Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Behavior of SFRC walls without conventional shear reinforcement

J. Carrillo

Department of Civil Engineering, Nueva Granada Military University, Bogotá, Colombia.

S. Alcocer

Institute of Engineering, National University of Mexico, UNAM.

J. Pincheira

Department of Civil and Environmental Engineering, University of Wisconsin-Madison, USA.

ABSTRACT: Steel fiber reinforced concrete (SFRC) has exhibited suitable tension strength and post-cracking deformation capacities. Performance observed during tests prompts SFRC as a prominent raw material for construction of low-rise concrete wall housing in Latin America. In order to evaluate the contribution of steel fibers to shear strength and displacement capacities of concrete walls, shaking table tests of six low-rise concrete walls were carried out. Variables studied were the fiber aspect ratio (64 and 80) and fiber dosage expressed in terms of the minimum fiber dosage specified by ACI 318 (45, 60 and 75 kg/m^3). Specimens were subjected to three earthquake hazard levels defining three limit states. Wall performance is presented in terms of the cracks pattern, failure mode and hysteretic response.

1 INTRODUCTION

Low-rise reinforced concrete walls are a popular type of residential construction in Latin America. Because of the large wall-to-floor area ratio, these are often designed with the minimum amount of vertical and horizontal reinforcement in the web. Fabrication and installation of this minimum reinforcement in relatively thin walls (100 mm) is labor intensive and time consuming. By comparing the seismic demand and measured capacity in terms of both strength and drift of 39 walls used in typical one and two stories high units, Carrillo and Alcocer (2012) found that the web reinforcement could be reduced with respect to that currently required for regions of low seismic hazard. For this regions, it was postulated that the amount of the web reinforcement could be reduced to one-half of the currently required minimum or, alternatively, use steel fiber-reinforced concrete to replace the web reinforcement.

Based on performance observed in steel fiber reinforced concrete beams, ACI 318 Building Code (2014) allows using steel fibers for replacing the minimum area of conventional shear reinforcement in flexural members. To evaluate the contribution of steel fibers to both shear strength and the displacement capacities of low-rise concrete walls, the behavior of six SFRC walls subjected to shaking table excitations is presented in this paper. Each wall was fabricated with a different type of SFRC that consisted of a different type of steel fiber and/or fiber volume. The fiber aspect ratios (length-to-diameter ratio, l_f/d_f) were 64 and 80. For each fiber aspect ratio, three fiber dosage expressed in terms of the minimum fiber dosage specified by ACI 318 (45, 60 and 75 kg/m^3) were used. Aimed at studying the seismic performance under different limit states, from onset of cracking to loss of lateral strength, specimens were subjected to three earthquake hazard levels. The initial period of vibration of the walls was established to agree with ambient vibration tests of typical low-rise housing. Wall performance is presented in terms of the observed progression of cracks, failure mode and hysteretic response.

2 EXPERIMENTAL PROGRAM

Shake-table tests of six steel fiber-reinforced concrete (SFRC) walls were conducted. Specimen geometry was based on the wall layout in two-story residential units commonly found in Latin America. Typical wall thickness and clear height in these units are 100 and 2400 mm, respectively. The floors often consist of 100-mm thick solid, cast in-place, slabs, though hollow core slabs are sometimes used. Because of the limitations in the payload capacity of the shake table, specimens were designed to be

approximately 80% (1:1.25) of the actual walls. Scaling of specimens was done using the simple law of similitude. Accordingly, the specimens were fabricated with the same materials used in the actual walls but with scaled dimensions.

2.1 **Characteristics of specimens**

Nominal geometry of SFRC specimens are shown in Figure 1. Main dimensions and characteristics of the SFRC used in the specimens are summarized in Table 2. Hook-ended steel fibers with a length-to-diameter ratio, l_f/d_f, of either 64 (l_f = 35 mm, d_f = 0.55 mm, type 1F) or 80 (l_f = 60 mm, d_f = 0.75 mm, type 2F) were used. Three fiber contents, namely 0.55, 0.75, and 1.0% were studied with each fiber type for a total of six SFRC wall specimens.

