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Seismic behaviors of thin slender structural walls reinforced with amorphous metallic fibers

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ABSTRACT

In the present study, steel reinforcement details for slender structural walls were developed, which were lighter than those required by current design codes. In the developed details, transverse re-bars at wall boundaries with a relatively wide spacing and amorphous metallic fibers (AMFs) were used. Five slender wall specimens with an aspect ratio of 2.7 were constructed and tested under cyclic lateral and constant axial loads: one of these specimens was a control specimen, which was designed in accordance with the Korean concrete design code (KCI 2012), and the other four specimens were reinforced with AMFs. Two primary parameters are the fiber volume fraction of AMFs and the spacing between the transverse re-bars; three different fiber volume fractions of 0%, 0.3%, and 0.6% and three different spacing of transverse re-bars of 60 mm, 90 mm, and 120 mm were used. The test results showed that thin slender walls reinforced with AMFs exhibited inelastic behaviors and performances similar to those of the control specimen in terms of flexural strength, drift capacity, energy dissipation, equivalent damping ratio, and strain distribution along the wall height. In particular, the walls reinforced with AMFs satisfied the drift level required for collapse prevention performance specified in ASCE 41-13. In addition, a practical analysis method evaluating the drift capacity of slender structural walls reinforced with AMFs was developed and verified by comparing its prediction with the test results.

1. Introduction

Special reinforced concrete structural walls have been widely used in apartment housing and office buildings as a seismic-force-resisting system in order to resist earthquake loads in high or moderate seismicity regions [1]. According to ASCE/SEI 7 [1] and previous investigations [2–5], in seismicity regions represented by the Seismic Design Category B through F, the structural walls subjected to cyclic lateral load need to develop ductile inelastic response including high lateral drift capacity, sufficient residual stiffness, and strength even after accumulation of damage caused by repeated load. For this reason, in current design codes including ACI 318-14 [6], special boundary elements consisting of closed hoops and ties are required to confine the concrete at wall boundaries so that the maximum concrete strain at the extreme compression fiber of wall cross sections exceeds a critical value [7,8]. For the purpose, the ACI 318-14 [6] code limits the maximum allowable hoop spacing to be one third of the wall thickness.

According to Chiu and Kim [9], Korea is in moderate seismicity regions. The southern, southeastern, and western of Korea are seismically more active than the other regions. In seismic design, an effective peak acceleration of approximately 0.21g is used for maximum considered earthquakes with a recurrence period of 2475 years [9,10]. In Korea, most structural walls in high-rise apartment buildings are designed as special structural walls using a high response modification factor of 5–8 to reduce the design earthquake load [1,11]. Such structural walls are slender ones with rectangular cross sections with a wall thickness (h) of approximately 200 mm [12]. Thus, in such slender wall types, the clear spacing measured face-to-face of hoops in the boundary elements is less than 80 mm when the reinforcement details are designed according to KCI 2012 [12]. Moreover, with narrow spacing hoops, the installation of reinforcement details is difficult and causes problems in concrete casting, which would reduce the ductile inelastic response of structural walls (Fig. 1) [7]. Thus, simplified reinforcement details for the boundary elements need to be developed for their application to slender structural walls having less thickness than 200 mm.

In East Asia, many experimental studies have been performed to develop simplified details for easy construction of slender structural walls with thin thickness. Chun et al. [13] developed lighter details of transverse reinforcement to overcome the difficulties in the reinforcement installation in slender walls having a thickness

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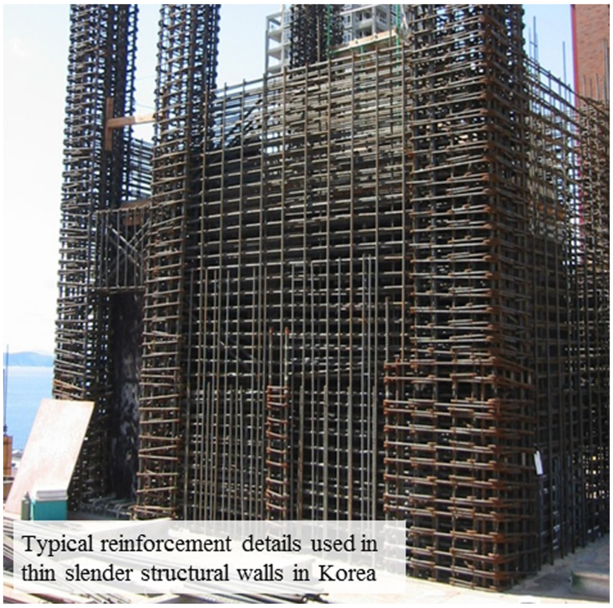

Fig. 1. Reinforcement congestion in thin slender structural walls.

of 200 mm, which were designed based on the guidelines given in KCI 2012 [12]. Fig. 2a presents the reinforcement details as requirement in KCI 2012 [12]; meanwhile, Fig. 2b shows the reinforcement details developed by Chun et al. [13]. In Fig. 2b, the transverse reinforcement composed of U-shaped bars and ties instead of closed hoops and ties in the boundary element of structural walls. In the test on the structural walls with the simplified details, it was found that the walls showed almost the same drift capacity as those of current details according to KCI 2012 [12].

