Operational Modal Analysis and Finite Element Model Updating of a 53-Story Building

Onur Avci, Khalid Alkhamis, Osama Abdeljaber, and Mohammed Hussein

Abstract This paper presents Operational Modal Analysis (OMA) and Finite Element (FE) model updating of a tall structure. Located in the West Bay area of Doha (Qatar), the structure was constructed between 2012 and 2016. It is a reinforced concrete building with shear wall cores located towards the center of the building plan. With 53 stories above the ground and 2 stories below ground, the 230 m (755 ft) tall building is being used for residential and hotel purposes. The material presented here is arguably the first published work on large-scale dynamic testing of a civil structure in Qatar. The wireless sensors used for testing are state-of-the-art equipment that can capture very low frequencies, something that cannot be accomplished with most of the conventional accelerometers available in the market.

Keywords Operational modal analysis · Finite element modeling · Structural dynamics · Tall structures · Model updating

1 Introduction

Operational Modal Analysis (OMA) and Finite Element (FE) model updating of a 53-story tower are presented in this paper. The structure was constructed between 2012 and 2016 and it is one of the tallest buildings in Qatar (Fig. 1a). The lateral load resisting system of the structure is concrete shear walls connected to reinforced concrete columns placed along the perimeter of the building with beams (Fig. 1b). The building has 53 stories above ground and 2 stories below ground, and it is being used for residential and hotel purposes. The building is 230 m (755 ft) tall. While this work is arguably the first published work on large-scale dynamic testing of a civil structure in Qatar, the wireless sensors used in this OMA work are state-of-the-art accelerometers sensitive enough to capture very low frequency modes of the structure. When the authors initially attempt to use standard wired sensors, it was realized that the conventional accelerometers which were successfully used in laboratory environment were not able to recognize the modal properties of lower frequency modes of the tower.

Basically, OMA is simply a modal testing method through which the dynamic characteristics of a structure is estimated based on the dynamic response under the ambient conditions [1–6]. This means the ambient forces and excitations the structure is subjected to during the operational use (wind, earthquake, traffic, machinery, human-excitations) are contributing to the analysis. The OMA methodology is often referred to as “ambient vibration modal identification” or “output-only modal analysis” by researchers [7–11]. Large structures like civil engineering infrastructure have been a good match for OMA use since it would be more difficult to excite a massive civil structure with artificial dynamic loading, than a much smaller laboratory structure. Therefore, the “output-only” component of OMA fits well for large structures. Researchers and engineers have been using the procedures developed for structural damage detection (SDD) and structural health monitoring (SHM) in OMA applications [12–17]. OMA results have always been found useful to verify the results of the computerized

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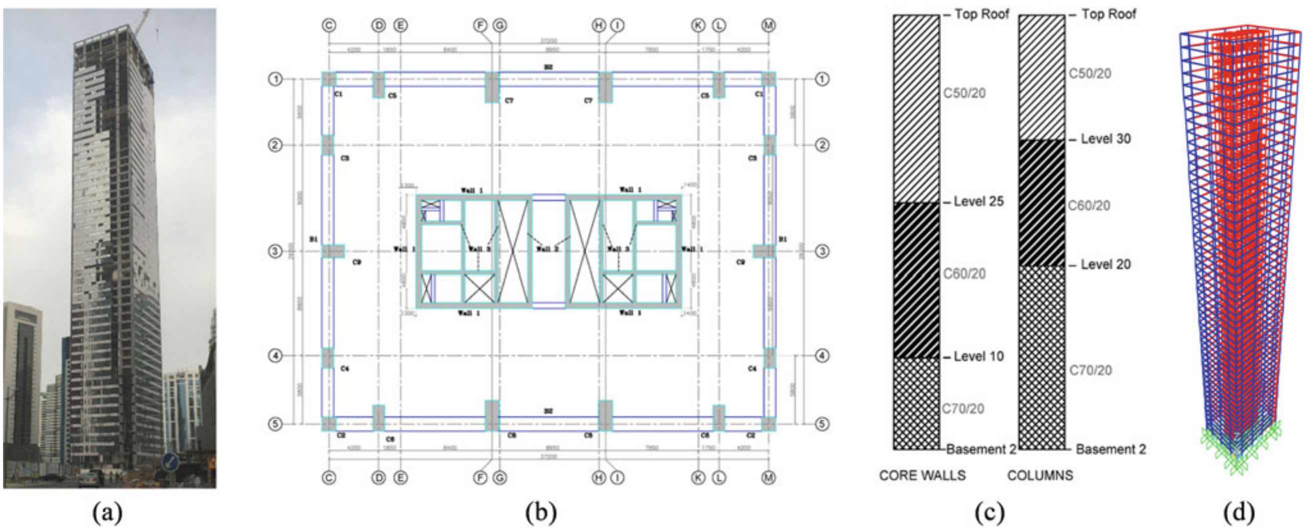


