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ORIGINAL PAPER

Dynamic behavior assessment of public buildings in Syria using non-linear time-history analysis and ambient noise measurements: a case study

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Abstract

This study evaluates the dynamic behavior and performance of vital reinforced concrete (RC) public building [Ministry of Higher Education (MHE)] designed in compliance with the old Syrian (non-seismic) building code. The real non-linear dynamic behavior of the MHE building has been checked by detailed dynamic numerical analyses (finite elements method—FEM) validated by a series of ambient noise measurements carried out on-site. The modeling approach for the thorough 3D dynamic analyses of the (RC) MHE building has been developed to be able to investigate the actual non-linear dynamic performance of widespread range of RC structures, providing the opportunity to set up a reliable detailed methodology to assess the real dynamic performance of the old vital structures designed according to the old Syrian (non-seismic) building code from the new seismic requirements perspective. The results of the frequency analyses, the nonlinear time history, and the experimental measurements have shown an excellent agreement. The study showed that the modeling approach by the FEM is reliable for predicting the actual dynamic behavior of RC structures, but it is very sensitive to the modeling assumptions. Furthermore, the dynamic performance analyses have revealed unsymmetrical behavior of the east–west wings about the *Y*-axis which could be attributed to the inefficient seismic rehabilitation executed in 2001.

Keywords Ambient vibration measurements · Natural frequency analysis · Nonlinear time-history analysis

Introduction

The increasing interest in the seismic performance assessment of existing constructions to ensure a sufficient level of safety has become a key issue for seismic engineering, in particular for existing buildings with public functions. Different techniques are usually employed to assess the vulnerability of existing buildings. One of these accurate evaluation techniques of seismic vulnerability is the costly real-sized and/or scaled experimental models of full structures that are usually used for evaluating the structures seismic vulnerability, especially in high seismicity hazardous countries like the USA, Japan, or Italy (Bhandari et al. 2018, 2019). However, the seismicity of Syria is actually passing with a relative quiescence (Abdul-Wahed and Al-Tahan 2010; Abdul-Wahed et al. 2011; Abdul-Wahed and Asfahani 2018), which entirely justifies the use of effective lower-cost techniques as numerical simulations and ambient noise. Most of the foregoing research studies in this domain were concentrated on the identification of the dynamic characteristics of structures from solely one of the mentioned seismic assessment techniques (Field vibration tests, Experimental full real size models/scaled models, or Numerical simulation). This study combining the ambient noise analysis with a thorough numerical simulation of the building, which considerably minimizes the uncertainty and the hypersensitivity effects of the numerical simulation, wherefore boosts the reliability of the analyses. The use of ambient noise measurements in the building operating conditions has allowed the calibration of the numerical model and developing the 3D non-linear numerical model by minimizing its hypersensitivity

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to the inputs and the initial assumptions (Mucciarelli et al. 1999; Navarro and Oliveira 2006; Mucciarelli et al. 2006, Formisano et al. 2018; Di Lorenzo et al. 2019, Formisano et al. 2020). Consequently, the calibrated numerical model has become significantly reliable for predicting the actual dynamic behavior of Syrian existing public RC structures designed according to the old Syrian (non-seismic) building code. Among field vibration tests, ambient vibration experiments are most common as they are non-destructive, economical, fast, and easy to implement (Nakamura et al. 1999,2000). Moreover, the test procedure does not affect the solidity and safety of the structure. Beskhyroun et al. (2020) have studied the dynamic behavior of a full-scale 13-story reinforced concrete building under forced vibration, ambient vibration, and distal earthquake-induced excitation. They have compared the field experiments results with the results of the building finite element model developed using SAP2000. Furthermore, numerical simulation and forced vibration have been used by Gomes and Lemos (2020) to characterize the dynamic behavior of the Baixo Sabor arch dam recently built in Portugal. Also, Betti et al. (2016) have used numerical analyses for assessing the seismic behavior of two Italian historical masonry buildings. Likewise, Conte et al. (2011) have conducted a series of dynamic tests and numerical analyses on a historical building located in Southern Italy (Lecce) to determine its dynamic response characteristics under operational conditions. While, Liu et al. (2014) have analyzed three examples from Beijing metropolitan area using the ambient vibration noise technique, among them studying the structural characteristics of a high-rise reinforced concrete building stimulated by ambient vibration noise. Moisidi et al. (2014) have performed ambient noise recordings to estimate the site response of the surface and near the subsurface structure of the small-scale Kastelli Basin in northwest Crete. Similarly, Lacanna et al. (2020) have employed the ambient vibration test to assess the dynamic behavior of the Baptistery of San Giovanni in Firenze (Italy). Moreover, Kamarudin et al. (2014) have conducted ambient noise study on the seismic damaged school building (a 4-story reinforced concrete frame laboratory building) and the adjacent buildings using triaxial 1 Hz seismometer sensors, in order of assessing the vulnerability of the damaged structure in both longitudinal and transverse axes. Furthermore, Moisidi et al. (2018) have identified the resonant frequency of soil and of modern and historical buildings in three major municipalities of Crete (Heraklion, Chania, and Rethymno) using ambient noise recordings (microtremors) considering the importance of soil–structure interaction. In this study, the dynamic behavior and the performance of vital public (RC) building are going to be assessed by detailed dynamic numerical analyses (FEM) validated by a series of ambient noise measurements carried out on-site under operation conditions. A series of detailed thorough non-linear time-history analyses have been used in the numerical analyses validated by the ambient noise measurements. The paper contributions in dynamic behavior identification and dynamic performance monitoring fields are:

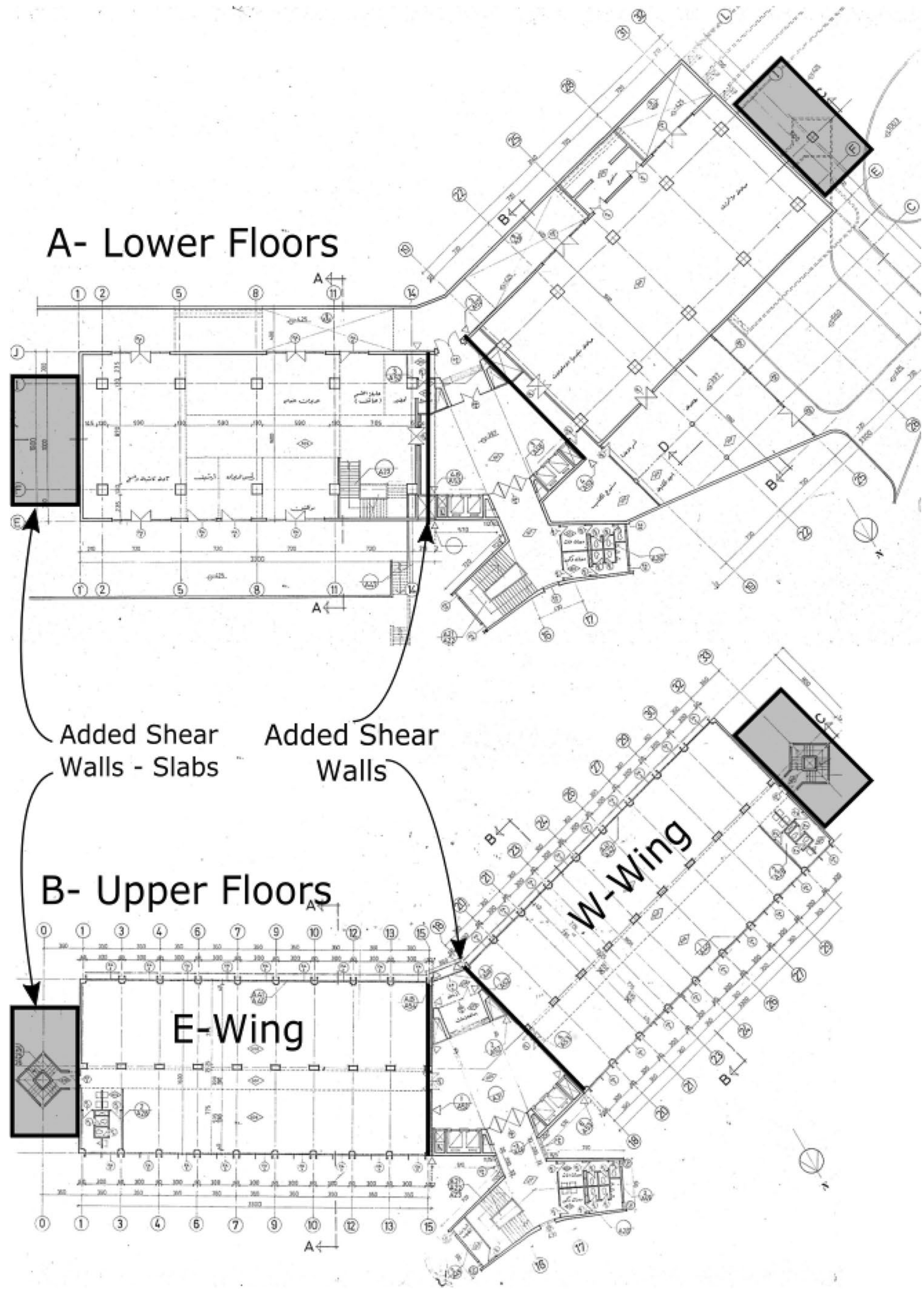
- Identification of the real dynamic performance of this vital public (RC) building designed according to the old Syrian (non-seismic) building code from the new seismic requirements perspective.
- Developing the reliability of the used numerical model by the comparison between the results of the non-linear time-history numerical model and the results of the ambient vibration testing.
- Investigation of the seismic efficiency of rehabilitation works executed on the MHE building in 2001.

The building description

Ministry of Higher Education (MHE) building is one of the biggest and busiest public buildings in Damascus, with its spacious (11) floors and thousands of users daily (employees and visitors). Furthermore, it has interesting features such as its (3) underground vaults, and its location among smaller old residential buildings in an area very close to the path of the Barda river. Moreover, the MHE building was designed and built in the early 1980s (Fig. 1) according to the old (non-seismic) building code requirements before implementing the new Syrian seismic code, all the above mentioned justify the choice of the MHE building for this study. The building consists of three parts, east, west identical wings, and central wing containing the stairs, elevators, and lobbies (Fig. 2). East and west wings are roughly 33 × 16 m in plan and have eleven floors in which three are underground floors. The east and west wings have vertical irregularities in columns changing from two rows of five large sections columns in each row in the lower floors (floor − 3 to floor 0) to three

Fig. 1 Building of the Ministry of Higher Education (MHE) in Syria

Fig. 2 Seismic rehabilitation of the MHE building in 2001



rows of ten relatively slender columns for each row in the upper floors (Fig. 3). Upper floors' columns are supported on large beams that have an approximate depth of 1.7 m. To overcome the inconsistency with the Syrian seismic code of 1997, which had seismic provisions for important buildings, the MHE building has been seismically rehabilitated in 2001 by adding shear walls to the internal side of the east and west wings, and shear core system to the external side (Fig. 2). Full coupling of old and new concrete could ensure dual action against lateral forces according to the 'General Company for Engineering Studies and Consulting' reports (GCEC 2001) on the stresses at linking regions of the old and new concrete parts. The rehabilitation parts were coupled using shear rods fixed in holes by means of Epoxy materials "Sika powerFix-1™". The cohesion supplied by the agent is bigger than the shear strength in coupled part locations; so, no separation between old and new concrete would occur (GCEC 2001). Before rehabilitation, three methods of testing to investigate the strength of the concrete were performed. The