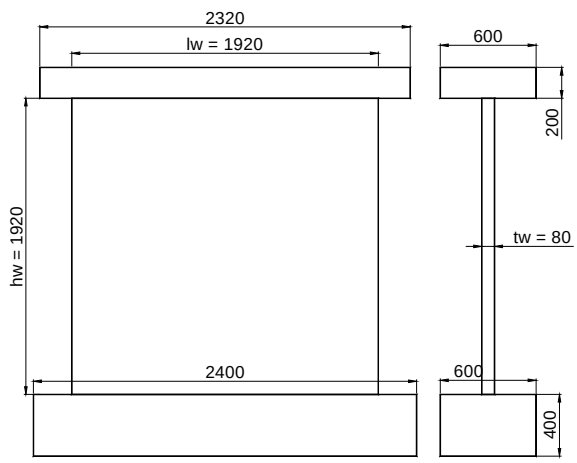

Figure 1. Geometry of specimens (dimensions in mm).

Table 1. Main characteristics of the wall specimens

Specimen designation	Fiber Type	Fiber content *		Wall specimen dimensions			
		kg/m³	V_f %	t_w mm	h_w mm	l_w mm	h_w/l_w mm
MC1F0.55		45	0.55	80	1920	1920	1.0
MC1F0.75	1F	60	0.75	81	1921	1924	1.0
MC1F1.00		75	1.00	84	1918	1925	1.0
MC2F0.55		45	0.55	82	1925	1919	1.0
MC2F0.75	2F	60	0.75	81	1921	1917	1.0
MC2F1.00		75	1.00	81	1920	1916	1.0

* Nominal values related to fiber content. See measured values in Table 6.

2.2 **Material properties**

The specified compressive strength of the SFRC was 25 MPa. Mean value of the measured mechanical properties of the SFRC are presented in Table 2. Properties were obtained from compression tests of standard cylinders, and from third-point loading bending tests of prismatic beams in accordance with ASTM C-1609 (2012). As shown in Table 6, the measured residual strengths of the mixes was not always compliant with that required by ACI 318 (2014). With type 1F fibers, only the mix with a fiber content of 1% was compliant, while with type 2F fibers, the mixes with 0.75% and 1% were compliant.

2.3 **Testing method**

Both, recorded and artificially generated ground motions were used in this study. These motions were selected to have different intensity in order to induce increasing levels of damage to the walls, ranging from minor cracking to complete loss of lateral strength. The Caleta de Campos ground motion (CA-71) recorded during the January 11, 1997, Michoacan earthquake in Mexico (M_W = 7.1) was chosen as the base earthquake record. Using the CA-71 record as a Green function (Carrillo *et al*., 2013), two additional records, CA-77 and CA-83, were numerically generated to simulate larger magnitude earthquakes of M_W = 7.7 and M_W = 8.3, respectively. Acceleration and displacement response spectra

for these motions are shown in Figure 2. Table 3 shows the protocol used for testing each of the wall specimens. All motions were applied in the in-plane direction of the walls.

Table 2. Measured mechanical properties of SFRC.

Mechanical property	1F				2F			
	V_f (%)				V_f (%)			
	0	0.55	0.75	1.00	0	0.55	0.75	1.00
Actual fiber content, D_f, kg/m^3	0	41.2	59.3	78.6	0	44.2	66.1	84.0
Actual volume fraction of fibers, %	0	0.52	0.76	1.00	0	0.56	0.84	1.07
Compressive strength, f_c, MPa	*	22.2	21.0	20.3	35.6	31.1	30.8	30.7
First-peak flexural strength, f_r, MPa	4.04	3.19	3.69	3.35	3.99	3.49	4.03	4.37
Maximum flexural strength, f_{max}, MPa	4.04	3.23	3.69	3.96	3.99	3.49	4.42	5.41
$f_{lc/300} / f_r$	0	0.72	0.80	1.12	0	0.79	1.02	1.17
$f_{lc/150} / f_r$	0	0.65	0.65	0.85	0	0.66	0.94	1.02

* Data not available.