Fig. 1 (**a**) Tower structure; (**b**) typical plan view; (**c**) variation of concrete strength along the height; (**d**) 3D FE model

simulations since the modal characteristics obtained from FE models are methodological procedures full of approximations based on the geometry of structural members, assumed material properties, and eigenvector analysis. Yet, in civil engineering applications, it is not easy to create a perfect FE model that can successfully predict all aspects of static and dynamic characteristics of a structure [18–21] since the overall structural behavior is a function of combination many parameters, assumptions, and interactions (e.g., member-to-member connections, structural mass, amplitude-dependent damping, creep-shrinkage effects, stiffness of cladding and/or façade elements, non-structural components, soil-structure interaction) [22–25]. The OMA results are not only compared to the Finite Element (FE) model results, but they are also being used in updating the FE models of structures. On another note, it is known that dynamic excitations applied at or around the modal frequencies have increasing effect of dynamic loads applied on the structures which are causing discomfort for the tenants and structural damage to the buildings. Therefore, monitoring and keeping track of variations on the dynamic properties of structures through OMA is valuable and pertinent for life-cycle assessment and structural integrity of civil infrastructure [26–31]. OMA results have also been reported to be utilized at various stages of construction to monitor and verify the performance, requirements, and assumptions at the site.

All elevated floors of the tested building are 300 mm thick flat slabs with drop panels. Floor-to-floor height is typically 3.5 m for all levels except the lobby and mechanical floors. The lateral load resisting elements (columns and shear walls) are connected to each other with beams varying in size (1.20 m × 0.45 m) and (1.00 m × 0.45 m) to create a diaphragm effect. During the OMA procedures, the building was still under construction with 90% of the work had been completed. Different grades and strength of concrete were used throughout the height of the tower for both core walls and columns (Fig. 1c), which is reflected in the FE model (Fig. 1d). Eigenvector analysis was chosen in the commercial FE software package, and first ten modes are targeted to be studied and then compared to the OMA procedures. The first ten modes predicted by the FE model are shown in Fig. 2.

2 Operational Modal Analysis

For the 53-story high structure, to capture the modes below 0.5–0.6 Hz range, ten TROMINO wireless sensors were used for data collection. In wireless sensor networks, time synchronization demands specific solutions whereas it is a standard task for wired sensors. Each node in wireless sensor networks has its own analog-to-digital (ADC) converter. The performance of the sensors used in this study had already been verified on various other OMA projects on large civil infrastructure. The sensor uses three channels each assigned for three orthogonal directions. Data was collected for a period of 90 min at a rate of 128 samples per second. First and last 10 min were removed from the 90 min to focus on the data collected in the middle chunk of the recordings. Two sensors were placed on the opposite corners of the instrumented floors. The instrumented floors were the 1st, 13th, 25th, 37th, and the 48th levels (a total of five levels on the tower) as shown in Fig. 3a. The first reference sensor was placed on the first floor. All collected data was uploaded to MEScope software to extract modal features. A sample data