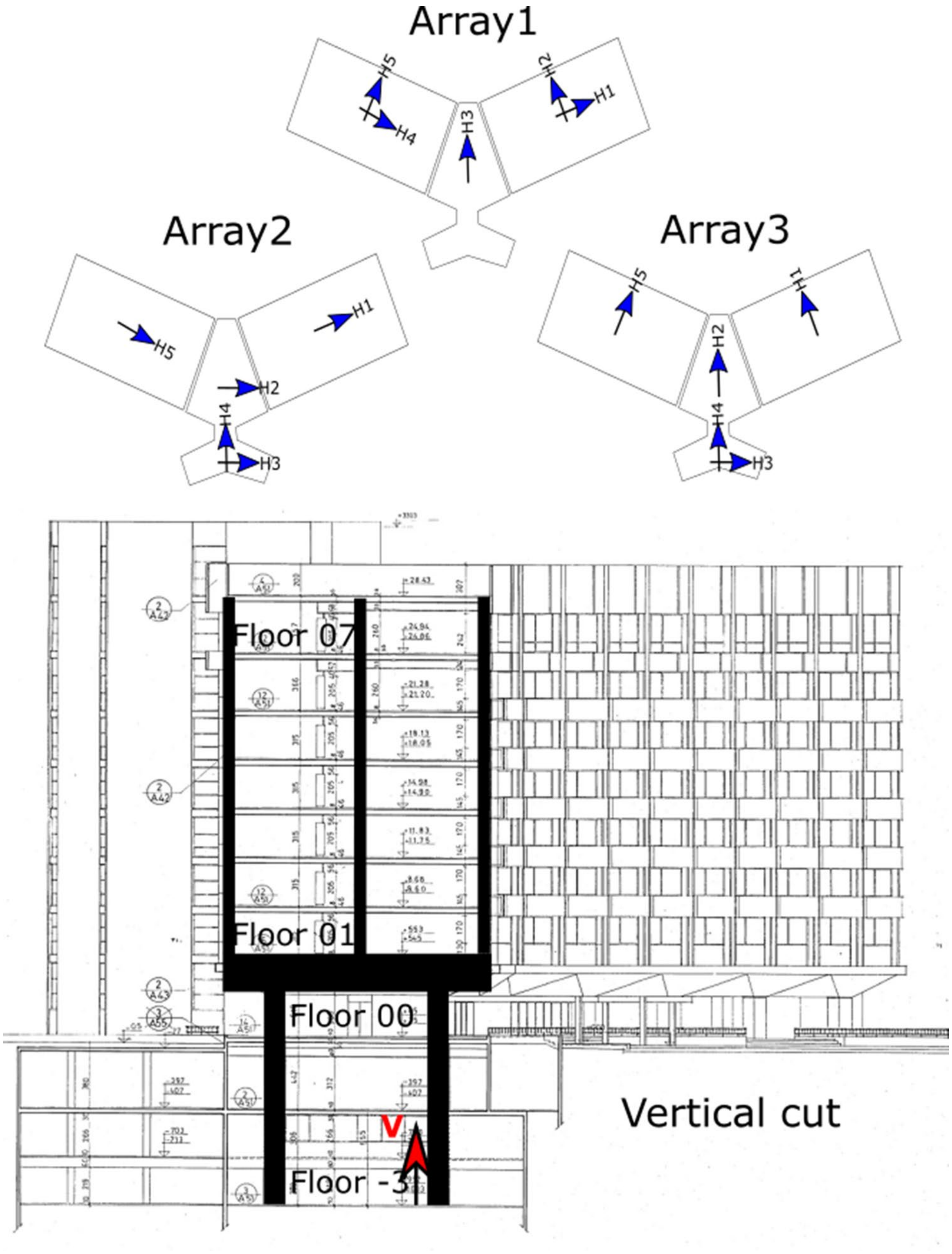


Fig. 3 Location of sensors. V indicates the vertical seismometer, which is kept fixed as reference in the-3rd underground floor. H1, H2, H3, H4 and H5 indicate the five horizontal seismometers, which are moved amongst the predefined positions and directions in three arrays on the 7th floor

first is cutting-out 16 concrete specimens from different locations in the building. The mean value of testing gave 288.3 kg/cm^2. The second was 80 tests performed using Schmit hammer at several locations, which gave a mean value of approximately 310.3 kg/cm^2. Ultra-sonic tests were also performed to ensure accurate values of concrete strength, 60 locations were considered and gave almost the same results of Schmit hammer tests. As a result, the mean value of concrete strength is about 30 MPa. Also, nominal yield stress for steel has been estimated to be 400 MPa as a basis for rehabilitation (GCEC, 2001). The foundation's system of the building has consisted of an individual foundation for each column and continuous foundations for the shear walls.

Data and analysis methods

The identification of the dynamic characteristics of structures (dynamic identification) has accomplished using: in situ ambient vibration tests, and thorough numerical modeling of the entire structure. The detailed numerical modeling has been carried out using FEM software Abaqus.

Experimental data

A wide range of experimental techniques could be used for measuring the vibration of structures by instrumentation of highly sensitive dynamic transducers (Navarro and Oliveira 2006). However, ambient vibration experiments are the most common with the important advantage of imposing a higher level of vibration in a controlled manner and analyzing the response. Moreover, it is non-destructive, cost-effective, rapid, easy to execute, and the test methodology does not affect the solidity and health of the structure. To accomplish the experimental methods, different exciting sources as ambient noise (micro tremors) tests, forced and free vibration tests, test explosions, as well as earthquake response measurements, can be used. Since the MHE building is located at Damascus city center and the seismicity of Syria is actually passing with a relative quiescence (Abdul-Wahed and Al-Tahan 2010; Abdul-Wahed et al. 2011; Abdul-Wahed and Asfahani 2018), which means no strong motion data are available, the most of previous exciting sources are not available or suitable. The concept of Nakamura technique (Nakamura 1989) depends on the principle of applying the ambient noise as input on the structure which will amplify it at different periods depending on the dynamic response of the building. In metropolitan areas, this technique could be applied by positioning at least 2 horizontal seismometers at the top floor and a vertical seismometer at the foundation level. The horizontal seismometers are to obtain the fundamental period in the orthogonal directions of building. The ambient noise measurements have been performed on the MHE building using five horizontal seismometers (indicated on Fig. 3 as H1, H2, H3, H4, and H5), which have been moved amongst the predefined positions and directions in three arrays on the top floor of the building. However, the vertical seismometer (indicated on Fig. 3 as V) has been kept fixed as a reference in the underground floor. All measurements were conducted after 15:00 PM. (end of daily work in the building) to avoid the high level of artificial noise. Obtained data were recorded, digitally converted, and stored using Paladin ESG recorder. The data acquisition system composed of Portable Paladin™ Monitoring System, 24 bit with 6 channels, and 6 short-period seismometers (Sercel Model L-4) of 1-s free oscillation. A time history of about 15-min-long microtremors signal was obtained for each record and sampled at a rate of 100 samples per sec. Three records were obtained from three different arrays of sensors positioning, where the horizontal seismometers were positioned in the three parts of MHE building's floor 7 (Fig. 3) and oriented according to the longitudinal and the transverse directions of each part.

