Arabian Journal for Science and Engineering (2023) 48:4245–4261
https://doi.org/10.1007/s13369-022-06886-3

RESEARCH ARTICLE–CIVIL ENGINEERING

Dynamic Properties of Low-Rise Concrete Walls Reinforced with Conventional Reinforcement or Steel Fibers

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Received: 29 October 2021 / Accepted: 11 April 2022 / Published online: 11 May 2022

Abstract

Experimental modal analysis allows characterizing the dynamic properties of structures from measurements of both the input forces and the structural response, which is known as the multiple input multiple output method (MIMO). This paper assesses the change of dynamic parameters obtained experimentally as a function of the maximum drifts and the type of web shear reinforcement of reinforced concrete (RC) and steel-fiber reinforced concrete walls emulating the first-story of a two-story house. The modal identification was carried out using the MIMO system, transfer functions—TF, and time window transfer functions—TWTF methods. The experimental program includes the response measured during shaking table tests of twelve isolated concrete walls subjected to acceleration records representing earthquakes with moment magnitudes of 7.1, 7.7, and 8.3. Six of the concrete walls were conventionally reinforced in the web using deformed bars or welded-wire mesh, and six concrete walls were reinforced with steel fibers. Results showed that the average differences in the identified natural frequencies with the MIMO system and the TF and TWTF methods were 2% and 4%, respectively. The frequencies of the walls estimated using the three methods ranged approximately between 6.5 and 3.5 Hz for drifts of up to 0.35%. It was observed that the level of drifts affected the fitting accuracy for the MIMO system, being more significant in RC walls. Therefore, dynamic parameters estimated using the MIMO system should be carefully verified for drifts higher than 0.7%.

Keywords Experimental modal analysis · Multiple input multiple outputs · Concrete walls · Steel fibers · Welded-wire mesh

1 Introduction

Low-cost and low-income housing in Latin American countries is usually built with concrete walls with web shear reinforcement made of deformed bars and welded-wire mesh. The high seismic hazard in countries such as Colombia, Peru, and Mexico obliges us to assess their behavior under earthquake demands, which depends on the geometry of the wall, the type of concrete and reinforcement, and the reinforcement configurations. One concern on damage assessment of earthquake-resistant walls is related to how to determine the dynamic characteristics of the walls for the undamaged and damaged condition; such information could be used to understand the effect of the earthquake on the wall [1], model updating [2] or damage detection [3]. There are several issues to be considered when using dynamic characteristics for detecting damage: (i) the changing level that a state of damage produces for the vibration modes is not necessarily uniform, (ii) each natural frequency presents a sensibility level that depends on the damage level [4], iii) the modal parameters could be affected by effects different to the damage, such as the presence of corrosion in the reinforcing steel bars [5], and the type of the chosen dynamic test could play a significant role for guarantying a correct modal identification.

The methods available in the literature for modal identification can be categorized into two major groups: Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). EMA allows characterizing the dynamic properties of structures from measurements of both the input forces and the structural response, which is known as the Multiple Input Multiple Output (MIMO) strategy, when more than either one dynamic load or acceleration measurement point are consid-

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ered. Li and Mau [6] proposed MIMO type modal systems to estimate the prevailing dynamic parameters in time windows by interpreting acceleration records. A significant number of researchers have applied forced vibration tests to the modal identification of reinforced concrete (RC) walls by using different modal identification methods. Carrillo et al. [7], Carrillo and Alcocer [8], and Carrillo et al. [9] showed the effect of the seismic demand on the dynamic parameters of concrete walls reinforced for web shear with deformed bars, welded-wire mesh, and steel fibers and located at the first level of a two-story residential dwelling. Regarding OMA, it is possible the dynamic characterization from ambient-type vibration, which is desirable for predicting the current state of a house with in situ walls. Gilles and McClure [10] carried out the in situ modal identification of 27 RC shear wall buildings in Montreal. They showed the effectiveness of the extended frequency decomposition method to identify the dynamic parameters over a range of building heights. Moaveni et al. [11] demonstrated that MIMO-type systems are better adapted to the dynamic behavior of RC wall structures when compared to Output-Only methods proposed by Overschee and Moor [12], and James et al. [13]. It is worth mentioning that computational intelligence techniques have collaborated to generalize the identification process [14].