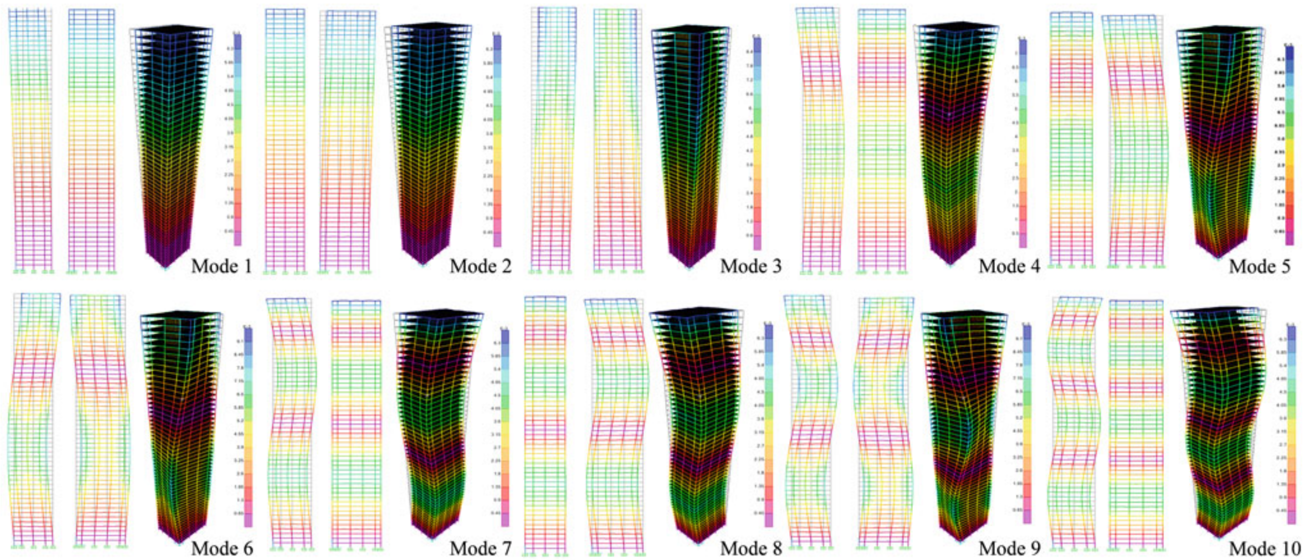


Fig. 2 First ten mode shapes predicted by the FE model

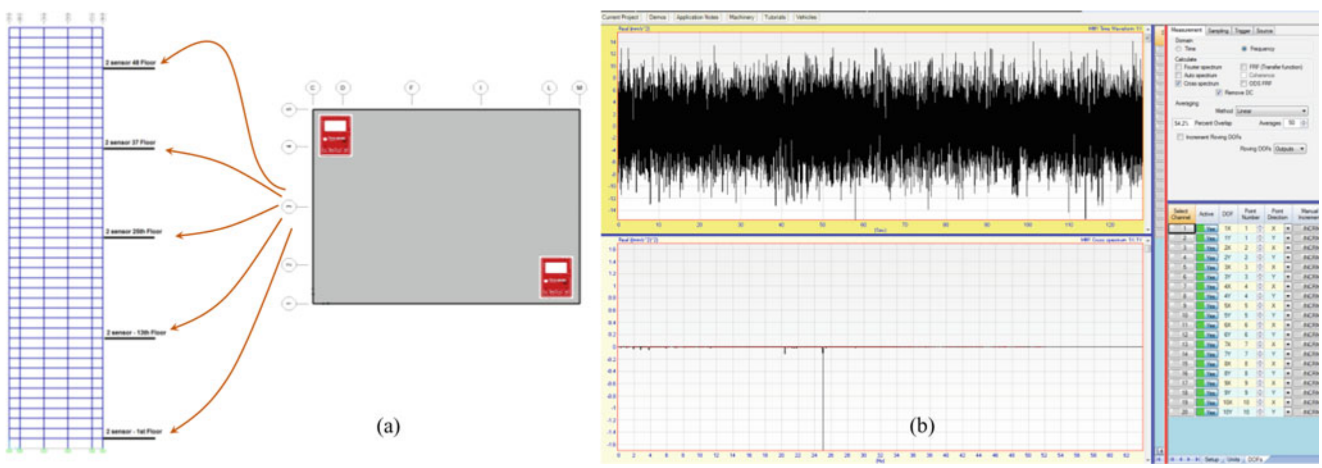


Fig. 3 (**a**) Sensor placement at five levels; (**b**) sample data acquisition window in MEScope

acquisition window is shown in Fig. 3b. Sample power spectral density windows captured in MEScope are shown in Fig. 4. The curve fitted mode shapes, mode descriptions, modal damping ratios, and modal frequencies per MEScope analysis are presented in Fig. 5.