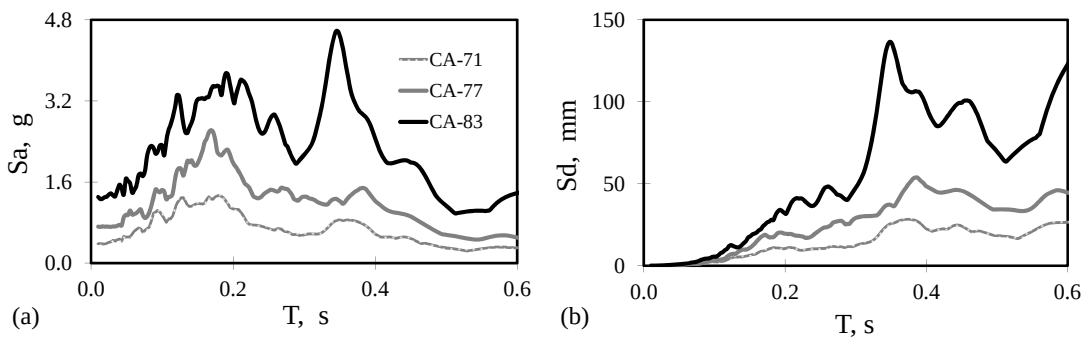

Figure 2. Acceleration and displacement response spectra of earthquake records for the prototype house.

Table 3. Shake table testing protocol

Event	Record	Target PGA		Total duration, s
		%	*g*	
1	CA-71	50	0.19	29.5
2		100	0.38	
3	CA-77	75	0.54	36.1
4		100	0.72	
5	CA-83	75	0.98	99.8
6		100	1.30	
7		150	1.95	
8		200	2.60	
9		200-R1*	2.60	
10		200-R2*	2.60	

*R1, R2 = First and second additional runs at 200% PGA of the CA-83 record.

The fundamental period of vibration of a typical two-story residential unit was estimated to be 0.12 sec (Carrillo and Alcocer, 2013). Taking into account the scale factors of the simple law of similitude (1.25), isolated wall models were designed to achieve an initial in-plane period of vibration of approximately 0.12/1.25 = 0.10 seconds. The dynamic weight used for achieving the desired design periods of walls with steel fibers 1F and 2F was 175.4 kN and 231.7 kN, respectively. An axial compressive stress of 0.25 MPa was uniformly applied to the walls and kept constant during the tests. This value was selected to correspond to the axial stress typically found in a first story wall of the prototype house.

3 TEST RESULT AND DISCUSSION

3.1 Observed crack patterns

The crack patterns observed after attainment of the peak lateral strength of the walls MC1F0.75 and MC2F1.00 are shown in Figures 3a and 3b, respectively. The lateral drift ratio, *R*, measured at peak shear strength is also shown in the figures. The drift ratio, *R*, shown corresponds to the average of the values measured in the two opposite directions of lateral displacement. As shown in the figures, all walls developed predominantly diagonal cracking, irrespective of the fiber type (1F or 2F) or fiber volume content, with few flexural (horizontal) cracks. The SFRC walls tended to develop a larger number of cracks as the fiber content increased, irrespective of the fiber type. As the walls were subjected to increased levels of shaking, cracking concentrated in two or three major inclined cracks that grew in width and length.

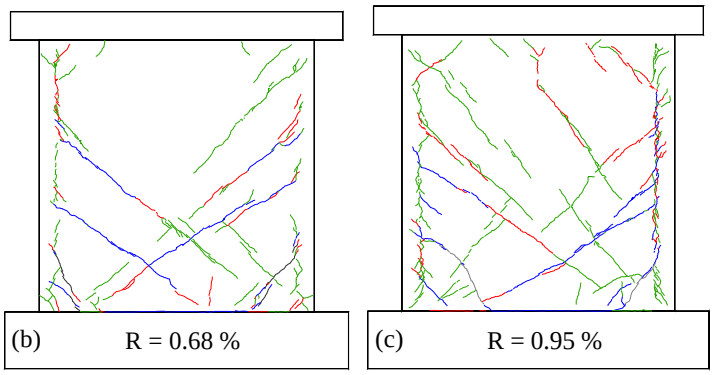

Figure 3. Crack patterns of walls at PSS limit state: (b) MC1F0.75, (c) MC2F1.00.