One of the properties more used in modal identification is the Transfer Functions (TF), which are spectral ratios between the Fourier spectrum of acceleration, velocity, or displacement records of response (Output) and input (Input). TF allows accurately computing the predominant natural frequency; however, TF requires additional methods such as the bandwidth method described in Chopra [15] to estimate a structure's damping (ξ). Fladung et al. [16], Ghobarah [17], and Mitchel [18] found that leakage and noise in the TF can affect the values of ξ estimated with TF and Time Window Transfer Functions (TWTF). The MIMO-type modal system proposed by Li and Mau [6], and Beck and Jennings [19] prevent the estimated dynamic parameters from being affected by factors unrelated to the structure's dynamic behavior since the system depends on an optimal solution of the general dynamic equation. Li and Mau [6], and Beck and Jennings [19] have shown that the displacements estimated with the dynamic parameters of the MIMO-type system are an alternative to the displacements estimated with the Double Integration (DI) method of the response acceleration records (Output). The DI method of the response acceleration records is used to estimate seismic displacement records in buildings where it is challenging to measure displacements directly. Arias and Martínez [20] showed that the DI method requires complex and specific signal processing methods for various acceleration records. Thus, TF could be used to identify the dynamic parameters of walls, such as expressed by Carrillo et al. [7]. The review of the available literature shows that the effects of seismic demand on the dynamic behavior of low-rise steel fiber reinforce concrete (SFRC) walls have not been assessed using a MIMO-type system.

This paper evaluates the effect of wall geometry, type of concrete, and web shear reinforcement on the dynamic properties of concrete walls for low-rise (two-story) houses subjected to seismic demands. The MIMO-type system, the TF, and TWTF are used in this paper to estimate the dynamic properties of RC and SFRC walls subjected to seismic demands. The accuracy of estimates by the MIMO-type system was evaluated by fitting the acceleration records measured in the top slab of the RC and SFRC walls, and the accelerations record estimated with the MIMO-type system. The Central Difference (CD) numerical method was used to estimate the response displacements and drifts of the RC and SFRC walls from the dynamic parameters estimated with the MIMO-type system and the TF and TWTF. The experimental program includes the response measured during shaking table tests of twelve isolated concrete walls subjected to acceleration records representing earthquakes with moment magnitudes of 7.1, 7.7, and 8.3. Six of the concrete walls were conventionally reinforced in the web using deformed bars or welded-wire mesh, and six concrete walls were reinforced with steel fibers. The study variables are wall geometry (solid and openings), type of concrete (normal and lightweight), steel ratio of conventional web shear reinforcement (0.125% and 0.25%), volume fractions of steel fibers (0.55%, 0.75%, and 1.0%) and aspect ratios (64 and 80) of steel fibers, and type of web shear reinforcement (deformed bar, welded-wire mesh, and steel fibers) of the walls.

2 Experimental Program

The specimens included in the experimental program are isolated walls designed to have dynamic properties like most walls on the first floor of a two-story house. The wall specimens were built at a slightly reduced scale of 1:1.25 (specimen's dimensions are equivalent to 80% of those of the wall in the dwelling), considering the payload capacity of the shake-table used in the tests. Mass was added to the top of the cantilever walls to guarantee that the natural frequencies of the walls correspond to the natural frequencies of the real wall. In addition, a compressive axial stress of 0.25 MPa was uniformly and constantly applied to the top slab of the walls during the tests to simulate the weight of the second story of the house. The edge elements of the walls were designed to avoid flexural failure during the tests and thus induce the shear failure mode characteristic of this type of low-rise wall. Records were applied through a shaking table over which models were bolted. Detailed information of the experimental program and the mechanical response of the wall specimens are reported by Carrillo and Alcocer [8], and Carrillo et al. [9].

