHCC walls due to the bridging action caused by the reinforcing fibers. Specifically, higher energy dissipation capacities and slower stiffness degradation characteristics were found for the SHCC walls compared to the RC wall. In terms of shear strength, it can be inferred from this study that the ACI Code can adequately predict the shear capacity of a RC wall but underestimates the shear strength of SHCC walls. In order to propose an equation that can evaluate the shear strength of SHCC walls, the direct tensile strength and a fiber-reinforcing (FR) index were considered. Also, a factor that describes the relationship between tensile and compressive strength was estimated using the results of earlier studies. This study shows that the shear strength of SHCC walls can be predicted using the proposed equation.

1. Introduction

Very strong earthquakes have caused massive destruction and casualties in recent years. Although most new buildings are designed according to current seismic codes and exhibit fairly good life safety design performance for preventing severe damage, the seismic performance of existing older buildings and facilities, which has not been identified by current seismic codes, remains a critical safety concern. Therefore, in order to ensure the strength, ductility, and rigidity that are needed to meet current seismic codes, various seismic retrofitting methods and/or materials based upon performance-based design concepts are urgently needed. Several design methods, such as the use of braces [1–3], dampers [4,5], and infill walls [6–8] are already available for seismic retrofitting and strengthening old structures. Seismic retrofitting materials, such as overlays with fiber-reinforced polymer [9–13], fiber composite material [14,15], and strain-hardening cement composites (SHCCs) [16–24], have been studied in recent years.

Among these seismic retrofitting materials, SHCCs encompass a wide variety of cement composites whose behavior under tensile stress is significantly more ductile than that of traditional fiber-reinforced concrete. When SHCCs are under tension, after the first crack appears, pseudo strain-hardening behavior is followed by multiple fine cracks that lead to a peak strength that is greater than the strength of the material when cracking first occurs. This pseudo strain hardening is due to the ability of the fibers to bridge the cracks and allow for the formation of steady-state crack distribution before stress localization occurs [25–28]. SHCCs have been proposed for a number of practical applications where their unique mechanical properties can improve the performance of structural members [29–31]. These properties of SHCCs include their enhanced fiber-to-matrix bonding property [32,33], tensile and flexural ductility, damage-tolerant characteristics, including crack growth resistance [34–38], durability [39,40], as well as their impact resistance [41–45]. The effectiveness of SHCCs as flexural or shear-strengthening materials for reinforced concrete (RC) structures has been demonstrated by the results of experimental investigations [46–48]. One such example is in the field of earthquake engineering, where structures are subjected to large inelastic displacements and therefore require adequate ductility and energy dissipation [49]. Recently, a significant amount of experimental and analytical research into SHCCs has been conducted for seismic applications that include infill walls or panels in non-ductile frame systems [50–53] and in bridge columns [54].

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Notations

a_s	shear ratio
α	factor between splitting tensile strength and direct tensile strength
b_w	thickness of wall (mm)
f'_c	compressive strength of concrete (MPa)
f_f	tensile strength of fiber (MPa)
V_f	fiber volume fraction of fibers mixed in SHCC
l_d	displacement in the diagonal direction (mm)
l_w	length of wall (mm)
n_{cr}	a total number of cracks which occurred in the assumed prismatic strut zone of shear walls
ρ_h	ratio of horizontal reinforcement
ρ_v	ratio of vertical reinforcement
ρ_1 or ρ_w	ratio of web reinforcement
z	effective internal arm ($\cong 0.8l_w$) (mm)

SHCCs recently have been proposed as an alternative to concrete for infill walls to retrofit non-ductile frames, because heavy reinforcement details are required for ordinary RC infill walls to exhibit stable behavioral characteristics (ductility and deformation) during a seismic event. The use of SHCCs has been proposed to equal or to improve the strength, ductility, energy dissipation capacity, and damage tolerance, and their retrofit performance for non-ductile frames has been evaluated experimentally [55]. However, although reinforcing fibers mixed into cement composites are very important in terms of their contribution to the strength and ductility with regard to the shear behavior of walls, the effect of these fibers on the shear behavior of the wall has not been adequately assessed. Therefore, to estimate the contribution that infill walls make to non-ductile frames, the shear strength and damage tolerance capacity of an individual wall should be evaluated first.