3.2 Failure modes

The failure mode of all walls may be described as a diagonal tension failure mode. Failure was sudden and was triggered by the abrupt and wide opening of one or two of the major diagonal cracks in the web, as shown in Figure 4. These major diagonal cracks extended from the inside face of the boundary element at the wall base at one end to the inside face of the boundary element at the other end. As shown in the figures, diagonal cracking was accompanied by bond failure (vertical cracks) along the longitudinal bars in the boundary elements. With further damage, the web was divided into two or four segments, offering little or no lateral resistance. At this stage, the lateral load was resisted primarily by frame action of the top slab and the boundary elements acting as columns. At the wall base, diagonal cracks penetrated the compression zone and eventually caused crushing of the concrete in that region. Forensic examination of the walls showed pull-out of steel fibers across the width and length of all major diagonal cracks, irrespective of the fiber type or fiber content used in the walls. No fracture of the steel fibers was observed, i.e., the failure mechanism of the SFRC along these diagonal cracks was governed by stretching of hooks at the ends and bond failure.

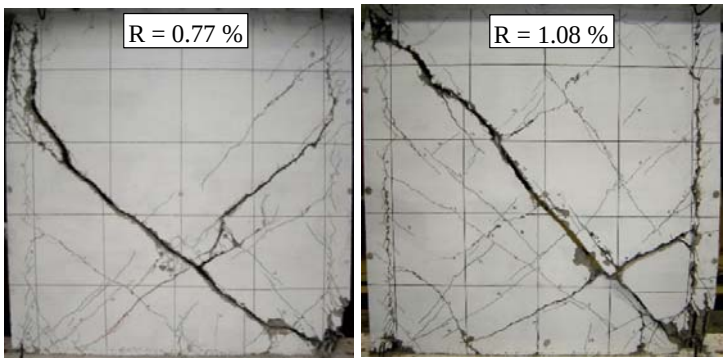

Figure 4. Crack patterns at failure of walls: (a) MC1F0.55, (b) MC2F1.00.

3.3 Hysteretic response

The recorded base shear and drift relations for selected SFRC specimens, representative of each fiber

type and content, namely, specimen MC1F0.75 and MC2F1.00, are shown in Figures 5 to 8. The relationships are shown for selected ground motions to illustrate the general response characteristics of the walls as described below. Under the ground motion CA-71 at 50% acceleration amplitude (event 1 in Table 3), all SFRC walls showed nearly elastic response with only minor hysteretic response, attributed mainly to the existing early-age shrinkage cracks. Under the full base ground motion (CA-71 at 100%, event 2), all SFRC walls developed diagonal cracking, as was expected. Development of diagonal cracks resulted in minor pinching of the hysteresis loops, but stable hysteretic behavior. The measured response under these events for walls MC1F0.75 and MC2F1.00 are shown in Figure 5.

