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The Seismic Response of the Reinforced Concrete Shear Walls Detailed with Self-Centering Reinforcement

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ABSTRACT

Today, code-compliant structures can survive strong earthquakes without collapsing. However, the survived structures are likely to sustain localized damage and overall permanent deformations. As a result, it can be of great benefit if the earthquake-resisting structures exhibit improved self-centering and damage resilience properties beside ductility. This paper presents the findings of a study performed on the improvement of the self-centering and damage resilience of reinforced concrete (RC) shear walls. In this study, the cyclic behavior of one conventional and three innovative shear walls, which were cast with fiber-reinforced concrete and detailed with steel and a type of self-centering reinforcement, including shape memory alloy, glass fiber reinforced polymer and high strength steel, is discussed. In addition, the finite element models of the specimens were developed, verified and employed to study the seismic behavior of the specimens under the 1985 Nahanni earthquake. In general, the innovative specimens showed an improved seismic performance in terms of peak and permanent drift ratios with respect to the control wall.

Keywords: Reinforced concrete shear walls, Self-centering, Innovative materials, Finite element modeling, 1985 Nahanni earthquake.

INTRODUCTION

In recent years, several studies have been performed on the application of advanced materials in the improvement of seismic performance of building structures. In case of reinforced concrete (RC) walls, Holden et al. [1] performed a study on the seismic performance of a precast concrete shear wall detailed with post-tensioned tendons and energy dissipating steel bars. As it was shown through experimental testing, the shear wall had substantial self-centering and damage mitigation in comparison to a conventional wall. On the other hand, the wall showed a limited energy dissipation capacity. Abdulridha et al. [2] investigated the seismic response of a shear wall reinforced with steel and shape memory alloy (SMA) bars. Despite of sustaining some damage, the shear wall showed notable self-centering properties with respect to a comparable conventional wall. Ghzizadeh and Cruz-Noguez [3] performed an experimental study on a low-rise shear wall cast with steel fiber reinforced concrete (SFRC) and reinforced with steel bars and glass fiber reinforced polymer (GFRP) bars. As the study demonstrated, the innovative wall had reduced permanent deformation and less concrete damage in comparison to a conventional RC shear wall.

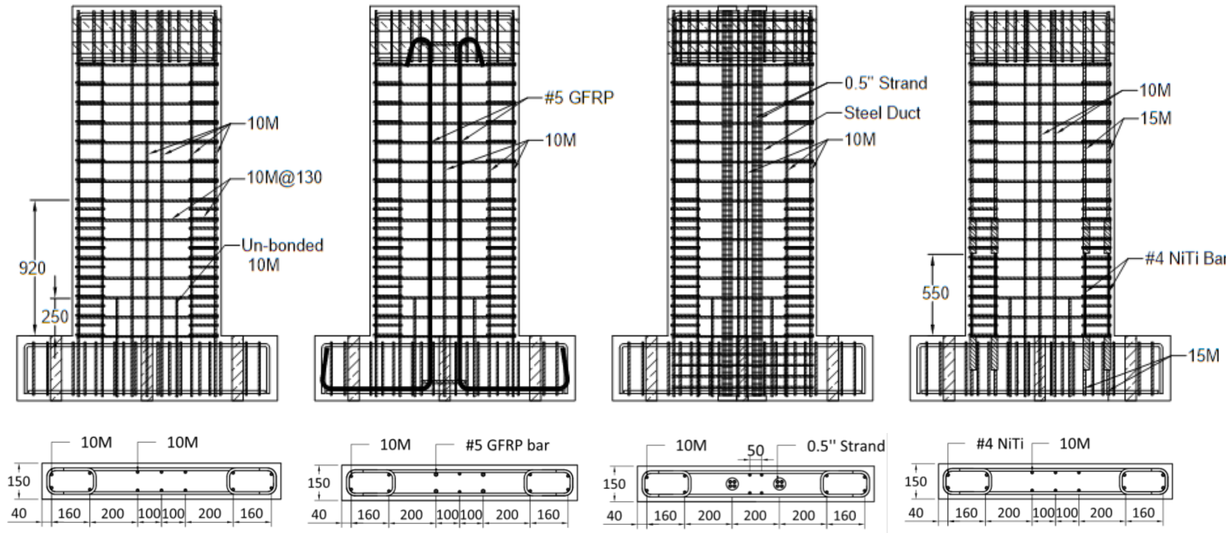
EXPERIMENTAL TESTING

This paper investigates the response of one conventional and three innovative shear walls designed to have improved self-centering and damage resilience. The walls had identical geometries but different reinforcing and cementitious materials. The innovative specimens were reinforced with conventional steel rebars and a type of self-centering reinforcement. The walls were also cast with fiber reinforced cementitious composites.