Data processing

The analyses of the results records were performed using a specific numerical code (Abdul-Wahed 2008, 2013, 2015). The data are split into a series of short time windows of 30-s duration each, and for each of these windows, the Fourier spectrum is calculated. The duration of records allows the averaging of the Fourier spectra on 20 short time windows and evaluating the stability of microtremors measurements. The duration of records allows the averaging of the Fourier spectra on 20 short time windows and

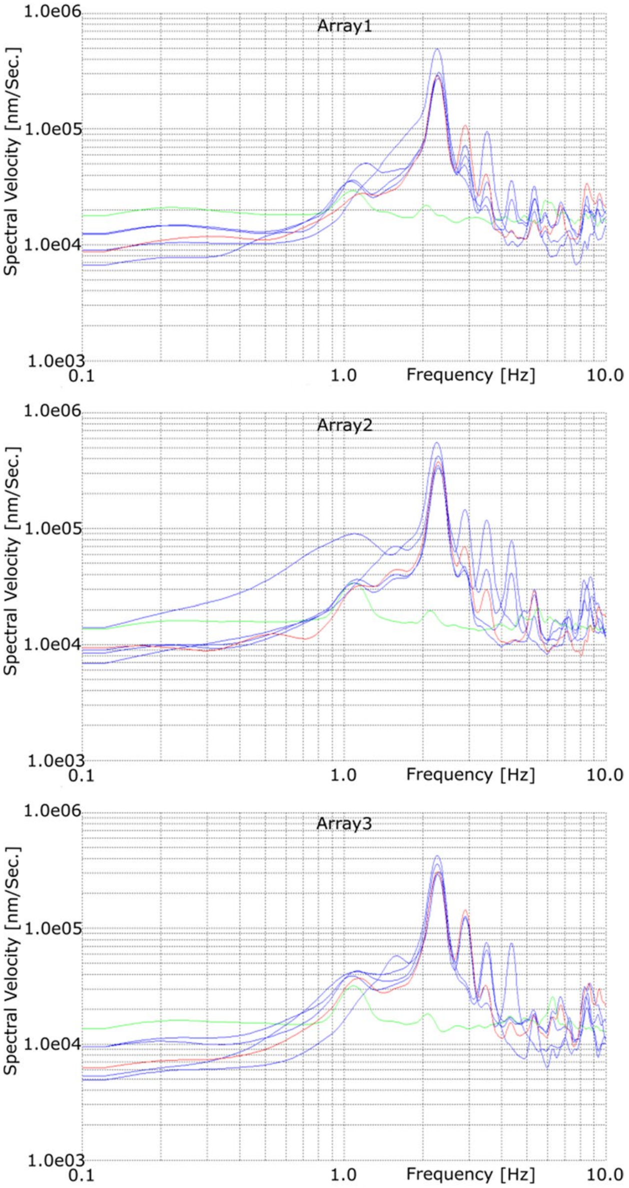


Fig. 4 Fourier spectra of ambient noise of three arrays. The green curve indicates the vertical seismometer. The red curve indicates the horizontal seismometer H5. The blue curves indicate the rest of horizontal seismometers: H1, H2, H3, and H4

evaluating the stability of microtremors measurements. Then, the standard deviation over all time windows was determined. Also, the dominant frequency and corresponding damping factor have determined on the averaged Fourier spectra for each record point (Fig. 4). Damping factors in both longitudinal and transverse directions of MHE building were calculated using the half-width band method (Dunand et al. 2002). The spectral ratios between the average horizontal spectra and the average vertical spectra (H\V) are calculated to obtain the fundamental frequency and amplification. In buildings, by considering the foundation level as a reference, the spectral ratios technique (Mucciarelli et al. 2004, 2006) demonstrates the same fundamental frequency as the simple analysis of peaks in the Fourier spectra (Fig. 5). The spectral ratios between the top floor records and the underground record provided the combined predominant frequencies and amplification factors of the entire building and ground expressed by values of spectral ratio above 1.0 (Amplification) and under 1.0 (de-amplification) (Fig. 5). The obtained ground (H\V) spectrum could help to separate the local manmade noise sources from those of natural origin that characterize the site conditions. Spectra of ground have exhibited a dominant frequency around 1.1 Hz at all records. This dominant frequency is in accordance with previous microzonation studies in Damascus (Zaineh et al. 2010,2012). A frequency of 1.1 Hz can be attributed to the soft deposits which are usually characterized by low-frequency range. Results of spectral ratios obtained from the analysis of ambient noise records point out the presence of noticeable amplification effects in the frequency range 2.0–2.5 Hz that appears stable in all the investigated positions. The results of Fourier spectra and spectral ratios are organized to show the results of measurements at every array of measurements and at each sensor of east and west wings in each array (Table 1). The obtained results are nearly similar in both longitudinal and transverse directions. The resonance characteristics were well recognizable directly from the Fourier spectra at each sensor. It is worth mentioning, in general, the Fourier spectra are well constrained, with overall small standard deviations. This shows that the spectra are very stable over the investigated windows, this result has been confirmed by examining more closely the spectrograms. Furthermore, The Fourier spectra show distinct peaks corresponding to the resonance frequencies of the building (Fig. 4). The lowest resonance frequency is clearly visible at all sensors throughout the building. Hence, these resonance frequencies can be interpreted as the first translational mode of the building's vibration in the transversal and longitudinal directions. The resulted analyses of horizontal records