2.1 Geometry and Reinforcement

The geometry of the RC and SFRC walls is shown in Fig. 1 to indicate the typical configuration for the three types of walls. According to the scale factor used for construction of specimens (1:1.25), the corresponding thickness of the prototype wall is 100 mm. This thickness is the minimum value required by NSR-10 [21] for houses up to three stories. Table 1 summarizes the characteristics of the web shear reinforcement and the measured dimensions of all twelve specimens, where t_w, l_w, and h_w are the measured thickness, width, and height of the RC and SFRC walls, respectively. Table 2 summarizes the measured mechanical properties of the steel wires and bars used as shear reinforcement in the RC walls. The nominal yield strength of the cold-drawn wires and deformed bars was 412 MPa and 491 MPa, respectively. Web shear reinforcement of RC walls is made of deformed bars (B) or welded-wire mesh (W), and the web steel ratio was equivalent to 100% and 50%, respectively, of the minimum ratio (ρ_{min}) recommended by NSR-10 [21] and ACI-318 [22]. The welded wire mesh used as web shear reinforcement of the walls comprised 4.1 mm-diameter wires spaced at 150 mm (6 in.) in both directions. In the case of walls with web shear reinforcement made of deformed bars, 9.5 mm-diameter (N3) bars spaced at 320 mm in both directions were used. Table 3 lists the measured mechanical properties of the normal- and lightweight concretes used in the RC walls. The mean value of the density of dried lightweight concrete was 1712 kg/m^3; the corresponding value for normal weight concrete was 2073 kg/m^3. Maximum size of coarse aggregate for normalweight and lightweight concrete was 20 mm and 13 mm, respectively [23].

Most of building codes in America, such as ACI-318 [22] and NSR-10 [21], prescribe the use of fibers made of steel for shear resistance of concrete members; synthetic fibers are not prescribed by these codes. Therefore, F1 and F2 hook-ended steel fibers were used as web shear reinforcement of SFRC walls. Steel fibers were not added to the concrete of walls with web shear reinforcement made of B and W. Aspect ratios (length to diameter, l_f/d_f) of F1 and F2 steel fibers were 64 ($l_f = 35$ mm, $d_f = 0.55$ mm) and 80 ($l_f = 60$ mm, $d_f = 0.75$ mm), respectively, and the specified tensile strength was 1100 MPa. The nominal dosages of F1 and F2 steel fibers (D_f) in SFRC walls were 45, 60, and 75 kg/m^3. Values of D_f were established in terms of the minimum dosage recommended by NSR-10 [21] and ACI-318 [22] to replace conventional stirrup reinforcement in beams ($D_{f\text{-}min} = 60$ kg/m^3). Thus, values of D_f for F1 and F2 steel fibers in the SFRC walls correspond to 75%, 100%, and 125% of $D_{f\text{-}min}$ (45, 60, and 75 kg/m^3). The corresponding volume fractions (V_f) of F1

Table 1 Measured dimensions and reinforcement of walls

Wall	Type of concrete	Dimensions			Openings		Type of web reinf	RC walls		SFRC walls		
		t_w mm	l_w mm	h_w mm	Door mm × mm	Window mm × mm		ρ_{min} %	$\rho_{h,v}$ %	$D_{f\text{-}min}$ %	D_f kg/m^3	V_f %
MCN50m	Normal	83	1916	1923	–	–	M	50	0.125		–	–
MCN100	Normal	84	1921	1924	–	–	B	100	0.250		–	–
MCL50m	Light	82	1917	1917	–	–	M	50	0.125		–	–
MCL100	Light	82	1912	1918	–	–	B	100	0.250		–	–
MVN50m	Normal	83	3042	1924	1681 × 720	965 × 689	M	50	0.125		–	–
MVN100	Normal	84	3042	1926	1681 × 721	959 × 689	B	100	0.250		–	–
MC1F0.55	Normal	81	1920	1920	–	–	F1			75	45	0.55
MC1F0.75	Normal	81	1924	1921	–	–	F1			100	60	0.75
MC1F1.00	Normal	84	1925	1918	–	–	F1			125	75	1.00
MC2F0.55	Normal	82	1919	1925	–	–	F2			75	45	0.55
MC2F0.75	Normal	81	1917	1921	–	–	F2			100	60	0.75
MC2F1.00	Normal	81	1916	1920	–	–	F2			125	75	1.00