Test Specimens

Four slender shear wall specimens were designed and constructed according to CSA A23.3-14 [4] and ACI 318-14 [5], the seismic provisions for designing reinforced concrete structures in North America. The shear walls had an aspect ratio of 2.0 and were supported as cantilevers while they were subjected to displacement reversals.

The baseline specimen of the study was a conventional steel RC shear wall termed the control wall (CW). The innovative walls, which had similar reinforcement layouts to the control wall (Figure 1), were designed to exhibit improved self-centering and damage resilience in comparison to the control wall. The walls were reinforced with hybrid reinforcing systems consisting of mild steel bars, and a type of self-centering reinforcement either SMA bars, GFRP bars, or high-strength steel strands. In addition, the innovative specimens were also cast with SFRC or engineered cementitious composite (ECC). Based on the innovative cementitious and reinforcing materials used in the construction of the specimens they were termed GFRP-ECC, PT-SFRC and SMA-SFRC. A detailed description of the design of the specimens is discussed in Tolou Kian and Cruz-Noguez [6].



(a) (b) (c) (d)

Figure 1. Reinforcement layouts of specimens: (a) CW, (b) GFRP-ECC, (c) PT-SFRC, (d) SMA-SFRC.

Materials

The materials used in this study can be described as reinforcing and cementitious materials. The different types reinforcement used were 10M (11.3 mm) steel rebars, #5 (15.9 mm) GFRP bars, #4 (12.7 mm) Nickel-Titanium (NiTi) bars, and 0.5-inch (12.7 mm) high-strength steel strands. The tensile stress-strain responses of the GFRP bars, high-strength steel strands and NiTi bars in comparison to 10M steel bars are shown in Figure 2. In terms of self-centering characteristics, GFRP and high-strength steel have broader ranges of linear response in comparison to mild steel, while NiTi exhibits super-elastic properties.

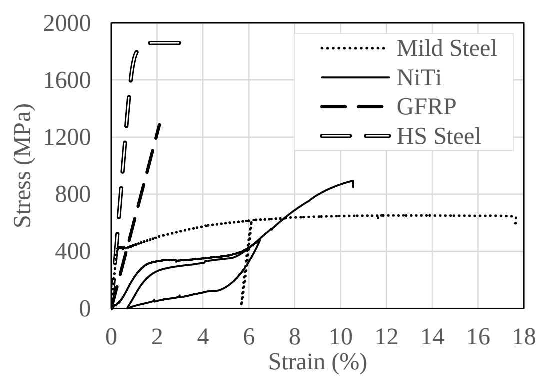


Figure 2. Stress-strain relationships of reinforcing materials.

The cementitious materials included normal concrete, ECC and SFRC. In general, fiber reinforcement, which is the case for ECC and SFRC, increases the tensile deformability of cementitious materials with respect to concrete. To identify the tensile properties of the fiber reinforced cementitious materials, appropriate testing procedures including direct tension and four-point load tests were performed on ECC prism and SFRC beam specimens respectively. The compressive responses of the materials were measured according to ASTM C39 [7]. The compressive strengths of the mixes with which the control, GFRP-ECC, PT-SFRC and SMA-SFRC walls were cast were 48, 38, 62, 51 MPa respectively. More details on the behavior of the materials are discussed in Tolou Kian and Cruz-Noguez [6].

Hysteretic Response

The hysteretic responses of shear wall specimens are shown in Figure 3. As can be seen in the figure, the responses were symmetric and stable, with the innovative specimens showing less residual drift ratios in comparison to the control wall. In the end the specimens experienced strength degradation and failed shortly after they underwent rebar failure.