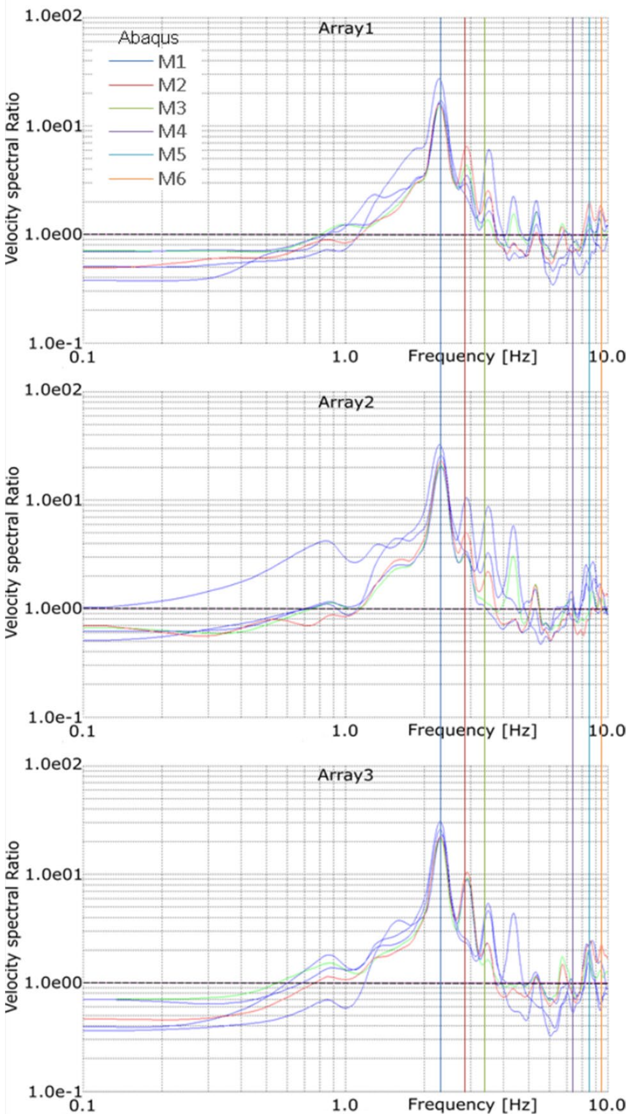


Fig. 5 Spectral ratios (H/V) of spectra of Fig. 4 vs. the Abaqus modes of vibration represented by vertical lines according to the Table 3

Table 1 Data processing results

Sensor	Fourier spectra		Spectral ratios
	Frequency (Hz)	Damping (%)	Frequency (Hz)
Array1			
H1	2.29 ± 0.02	4.81 ± 0.69	2.29 ± 0.03
H2	2.29 ± 0.03	4.81 ± 0.65	2.29 ± 0.03
H4	2.29 ± 0.02	4.26 ± 0.63	2.31 ± 0.03
H5	2.27 ± 0.01	4.30 ± 0.39	2.27 ± 0.02
Array2			
H1	2.29 ± 0.02	4.25 ± 0.28	2.32 ± 0.03
H5	2.27 ± 0.01	4.25 ± 0.41	2.32 ± 0.03
Array3			
H1	2.27 ± 0.01	4.30 ± 0.48	2.29 ± 0.13
H5	2.27 ± 0.01	4.30 ± 0.44	2.29 ± 0.03

indicated to pronounced frequencies in both longitudinal and transverse directions, where a sharp fundamental mode is recognizable at 2.27 Hz with a correspondent damping ratio of approximately 4.3%. The results of west and east wings agreed significantly (Table1). Moreover, it revealed relatively high (H/V) amplifications between 20 and 30 times (Fig. 5).

Numerical modeling

Numerical modeling of the structural features of this relatively complex and irregular building was considerably complicated and costly in terms of time and effort. Particularly, with the essential target of developing a general reliable calibrated nonlinear numerical model able to predict the realistic dynamic behavior of an old (RC) public buildings, and infrastructures that have been designed according to the old Syrian (non-seismic) building code. Abaqus (general purpose FEM software) has been used in this research to carry out modeling and analysis of the building. Abaqus was originally designed to run text input files (*.inp) containing the full description of the (FEM) model (called model data) and type of analysis along with the loading on the model (called history data). Furthermore, modern Abaqus has also a scripting interface for simplifying and increasing the productivity of modeling (Abaqus 2011). This interface is an extension of the Python object-oriented programming language and serves as a programming-based environment for creating all aspects of the model. A python module of MHE building ('3DBuildingTranlator.py' file) has been programmed using Abaqus scripting interface. This module can be run by Abaqus and reads the details of the building prepared in advance to create the model of the building. Abaqus/standard that depends on the finite element method was used in the analysis. Mesh size of 1 m for beam elements and shell edges has been used due to sensitivity analysis of several sizes. For MHE building as it consists of two symmetric east and west wings and central wing for elevators and stairs. The central wing is consistent with the modern code of earthquakes in Syria because all of the vertical supporting members are shear walls; therefore, no retrofitting was required. However, east and west wings are identical and the east one is chosen for modeling. Center-line dimensions are used in the model members, including beams, columns, etc. Self-weight, dead, and live loads are applied as masses distributed per area in accordance with the load's requirements in public office buildings (Syrian Seismic Code 2012). The nonlinear behavior of the concrete material has been modeled by using the Concrete Damaged Plasticity model (CDP) (Lubliner et al. 1989; Lee and Fenves 1998) for shell elements and elastic-perfectly plastic material for beam elements. Moreover, the elastic-perfectly plastic model has been adopted to simulating the steel behavior, the properties of materials have given in Table 2.

Table 2 Properties of the used materials (CEB FIP 2010)

Steel			Concrete		
f_y (MPa)	E_s (MPa)	ν	f'_c (MPa)	E_c (MPa)	ν
400	200,000	0.3	30	30,588.6	0.2

No rigid diaphragm hypothesis is considered for slab systems so that a more accurate 3D response is anticipated. Fixed boundary conditions at the base of columns and shear walls are assumed. Nonlinear geometry effects (P–Δ effect) are included in the analysis. Rigid coupling over the entire connection zone for the wireframe modeling approach at column-to-beam connection is used to reduce the error resulting from the flexure deformation of center-to-center