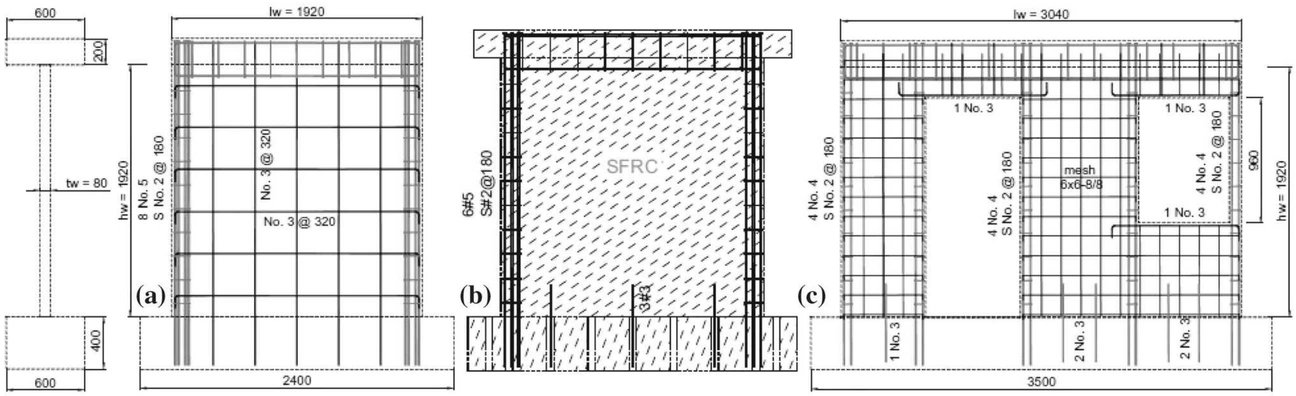

Fig. 1 The geometry of walls with web shear reinforcement that are made of: **a** deformed bars, **b** steel fibers, **c** welded-wire mesh, dimensions in (mm)

Table 2 Measured mechanical properties of reinforcement B and W

Mechanical property	N5	N4	N3	N2	–
Type of reinforcement	B	B	B	B	W
Diameter (mm)	15.9	12.7	9.5	6.4	4.1
Yield stress, f_y (Mpa)	411	425	435	273	630
Yield strain, ε_y	0.0022	0.0025	0.0022	0.0019	0.0036
Strain hardening, ε_{sh}	0.0119	0.0071	0.0130	0.0253	–
Ultimate strength, f_u (Mpa)	656	677	659	388	687
Strain at ultimate strength, ε_{su}	0.0789	0.0695	0.0730	0.1426	0.0082
Elongation (%)	12.2	9.1	10.1	19.2	1.9

Table 3 Measured mechanical properties of concrete

Wall	RC walls		SFRC walls					
Type concrete	Normal	Light	Normal with F1			Normal with F2		
Fiber dosage, D_f, kg/m^3	–	–	41.2	59.3	78.6	44.2	66.1	84.0
Volume fraction of fibers, V_f, %	–	–	0.52	0.76	1.00	0.56	0.84	1.07
Compressive strength, f_c, MPa	24.8	21.0	22.2	21.0	20.3	31.1	30.8	30.7
Tensile splitting strength f_t, MPa	2.1	1.4	2.5	2.3	2.6	3.6	4.3	4.4
Flexural tensile strength, f_{max}, MPa	3.8	3.3	3.2	3.7	4.0	3.5	4.4	5.4

and F2 fibers were 0.55%, 0.75%, and 1%, respectively. Values of V_f of steel fibers were estimated as the ratio of dosage and the density of the steel fibers in the form of a percentage. The maximum tensile strength of F1 and F2 steel fibers specified by the manufacturer is 1100 MPa. Prismatic beam specimens of SFRC with F1 and F2 steel fibers with D_f of 45, 60, and 75 kg/m^3 were tested per ASTM-C1609 standard [24]. Table 3 summarizes the measured values of D_f and the corresponding values of V_f, and the mechanical properties of plain and SFRC concrete measured during the tests of prismatic beam- and cylinder-type specimens used for the construction of the walls. Details of the experimental program comprising the shaking table of the RC and SFRC walls are described by Carrillo J. and Alcocer [8], and Carrillo et al. [9], respectively.

2.2 Seismic Demand

The seismic demand was characterized by the S90E component of the earthquake event measured at the Caleta de Campos station (CA-71) and recorded on January 11, 1997, in Michoacán, Mexico, with a moment magnitude (Mw) of 7.1. This earthquake was selected because it is a seismic event that could potentially damage low-rise dwellings. Two additional records CA-77 and CA-83, were numerically simulated for magnitudes of Mw = 7.7 and Mw = 8.3, respectively, considering the characteristics of the record CA-71. The magnitudes were selected to induce all the damage states in the walls. The wall specimens were subjected sequentially to the series of records (PGA) described in Table 4. All earthquake records were applied at the base of the walls

Table 4 Seismic demand simulated on shaking table

No	Record	PGA		Duration (seg)
		%	g	
0	WN	–	0.01	120.0
1	CA71	50	0.19	29.5
2		100	0.38	
3	CA77	75	0.54	36.1
4		100	0.72	
5	CA83	75	0.98	99.8
6		100	1.30	
7	WN	–	0.01	120.0

in the direction of the web of the walls. A white noise (WN) signal was applied at the beginning and the end of the tests to identify the dynamic properties of the walls associated with no-damaged and damaged conditions, respectively.