3 Finite Element Model Updating

After the OMA procedures, natural frequencies obtained from OMA are compared to the FE natural frequency predictions. The error between the two are calculated and presented in Table 1. It is noted that the average absolute error is 15.3%, and when the torsional modes (modes 3, 6, and 9) are excluded, the average absolute error is 15.5% for the remaining modes. The Modal Assurance Criterion (MAC) plot is also presented in Table 1. The MAC is commonly used as a statistical indicator by researchers and practitioners. It is used simply to determine the similarity of two mode shapes. It is reported to be sensitive to relatively larger variations, and partially insensitive to relatively smaller variations in mode shapes [32–37]. Based on the MAC plot in Table 1, it is observed that the correlation for modes 3, 7, 8, and 10 needs improvement. Therefore, it is decided that the FE model is updated in an attempt to improve the correlation between the OMA and FE model natural frequencies. Updating FE models has been discussed extensively in the literature, and modifications on various parameters such as mass,

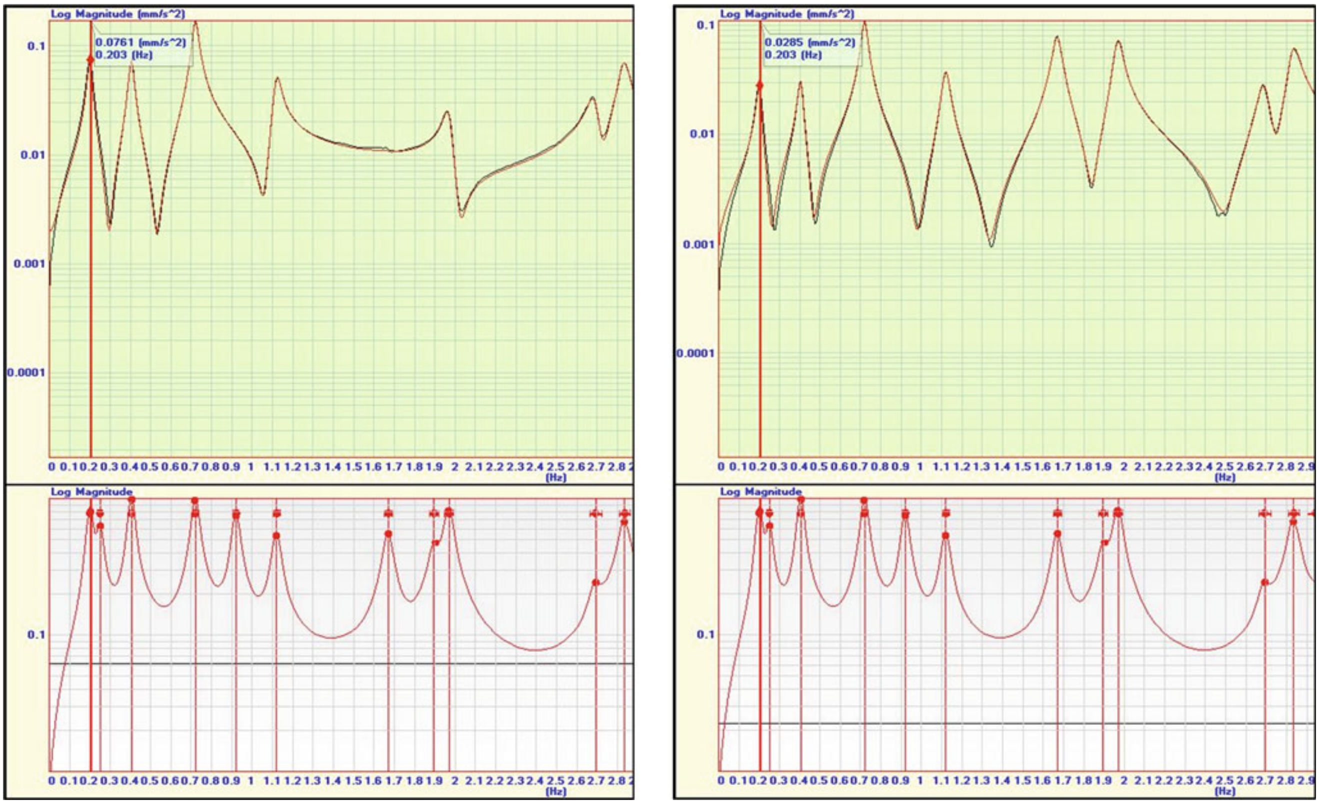
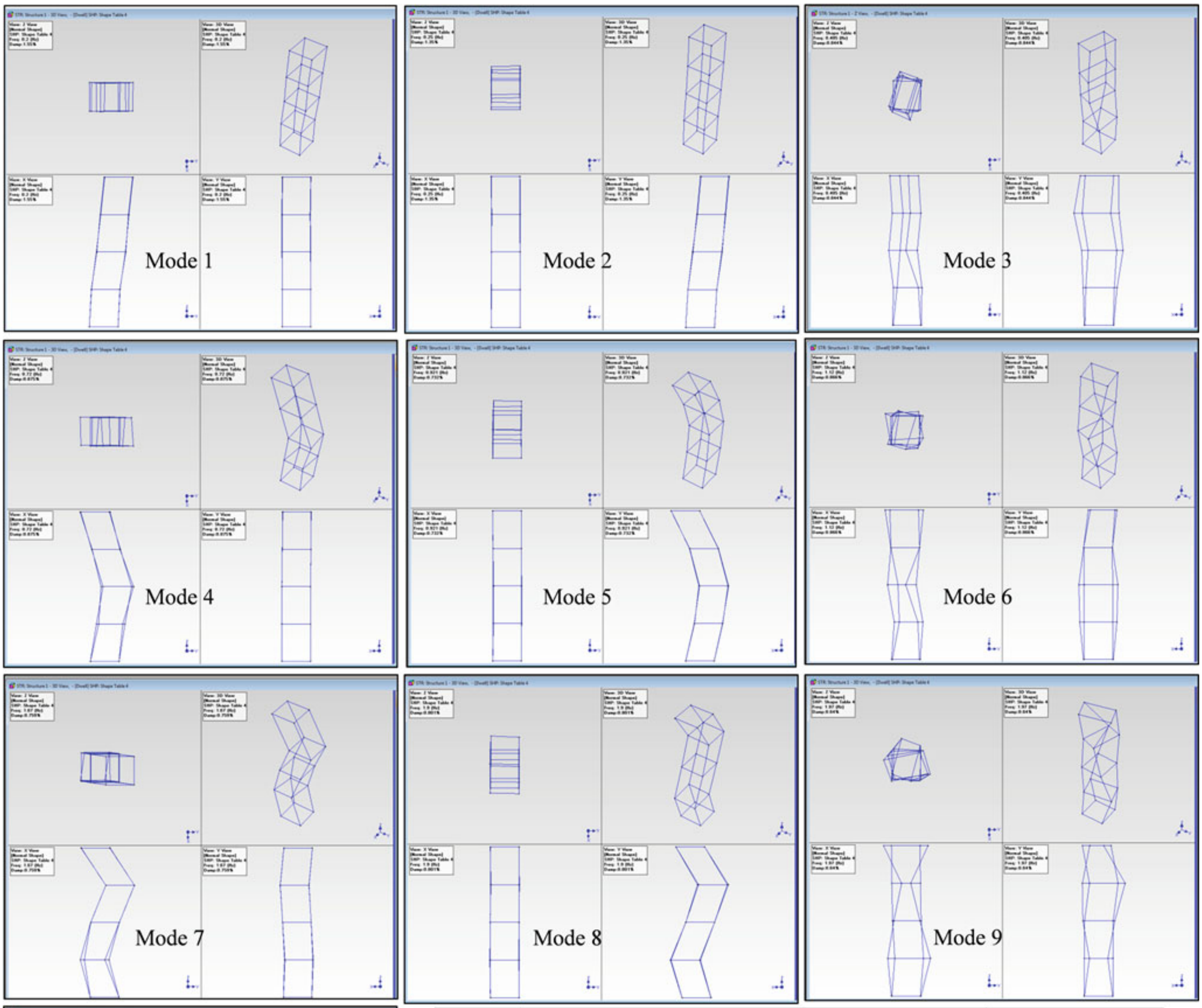