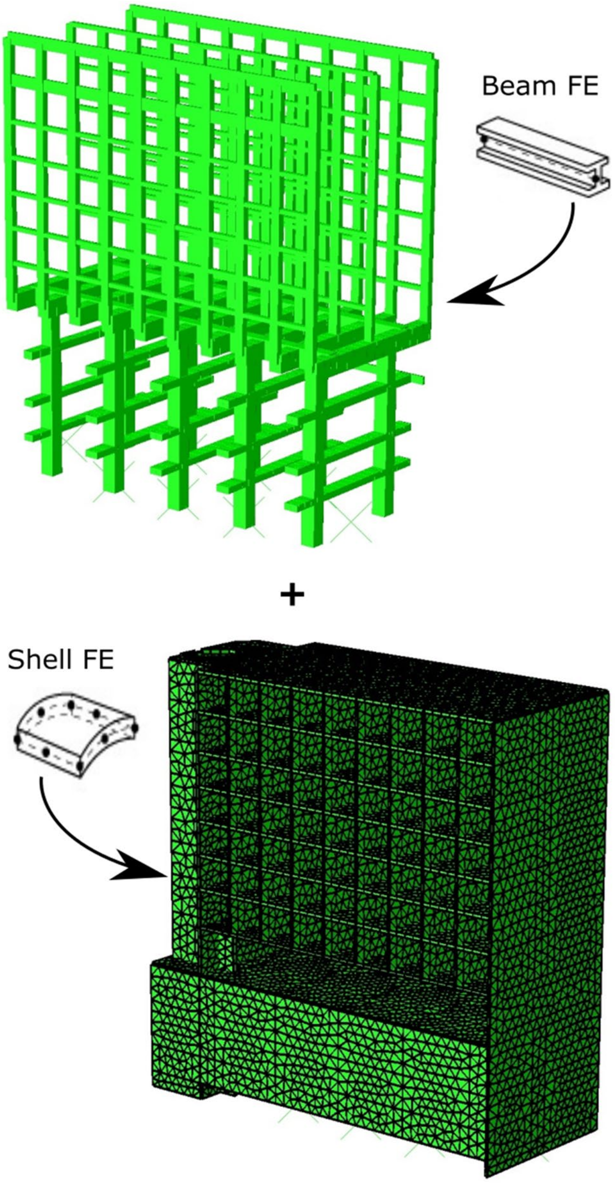


Fig. 6 3D Abaqus model of MHE building

modeling of the beam. The Abaqus model of MHE building wings consists of two parts: frames part and shells part (Fig. 6). The frames part includes the wire-like elements namely beams and columns of the frame system. This type of finite elements is B31 beam of Abaqus structural elements library. It has the most cost-effective adequate performance in large beam/column network systems for its low number of degree of freedom in the model as a whole.

The shells part includes the plate like slabs and walls of the model. For most of the applications large strain shell elements (S4R, S3R, and SAX1), are used in this model, where the S4R is a quadrilateral element for general-purpose applications, and S3R is a triangular element which may be suffering the shear-locking. Reinforcing is incorporated using rebar layers property of the shell section in Abaqus. A surface to surface and node to surface tie constraints are used between the members of the two parts of the model at intersecting regions to join the frame part with the shell part. A "proposed" 5% damping ratio is used in the model which reflects the results of experimental measurements previously reached and accorded with the recommendations for damping ratios in R/C buildings. The damping of the system could be assumed as Rayleigh damping (Chopra 2012), where:

$$C = \alpha M + \beta K, \tag{1}$$

$$\xi_{\mathrm{n}} = \frac{\alpha}{2}\frac{1}{\omega_{\mathrm{n}}} + \frac{\beta}{2}\omega_{\mathrm{n}}, \tag{2}$$

where C, M, and K are the damping, the mass, and the stiffness matrices, respectively. α, β are mass-proportional coefficient and stiffness proportional coefficient, respectively. ε_{m} is the damping ratio and ω_{n} is the natural frequency of the structure. As stiffness proportional damping is associated with high frequencies, the Rayleigh approach becomes questionable in the case of high P–Δ effect and/or significant material strength and stiffness deterioration (Alipour and Zareian 2008). An alternative procedure could be the only use of mass-proportional damping:

$$C = \alpha M, \tag{3}$$

$$\xi_{\mathrm{n}} = \frac{\alpha}{2}\frac{1}{\omega_{\mathrm{n}}}. \tag{4}$$

The coefficient of mass-proportional damping α has to be calculated by:

$$\alpha = 2 \times \omega_{\mathrm{n}} \times \xi_{\mathrm{n}}, \tag{5}$$

where the value of ω_{n} can be extracted from the frequency analysis of the model, performed by Abaqus. Earthquake loading was applied on the east wing of the building model by enforcing foundations of the walls and columns to shake under acceleration records see Fig. 7.

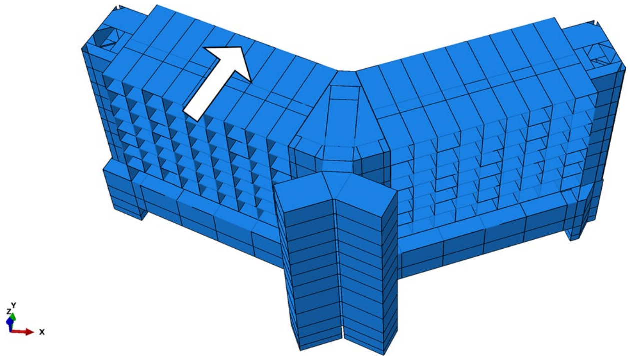


Fig. 7 Direction of earthquake at East wing only

Results and discussion

Natural frequency analysis

Identification of the real dynamic performance of the MHE building under seismic loads requires the characterization of the natural frequencies and the corresponding mode shapes of the structural system. Despite the fact that the partition walls are not a part of the supporting structural system, but they increase the lateral stiffness of the building, they have an effective role in natural frequency analysis (Poovarodom and Charoenpong 2008). Therefore, the partition walls should not be neglected in this analysis. These wall's behavior was assigned to have concrete behavior model-like brittle material model with the strength of $f_{\mathrm{c}} = 7$ MPa. Lanczos method has been used in the frequency analysis. This method is based on a rational hypothesis of requested frequencies varies between an upper limiting cutoff frequency of 33 Hz; down to the lower limiting frequency of 0.33 Hz (Abaqus, 2011). Accordingly, 66 modes have been obtained from the analysis with a total effective mass in *X*, *Y*, and Z directions of 17,345 tons (94% of the total mass of the model), 17,205 tons (93%), and 15,424 tons (83%), respectively. The characteristics of the first 6 modes are of special interest (Chopra 2012) (Fig. 8). These modes of vibration were compared with the obtained frequencies from the ambient noise measurements. As the MHE building not considered as high-rise building, the high-frequency modes should not have a significant role. Therefore, the focus is particularly on the first mode affecting the building in the *Y*-direction. If a strong earthquake occurs in this direction, it is anticipated that the most severe consequences would occur. A good agreement is noted between the results of numerical frequency analyses and the (*H*/*V*) spectral ratios