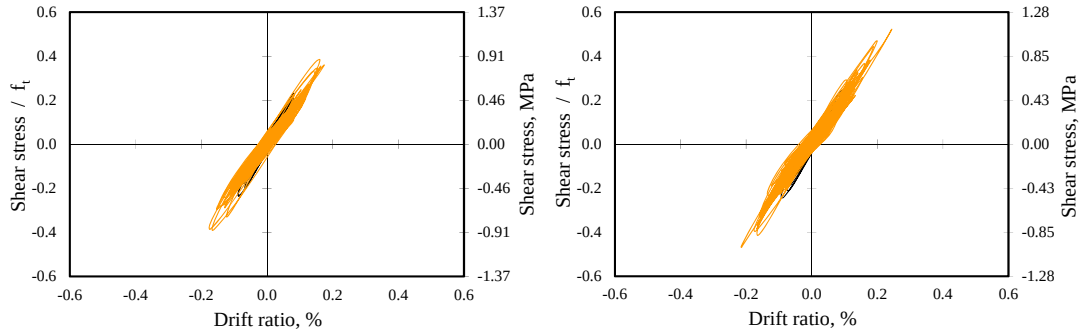

Figure 5. Hysteretic response of specimens until ground motion CA-71 at 100%: (a) MC1F0.75, (b) MC2F1.00.

Under the CA-77 events (3 and 4), existing diagonal cracks propagated further and new, additional diagonal cracks developed. Nonetheless, wall response remained stable but with hysteresis loops that showed increased pinching and stiffness degradation with loading cycles (see Figure 6).

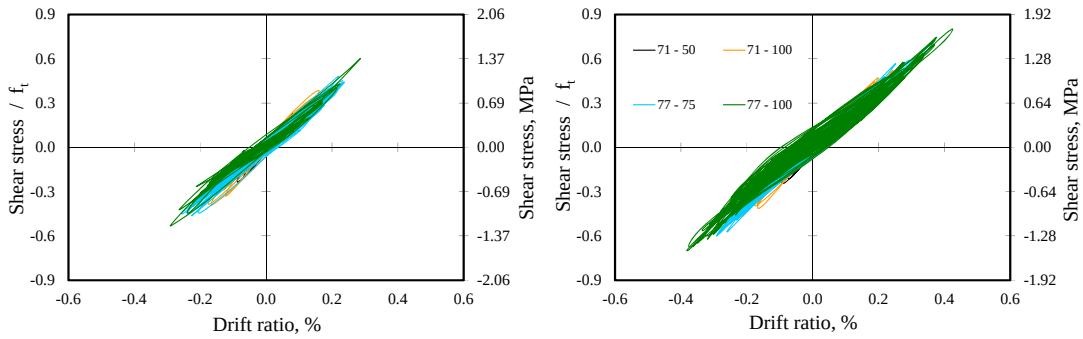

Figure 6. Hysteretic response of specimens until ground motion CA-77 at 100%: (a) MC1F0.75, (b) MC2F1.00.

The maximum recorded lateral resistance of all SFRC walls was reached during the CA-83 record, but for different amplification levels of the record. The measured hysteretic response for walls MC1F0.75 (event 7) and MC2F1.00 (event 8) corresponding to the events when the peak shear strength (PSS) was attained is shown in Figure 7. As can be seen, hysteretic response during these events remained stable, but with evident pinching of the hysteresis loops and stiffness decay with loading cycles.

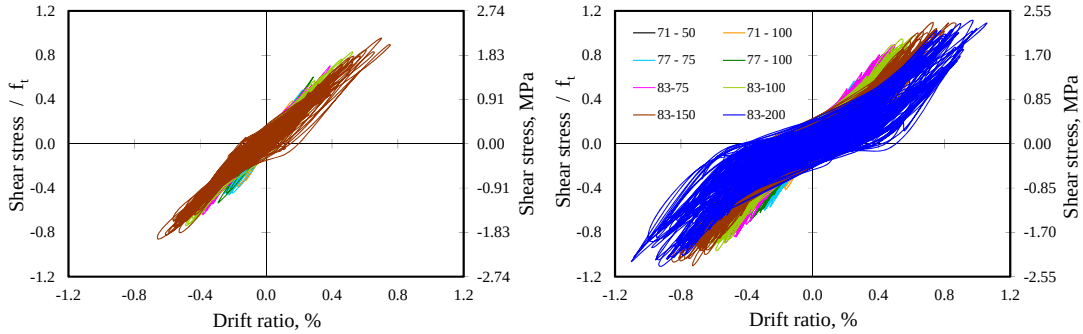

Figure 7. Hysteretic response of specimens until ground motion when the PSS was attained: (a) MC1F0.75, (b) MC2F1.00.