This paper aims to verify the effects of reinforcing fibers on the shear behavior of SHCC walls and to propose an equation for evaluating the shear strength of SHCC walls. To fulfill this goal, five shear walls composed of different fiber types and fiber volume fractions were tested under quasi-static and cyclic lateral loadings in this study.

2. Experimental program

2.1. Materials

The SHCC matrices used in this study were composed of hybrid ultra-high molecular weight polyethylene (PE) fibers and polyvinyl alcohol (PVA) fibers, and cement. 0.2 percent methyl cellulose-based viscosity-modifying admixture (MC) at cement weight fractions was used to improve distribution of fibers without forming fiber ball. The amounts of MC was determined from the test results of pre-mixing such as flowability and mechanical properties before this test. Table 1 presents the physical properties of the PE and PVA fibers.

SHCC is a micromechanically-based designed high-performance fiber-reinforced cement composite with high ductility and improved durability due to small crack widths (i.e., fine cracks). To increase the compactness of the interfacial transition zone (ITZ) between the cement matrix and the reinforcing fiber, standard SHCC mixtures typically are produced with microsilica sand (200 μm maximum grain size). In this study, microsilica sand (grain sizes ranging from 105 μm to 120 μm) was used as the fine aggregate for the SHCC mixtures in order to ensure the compactness of the ITZ between the cement matrix and the reinforcing fiber. The total fiber volume fractions of the SHCC matrix that were used were 0.75 percent or 1.50 percent. In the conventional concrete specimen, coarse aggregate (grain size ≤ 18 mm), cement, fly-ash, and water were used. The water-to-cement ratio for all the matrices was 0.45, and the specified compressive strength of the cylindrical specimens was 40 MPa. The mix proportions for the concrete and SHCC used in this study are listed in Table 2.

All specimens were stored at 23 °C and 95 percent to 100 percent relative humidity for approximately 24 h, whereupon they were demolded, and then all specimens were cured in water at 23 °C ± 2 °C for 28 days. As the steel reinforcement, deformed rebar with a diameter of 6 mm (D6) was used in the walls. Tensile tests on the steel reinforcement were performed on five tensile samples. The steel reinforcement showed a yield strength value of 291 MPa at 0.19 percent strain and an ultimate strength of 375 MPa at 0.58 percent strain.

2.2. Mechanical properties of SHCC

Material tests were conducted at 28 days to determine the effects of fiber volume fraction on the mechanical properties of SHCC. Monotonic compressive tests were carried out on cylindrical specimens that were 100 mm in diameter and 200 mm in height. The compressive strength and elastic modulus values were determined in accordance with ASTM C39 [56] and ASTM C469 [57], respectively. Tensile coupon tests were performed monotonically to examine the effect of the reinforcing fibers on the tensile performance of the SHCCs. The results of the compressive and tensile tests are presented in Table 3, and each test result in the table is the average of the five specimens. Compared to the tensile test results, the compressive test results are relatively stable except elastic modulus (E_c). As reported in van's research [35], the coefficients of variation (COV) of the tensile strain at first crack and peak strength are relatively large.

Fig. 1 shows the compressive and tensile stress-strain curves for all the specimens. As shown in Fig. 1(a), the SHCC specimens exhibit relatively similar compressive behavioral characteristics: 46.70–49.90 MPa in compressive strength and above 4000×10^{-6} in strain. However, the PVA1.30 + PE0.20 mixture shows 3325×10^{-6} strain, which is about 21 percent less than that of the other SHCCs. The hydrophilic nature of the PVA fiber makes it apt to rupture instead of being pulled out due to its tendency to bond strongly to the cement matrix [58].

Table 1
Physical properties of reinforcing fibers.

Fiber	Density (g/cm^2)	Length (mm)	Diameter (μm)	Aspect ratio (L/D)	Tensile strength (MPa)	Elastic modulus (GPa)
PE	0.97	15	12	1250	2500	75
PVA	1.30	12	39	307	1600	40