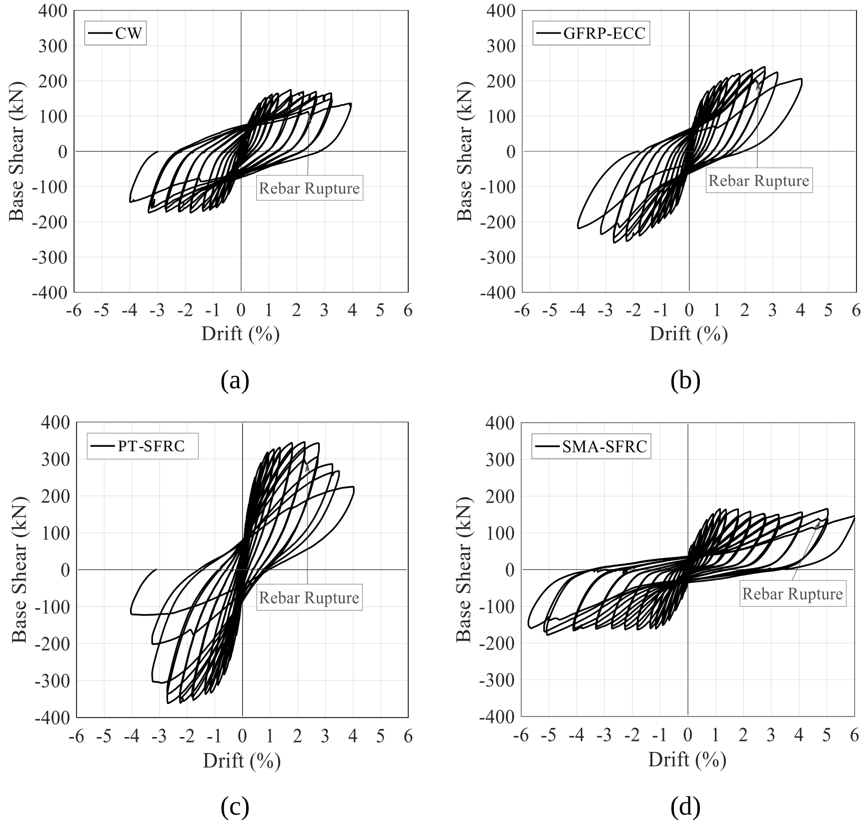


Figure 3. Hysteretic responses of specimens: (a) CW, (b) GFRP-ECC, (c) PT-SFRC, (d) SMA-SFRC.

Numerical Modeling of Shear Wall Specimens

Material Models

VecTor2, which is a powerful finite element (FE) program specializing in the analysis of reinforced concrete members, was used to calculate the response of the specimens. In VecTor2, cracked cementitious materials are modeled according to modified compression field theory by Vecchio and Collins [8] as orthogonal materials with rotating cracking patterns. Then, the cementitious materials were associated to plane-stress rectangular elements. The longitudinal reinforcement in specimens including bars and strands were modeled discretely with truss elements, while horizontal reinforcement in the walls was modeled as smeared reinforcement. In addition, bond-slip properties of the reinforcement were defined between the truss and concrete elements using link elements. Figure 4 shows the stress-strain relationships of different types of reinforcement used in this study.

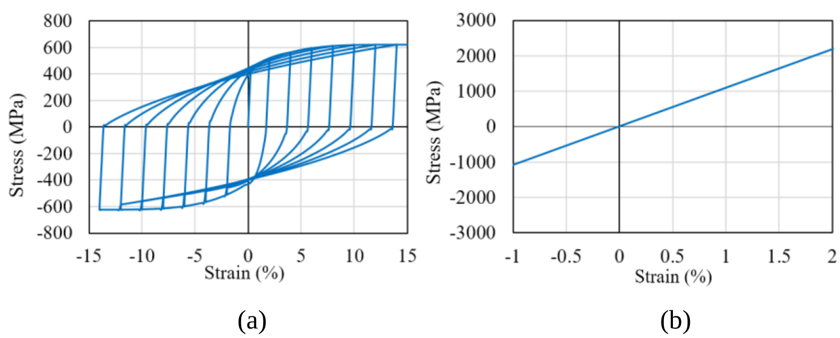
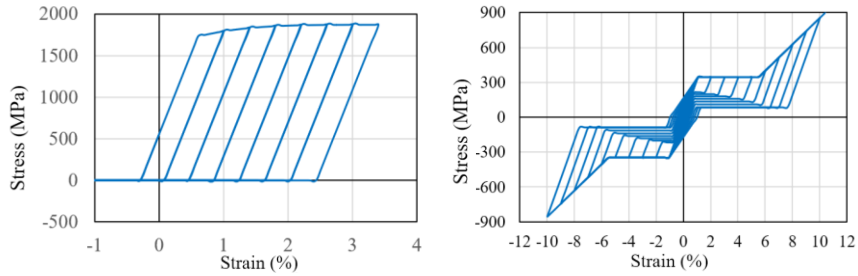