2.3 Processing of Records

The excitation (Input) and response (Output) acceleration records used in the MIMO-type system and the TF and TWTF were measured at the base and at the top slab of the walls tested under shaking table excitations. All acceleration records used in this study were filtered with a 4-pole band-pass filter due to the characteristics of the recorded signals. According to the features of the recording sensor, the maximum filtering frequency was 50 Hz. The minimum filtering frequency was 1 Hz and was defined with the Fourier spectra of the acceleration records. The predominant frequencies of the structure were within the analysis band of the Fourier spectrum. The limiting values of the intense phase were estimated using Aria's intensity measure. The linear MIMO-type analysis system used three-time windows within the intense phase of the acceleration records, as shown in the example of the acceleration record in Fig. 2. The dynamic parameters estimated with the MIMO-type systems depend on how the response accelerations (Output) fit the accelerations estimated with the MIMO-type system. The fitting accuracy (F_{MIMO}) was estimated using Eq. (1) and was used to estimate the maximum difference between the estimated accelerations with the MIMO-type system and the measured response acceleration records (Output).

$$F_{MIMO} = \left| \frac{A_{mes} - A_{MIMO}}{A_{mes}} \right| \times 100 \quad (1)$$

where A_{mes} is the acceleration measured in the top of the walls and A_{MIMO} is the acceleration estimated with a MIMO-type system. In this study, the MIMO-type system used two vibration modes per window; the first mode was used to estimate the dynamic parameters and the second one is a tuning mode whose modal participation factor is close to 5%. The TWTF functions used three-time windows within the intense earthquake phase of the acceleration records, as shown in the example of a response acceleration record (Output) in Fig. 2. The dynamic parameters estimated with TF functions for the total duration of the acceleration records were taken from Carrillo et al. [7], Carrillo and Alcocer [8], and Carrillo et al. [9]. TF functions were used to estimate the dynamic parameters using the entire duration of the acceleration records. The predominant frequencies (f) correspond to the largest amplitude of the transfer functions. The bandwidth method described in Chopra [15] was used in this study to estimate the predominant ξ utilizing the TF and TWTF.

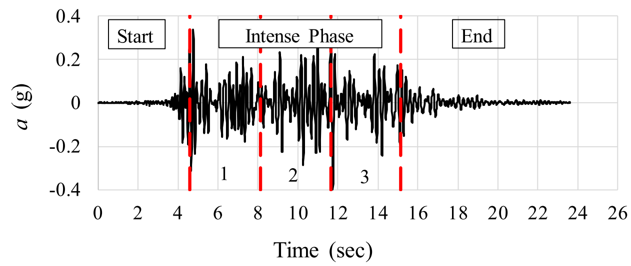

Fig. 2 Time windows within the intense earthquake phase

2.4 Response Displacements

The response displacements (Output) at the top slab of the wall specimens were estimated with the Central Difference (CD) method described in Chopra [15]. The CD is a numerical method that allows the solution of differential equations by transforming the derivatives in finite differences; thus, it can solve the equation of motion for multiple degrees of freedom. It is possible to use the dynamic parameters such as f and ξ to estimate the response acceleration, velocity, and displacement records (Output) of an element subjected to an excitation (Input), in this case, a base acceleration. The excitation acceleration records at the base (Input) were measured on the bottom slab of the walls tested under shaking table excitations. The maximum drifts of the RC and SFRC walls were estimated using Eqs. (2) and (3).

$$\Delta_{max\text{ - }m} = \frac{D_{max\text{ - }m}}{h} \times 100 \quad (2)$$

$$\Delta_{max\text{ - }c} = \frac{D_{max\text{ - }c}}{h} \times 100 \quad (3)$$

where h is the height of the wall in mm, $D_{max\text{-}m}$ are the maximum displacements in mm measured in the upper slab of the walls, and $D_{max\text{-}c}$ are the maximum displacements in mm estimated with the DC method.