It is noted that attainment of the maximum lateral strength did not always result in the loss of the gravity load-carrying capacity of the SFRC walls. For example, wall MC1F0.75 endured three additional events of larger intensity (events 8 through 10) without loss of gravity-load carrying capacity after developing the peak shear strength. Similarly, specimen MC2F1.00 sustained two additional events of larger intensity (events 8 through 9) before losing its gravity load-carrying capacity. The measured responses at these stages for these walls MC1F0.75 and MC2F1.00 are shown in Figure 8.

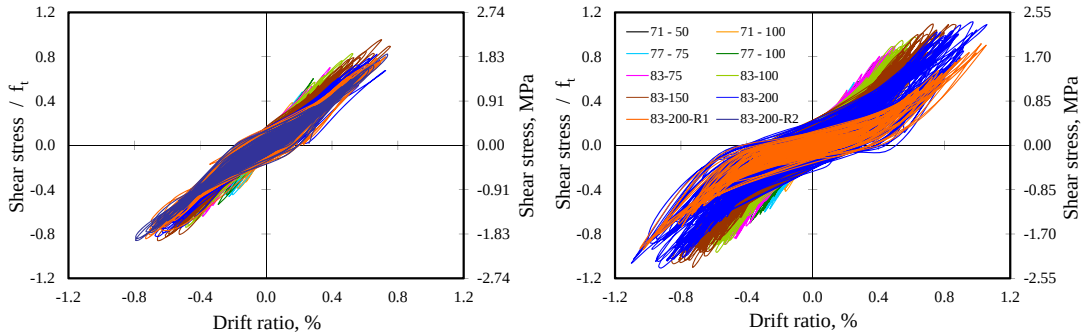

Figure 8. Hysteretic response of specimens until ground motion when the PSS was attained: (a) MC1F0.75, (b) MC2F1.00.

4 CONCLUSIONS

In this study, the global seismic performance of low-rise, Steel Fiber Reinforced Concrete (SFRC) walls was presented and discussed. Although all walls exhibited a diagonal tension failure mode, it was sudden and was triggered by the abrupt and excessive opening caused by pull-out and subsequent stretching of hooks of steel fibers across of one or two of the major diagonal cracks in the web. When comparing crack patterns of SFRC walls, they were observed more diagonal cracks of smaller width as the fiber dosage was increased, and better uniform distribution of web cracking as the aspect ratio of the fiber was higher. When assessing the hysteretic response, the lower pinching of hysteresis curves of SFRC walls suggest that the confinement provided by steel fibers to concrete and the low level web cracking, helped to improve the energy dissipation capacity of the walls. The inelastic portion of the curves was limited, particularly for walls having volume fraction lower than 1%. For walls having volume fraction higher than 1%, values of drift demands close to 1.1% were recorded.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of construction materials from Cemex Group (concrete) and Bekaert (steel fibers), as well as the extensive assistance in the experimental testing of staff and students of the Structural Engineering Laboratories of the Instituto de Ingeniería at UNAM. The first author expresses his gratitude to the Universidad Militar Nueva Granada (UMNG, Colombia) for granting academic and research scholarships.

REFERENCES:

ACI Committee 318. 2014. Building code requirements for structural concrete and commentary (ACI 318-11). *American Concrete Institute*, Farmington Hills, Mich.

ASTM-C-1609. 2012. Standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading). West Conshohocken, PA, USA, 8 pp.

Carrillo, J. and Alcocer, S. 2013. Simplified equation for estimating periods of vibration of concrete wall housing. *Engineering structures*, 52, 446-454.

Carrillo, J., Rubiano A. and Delgado, E. 2013. Evaluation of Green's functions when simulating earthquake records for dynamic tests. *Ingeniería e Investigación*, 33(3), 28-33.

Carrillo, J. and Alcocer, S. 2012. Seismic performance of concrete walls for housing subjected to shaking table excitations. *Engineering structures*, 41, 98-107.