Figure 4. Continued

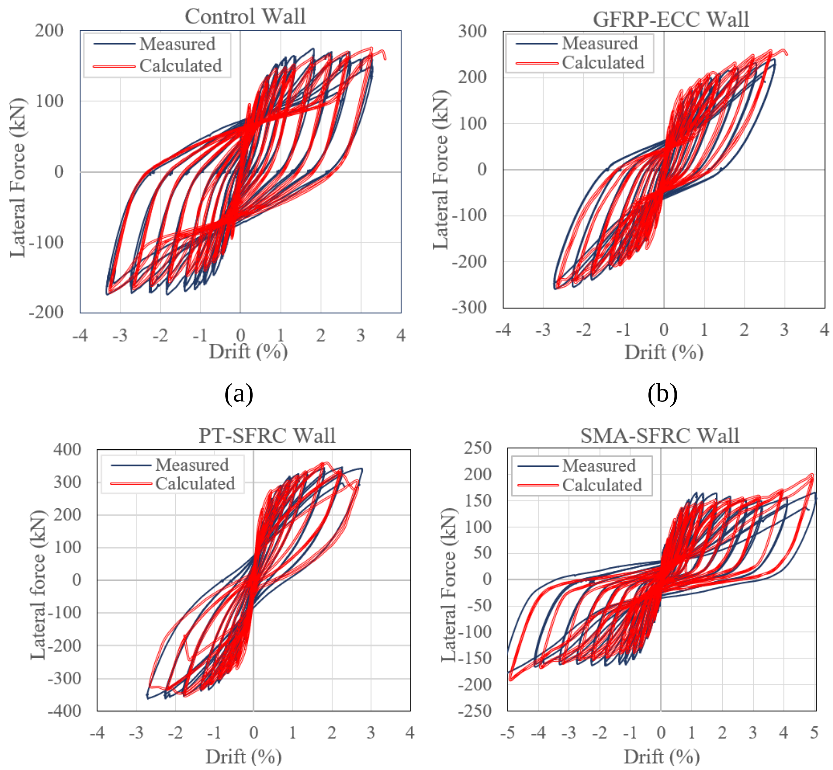


(c) (d)

Figure 4. Behavioral models for: (a) steel bars, (b) GFRP bars, (c) post-tensioned steel strands, (d) SMA bars.

Model Verification

Figure 5 illustrates the measured and calculated hysteretic responses of specimens. As can be seen in the figure, numerical models of the walls were able to closely predict the behavior of specimens during testing. The models predicted the peak strength, failure modes and deformability of specimens closely.

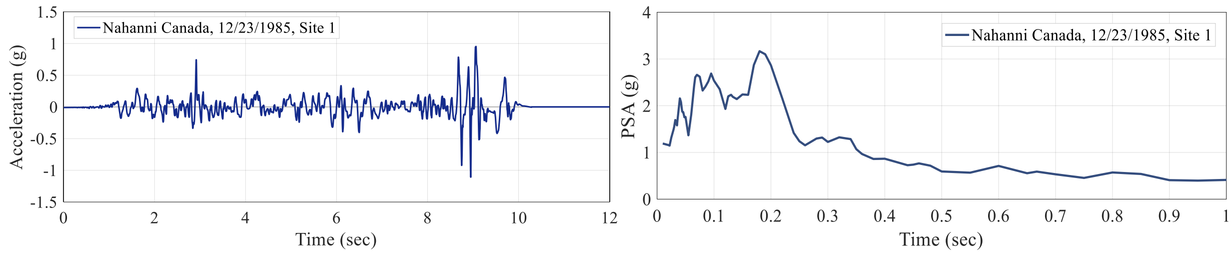


(c) (d)

Figure 5. Calculated and measured hysteretic responses specimens: (a) CW, (b) GFRP-ECC, (c) PT-SFRC, (d) SMA-SFRC.