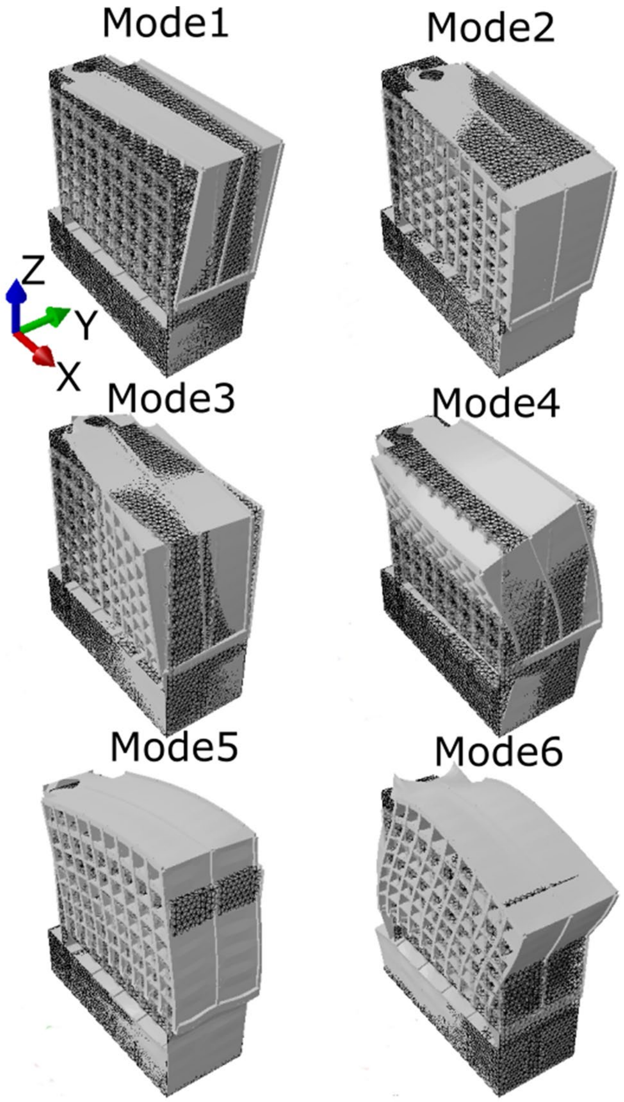


Fig. 8 Natural frequency analysis mode shapes of MHE building by Abaqus

of ambient noise measurements for both the resonance dominant frequencies at approximately 2.3 Hz, and notably for the fundamental frequency (Fig. 5). This indicates that numerical modeling has considerable credibility precisely for the linear response of the model. In natural frequency analysis, the eigenvalue frequency and direction of every mode have been reported in the output results. The data for the six initial modes of the frequency analysis of the model are presented in Table 3.

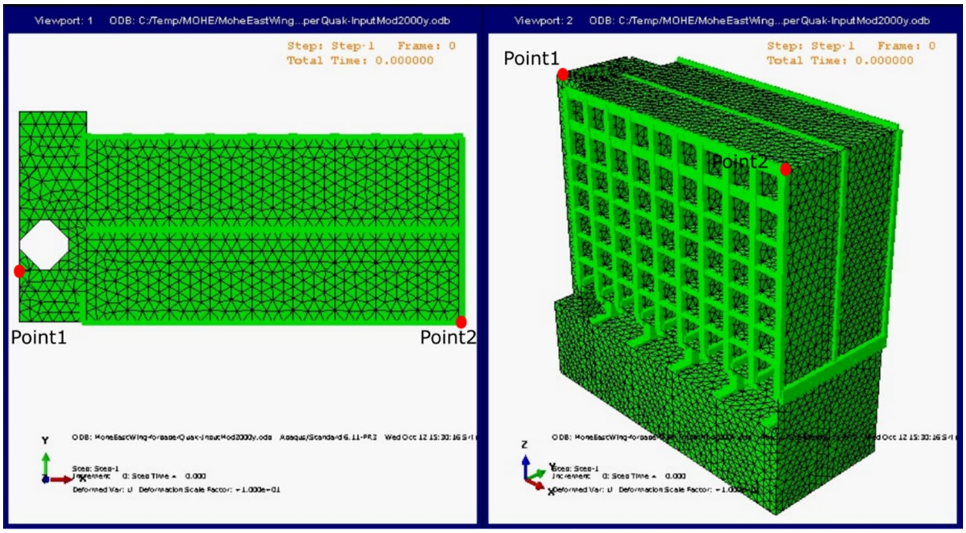
Table 3 Initial modes of frequency

Mode	Eigen value	Frequency (Hz)	Direction
1	210.04	2.31	*Y*
2	317.04	2.83	*X*
3	449.44	3.37	*Y*
4	2124.1	7.34	*Y*
5	2801.2	8.42	*Z*
6	3502.3	9.41	*Z*