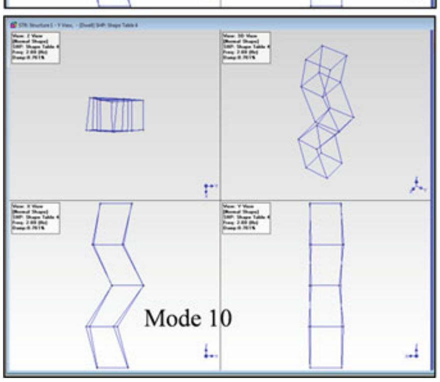
Fig. 4 Power Spectral Density windows in MEScope

elastic modulus, moment of inertia, fixities, cracked sections, and loads on the FE models are accepted ways of approaching the measured structural parameters [38–46]. In experimental testing, regardless of static and dynamic properties, the FE models are calibrated with the measured results collected on the actual structures [47–55]. The first attempt of updating the FE model here in this work was decreasing the self-weight of the building. A drastic decrease of 42% is applied on the concrete mass to observe the outcome, and the resulting (updated) FEM-predicted frequencies and the corresponding MAC plot are presented in Table 2. With this FE model, it is noted that the average absolute error is 10.4%, and when the torsional modes (modes 3, 6, and 9) are excluded, the average absolute error is 5.9% for the remaining modes. While there are enhancements on the MAC plot on Table 2 when compared to Table 1, it is decided that the FE model is updated again, to see the effect of changes on the modulus of elasticity. Therefore, this time the elastic modulus is increased drastically (70%) to observe the outcome. The resulting (updated) FEM-predicted frequencies and the corresponding MAC plot are shown in Table 3. Again, there are improvements observed on the MAC plot on Table 3. With this FE model, it is noted that the average absolute error is 9.5%, and when the torsional modes (modes 3, 6, and 9) are excluded, the average absolute error is 5.8% for the remaining modes. The FE model is then updated with modifications on both mass and elastic modulus, simultaneously. This time the update is done by relatively reasonable numbers: 22% decrease in mass and 25% increase in elastic modulus. In addition to these modifications in the mass and elastic modulus, for this FE model update, the torsional fixities of the columns and walls are decreased by 50%. The updated results are presented in Table 4. Based on these changes on the FE model, it is observed that the MAC plot is further improved; the average absolute error has come down to 7.7%, and when the torsional modes (modes 3, 6, and 9) are excluded, the average absolute error has come down all the way to 5.1% for the remaining modes.

4 Conclusions

In this paper, Operational Modal Analysis (OMA) and Finite Element (FE) model updating of a 53-story structure in Qatar is presented. The 230 m tall structure was tested with wireless sensors. Focusing on the first ten modes of the structure, OMA procedures were completed. Meanwhile, natural frequencies of the structure were predicted with a commercial finite





Mode number	Mode description	OMA measured frequency (Hz)	OMA measured damping ratio (%)
1	Translation in E-W direction	0.200	1.550
2	Translation in N-S direction	0.250	1.350
3	Torsional	0.405	0.844
4	Translation in E-W direction	0.720	0.875
5	Translation in N-S direction	0.921	0.732
6	Torsional	1.120	0.866
7	Translation in E-W direction	1.670	0.759
8	Translation in N-S direction	1.900	0.801
9	Torsional	1.970	0.640
10	Translation in E-W direction	2.690	0.761

Fig. 5 MEScope results for mode descriptions, mode shapes, modal frequencies, modal damping ratios

element modeling software. Since the resulting Modal Assurance Criterion (MAC) plot needed improvement, the FE model was updated/calibrated several times by decreasing the mass, increasing the elastic modulus, and partially releasing the torsional restraint on columns and walls. With each FE model update, it is observed that the MAC plots were improved, and the errors between the measured and predicted frequencies decreased. As such, a successful FE model updating procedure has been demonstrated. It is also important to note that the work presented here is arguably the first published work on large-scale dynamic testing of a civil infrastructure in Qatar.

Table 1 Measured and FEM-predicted natural frequencies

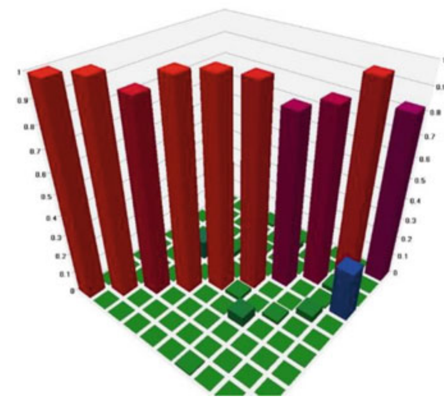
Mode number	FEM Predicted Frequency (Hz)	OMA Measured Frequency (Hz)	Error (%)	Modal Assurance Criterion (MAC) Plot
1	0.1504	0.2000	-24.8	
2	0.2062	0.2500	-17.5	
3	0.4724	0.4050	16.6	
4	0.6059	0.7200	-15.8	
5	0.7501	0.9210	-18.6	
6	1.2939	1.1200	15.5	
7	1.4357	1.6700	-14.0	
8	1.6165	1.9000	-14.9	
9	2.2104	1.9700	12.2	
10	2.6090	2.6900	-3.0	
Average absolute error (%)			15.3	
Average abs. error excluding torsional modes (%)			15.5	