Seismic Behavior

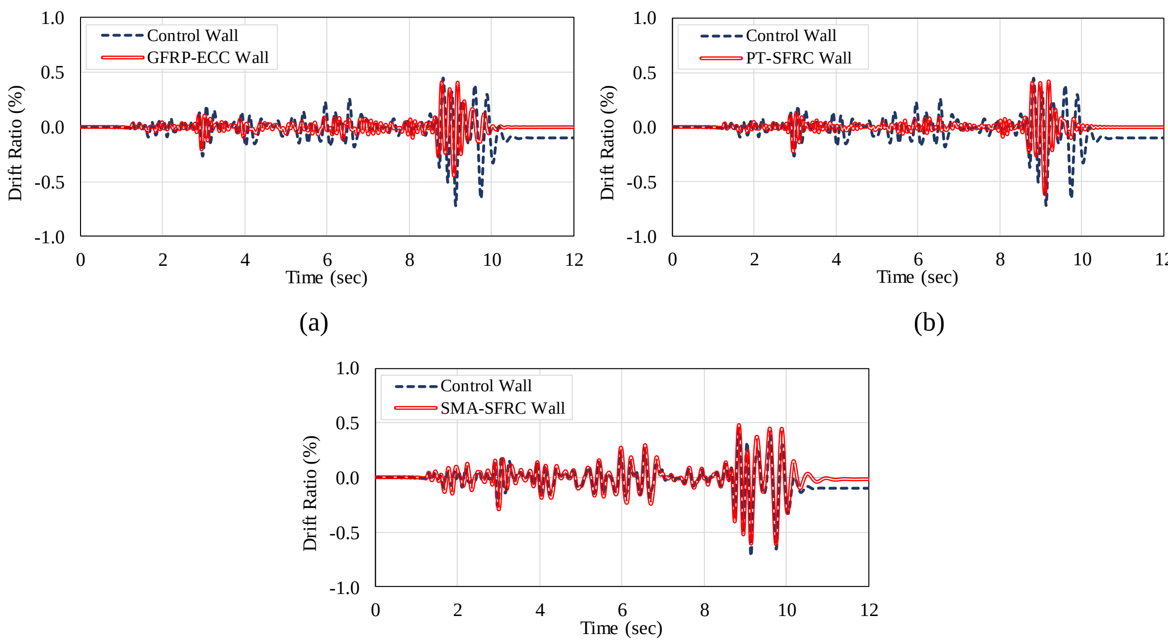
To study the response of the specimens in real-life situations, the verified models of specimens were analyzed under the 1985 Nahanni earthquake acceleration record at site 1. Figure 6 shows the acceleration record and the pseudo spectral acceleration of Nahanni earthquake in terms of gravity acceleration, g. In order to perform seismic analyses, lump masses were assigned to the top node of each specimen along the horizontal and vertical directions. The masses were tuned in a way that all the specimens had a fundamental period of 0.1 sec, the typical period of one-story buildings. Also, the damping ratio of the first and second modes of vibration of the specimens were specified as 5%.



(a) (b)

Figure 6. The 1985 Nahanni earthquake: (a) recorded acceleration, (b) pseudo spectral acceleration.

Figure 7 shows the response history of each innovative specimen in comparison to the control wall. As can be seen, the GFRP-ECC and PT-SFRC walls experienced smaller drift ratios in comparison to the control wall throughout the earthquake. The SMA-SFRC wall, on the other hand, had similar response history as the control wall during the seismic excitation. All the innovative walls experienced lower maximum drift ratio in comparison to the control wall, and after the completion of earthquake loading, the innovative walls exhibited reduced residual drifts with respect to the control wall. Table 1. summarizes the maximum and residual drift ratios of the specimens during and after the earthquake.



(c)

Figure 7. Response histories of the innovative specimens vs. the control wall: (a) GFRP-ECC, (b) PT-SFRC, (c) SMA-SFRC.

Table 1. Peak and residual drift ratios of specimens.

Specimen	Peak drift (%)	Residual drift (%)
CW	−0.72	−0.099
GFRP-ECC	−0.44	−0.001
PT-SFRC	−0.61	−0.001
SMA-SFRC	−0.62	−0.017

CONCLUSIONS

This paper presents the findings of a study performed on the seismic response of innovative shear walls with improved self-centering and damage mitigation properties. The following conclusions were drawn from this study.

1. The innovative shear walls showed improved self-centering in comparison to the control shear wall under cyclic loads.
2. The FE models of the shear walls analyzed by VecTor2 were able to accurately predict the strength of the specimens as well as their maximum and residual drift ratios.

3. The innovative shear walls with fundamental period of 0.1 sec, experienced smaller peak and residual displacements in comparison to the control shear wall under the 1985 Nahanni earthquake.

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