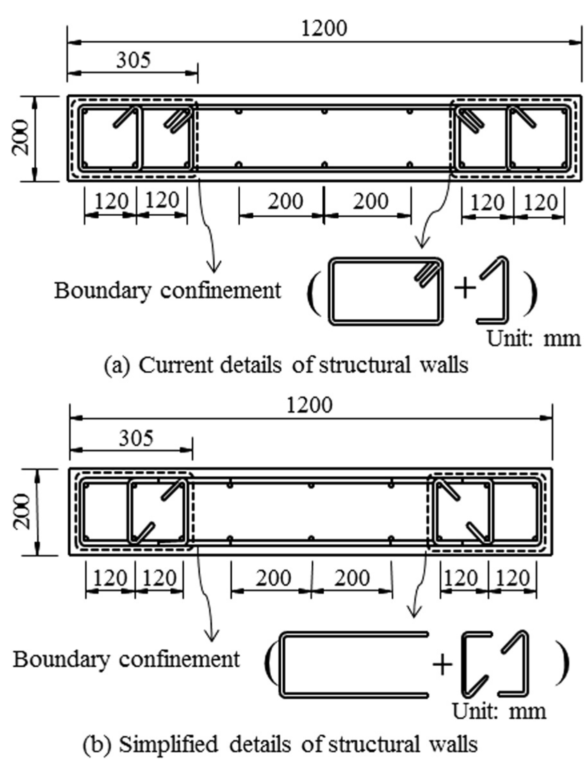

Fig. 2. Current and simplified steel reinforcement details proposed by Chun et al. [13].

Takahashi et al. [14] also proposed several reinforcement details of special boundary elements for walls with very thin thickness (94–140 mm) composed of ties only, and performed experimental studies on ten wall specimens having thin thickness with the simplified details. However, some of the wall specimens failed in compression immediately after flexural yielding without presenting sufficient drift capacity.

Dazio et al. [15] developed new details of structural walls using hybrid fibers with a fiber volume fraction of 3.5–6.0% without transverse reinforcement and performed structural tests. The test results showed that the specimens were able to present sufficient displacement ductilities exceeding 8.0 and their ultimate drifts ranged from 3.2% to 4.2%. Parra-Montesinos et al. [16] also performed a test to investigate the applicability of fiber reinforced cement composite (FRCC) materials using 2.0% fiber volume fraction of steel fibers, and found that the addition of the fibers could reduce the amount of transverse reinforcement in the boundary elements while presenting enough seismic performances.

A new type of fibers, which are amorphous metallic fibers (AMFs), have been developed for their application to structural members, and the material characteristics of the AMFs were investigated [17–19]. The configurations and mechanical properties of the AMFs were presented elsewhere [17–19], and they differ to those of conventional steel fibers. The AMFs used in this study are straight ribbon type fibers made of an amorphous alloy of the Fe family (see Table 1 and Fig. 3). In addition, the thickness of AMFs is 29 μm while conventional steel fibers have a thickness varying from 0.5 to 1.0 mm [20]. Thus, for a given fiber volume fraction, when using AMFs, a greater number of fibers can be placed in concrete crack surfaces than conventional steel fibers, which is expected to be beneficial for crack control. In addition, the AMFs show a rough surface, whereas conventional steel fibers have a smooth surface and a constant diameter. This rough surface has been found to improve the bond strength between the fibers and the cementitious materials [17].

In the present study, simplified reinforcement details for boundary elements of slender structural walls are developed using a small amount of AMFs. The main test parameters are a fiber volume fraction varying from 0% to 0.6% and a hoop spacing in the boundary element varying from $h/3$ to $2h/3$. In total, five slender structural wall specimens were made and tested under cyclic lateral load combined with constant axial load. The seismic performances of slender structural walls reinforced with AMFs were investigated and compared to those of a control specimen. In addition, a practical analysis method for predicting the drift capacity of the slender structural walls reinforced with AMFs was proposed considering boundary confinement effect and material characteristics of AMF reinforced concrete.

2. Experimental program

2.1. Materials

In this study, the specific concrete mixture for the design compressive strength $f'_c = 27$ MPa was employed and the concrete mix

Table 1
Geometrical and material properties of AMFs.

Parameters		Amorphous metallic fibers (AMFs)
Fiber thickness	(μm)	29
Fiber length	(mm)	30
Fiber width	(mm)	1.6
Yield tensile strength	(MPa)	1700
Modulus of elasticity	(MPa)	140,000
Density	(kg/m^3)	7200