Nonlinear time-history analysis

As the model's frequency analysis has shown a good agreement with the experimental dynamic characterization of the building, therefore, the dynamic time-history nonlinear analysis could probably produce relatively accurate results under earthquake excitation, which is crucial in predicting the real dynamic behavior of the structure in various configurations and under several earthquake time histories. Following the seismic rehabilitation carried out on the MHE building in 2001, the east and west wings lost their symmetry in plan-view about *Y*-axis. Consequently, the time-history analysis is aimed to foresee the effect of such irregularity on the building's performance during a strong earthquake. Moreover, further dynamic properties investigations can be pursued, which might incorporate the nonlinear behavior of the structure. In this analysis, three earthquake acceleration time histories of increasing return period of 475 years "Rare", 975 years "Very Rare", and 2000 years have been used. These earthquakes, with different intensities, have to be considered in "Life Safety" and "Collapse Prevention" performance levels (FEMA-273 1998). The seismic loadings were applied in the direction of the first mode of vibration (Fig. 7). Figure 8 illustrates the first 6 modes of vibration that were obtained through frequency analysis. Accordingly, the incited velocities were in the same *Y*-direction. The velocities at two opposite points at the roof (Fig. 9) demonstrate the negative impact of the executed rehabilitation on the seismic performance of the MHE building. Moreover, the dominant frequencies (F1 = 3.36 Hz, F2 = 2.36 Hz, and F3 = 1.84 Hz) in Fourier analysis (Fig. 10) affirm the unsymmetrical effect of the executed rehabilitation on the seismic performance of the building. The frequency of point 2 ($F = 2.36$ Hz) almost agrees with the *Y*-direction dominant frequency obtained from frequency analysis and experimental measurements. While for point 1, situated at the shear walls–slabs system roof, other frequencies of ($F = 1.84$ Hz and $F = 3.36$ Hz) have appeared. This might be attributed to the unequal stiffness at the opposite sides of the building after rehabilitation. This lack of regularity has caused the torsional movement response of the east wing under earthquake motion. The torsional movement takes place around the stiffer side of the east wing along *X*-axis during earthquake vibration. This might be due to the lack of full understanding of the expected response of the east wing, and the lack of advanced dynamic time-history

Fig. 9 Observed points under nonlinear time-history analysis of 3D building



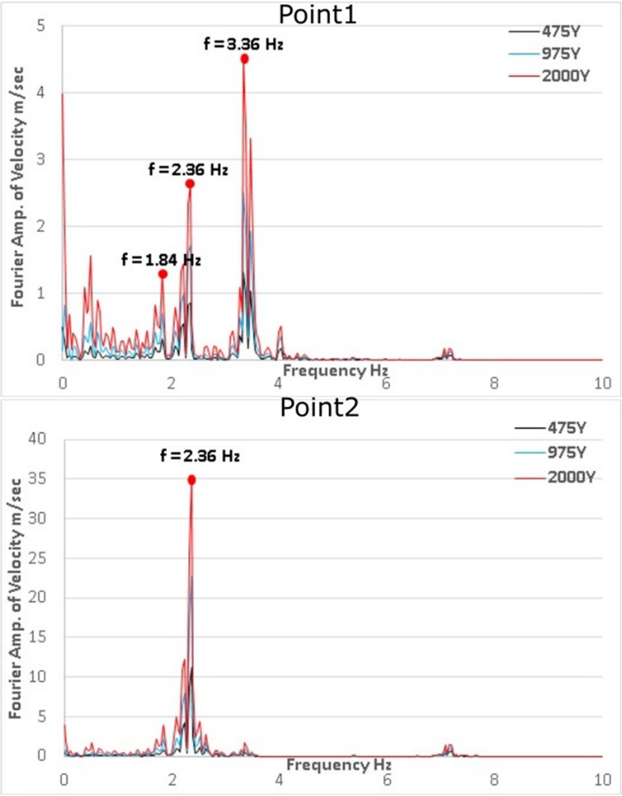


Fig. 10 Fouier transformations of velocities from time-history analysis

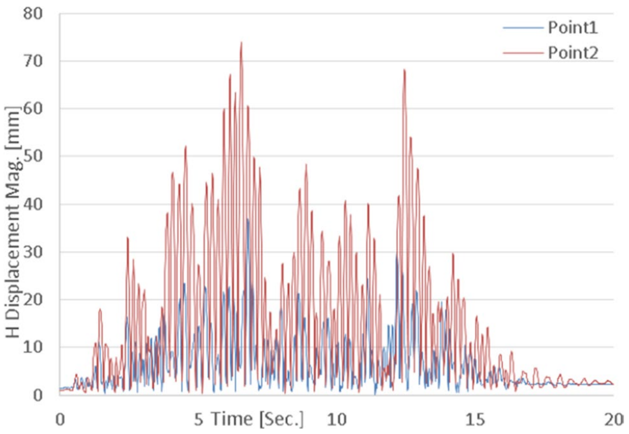


Fig. 11 Horizontal displacement magnitude during earthquake shaking of building

analysis at the time of designing and executing the seismic rehabilitation in Syria. A sort of irregularity in the plan-view of the building lead to unexpected response. The horizontal displacements for the two observed points under 2000 year return period earthquake are investigated (Fig. 11). The horizontal displacement magnitudes at every time increment are considerably larger at the side of point 2 of those at point 1. In addition, the added walls near point 2 suffered the largest amount of accumulated plastic strain when compared with the walls near point1. This is true also for the slender columns at upper stories where the magnitude of rotation increases.

Conclusion

In this study, the dynamic behavior of MHE reinforced concrete building was investigated using ambient vibration measurements and numerical modeling. Dynamic characteristics of the building were determined using the ambient vibration measurements recorded in each horizontal and vertical seismometers distributed throughout the top floor. A 3D thorough finite element model of the building was also programmed by the use of the python module in the

(FEM) software Abaqus to compare the model properties of the building to the identified counterparts measured from ambient vibration experiments. Furthermore, the aforementioned detailed 3D finite element model has been developed by consecutive enhancements to set up a reliable, efficient, and detailed methodology to assess the real dynamic performance of the RC vital structures. The results can be summarized in these interesting points:

1. The natural frequency and mode shape values extracted from the numerical model and the ambient vibrations measurements have agreed significantly which emphasizes their capability on identification of the real dynamic performance of the RC MHE building. For Mode 1 of vibration, the difference between measured and simulated results did not exceed 1%.
2. The east and west wings of the MHE building have lost their symmetry in plan-view about *Y*-axis due to the inefficient seismic rehabilitation works executed in 2001, which could trigger a rotational movement and consequently additional stresses/strains in the building. For analysis under earthquake excitation about *X*-axis, the columns and wall members at − 3 story did not develop plastic deformation; while for analysis about *Y*-axis, they did.
3. Finally, slight differences in predicted frequencies have been observed between the nonlinear numerical analysis and the experimental results, which could be attributed to overlooking the soil–structure interaction effect in the numerical model.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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