Table 2 Measured and updated FEM-predicted natural frequencies (decrease in mass)

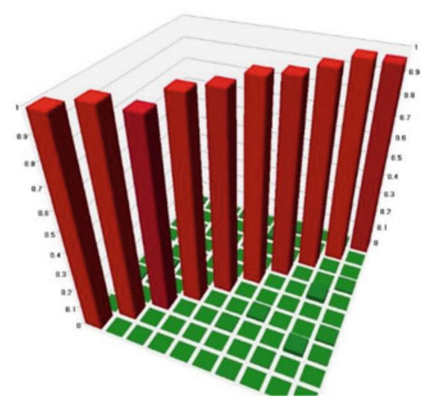
Mode number	FEM Predicted Frequency per model update (modified mass)	OMA Measured Frequency (Hz)	Error (%)	Modal Assurance Criterion (MAC) Plot
1	0.2009	0.2000	0.4	
2	0.2555	0.2500	2.2	
3	0.5232	0.4050	29.2	
4	0.7535	0.7200	4.7	
5	0.9877	0.9210	7.2	
6	1.3288	1.1200	18.6	
7	1.8112	1.6700	8.5	
8	2.0745	1.9000	9.2	
9	2.2532	1.9700	14.4	
10	2.9422	2.6900	9.4	
Average absolute error (%)			10.4	
Average abs. error excluding torsional modes (%)			5.9	

Table 3 Measured and updated FEM-predicted natural frequencies (decrease in mass)

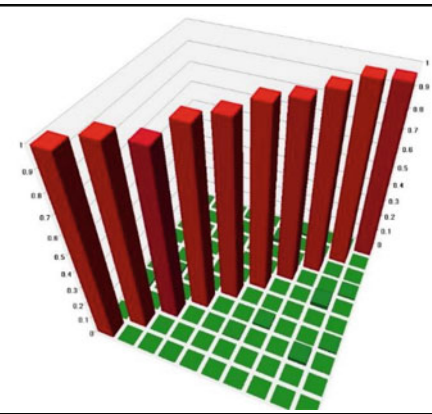
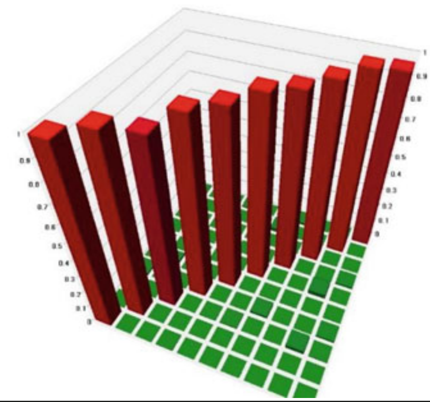
Mode number	FEM Predicted Frequency per model update (Modified elastic modulus)	OMA Measured Frequency (Hz)	Error (%)	Modal Assurance Criterion (MAC) Plot
1	0.1961	0.2000	-2.0	
2	0.2588	0.2500	3.5	
3	0.5010	0.4050	23.7	
4	0.7550	0.7200	4.9	
5	0.9780	0.9210	6.2	
6	1.3170	1.1200	17.6	
7	1.7920	1.6700	7.3	
8	2.0866	1.9000	9.8	
9	2.2321	1.9700	13.3	
10	2.8785	2.6900	7.0	
Average absolute error (%)			9.5	
Average abs. error excluding torsional modes (%)			5.8	

Table 4 Measured and updated FEM-predicted natural frequencies (decrease in mass + increase in elastic modulus + partial torsional release on columns and walls)

Mode number	FEM Predicted Frequency per model update (Modified mass and elastic modulus)	OMA Measured Frequency (Hz)	Error (%)	Modal Assurance Criterion (MAC) Plot
1	0.1865	0.2000	-6.8	
2	0.2434	0.2500	-2.6	
3	0.4713	0.4050	16.4	
4	0.7350	0.7200	2.1	
5	0.9730	0.9210	5.6	
6	1.2758	1.1200	13.9	
7	1.7559	1.6700	5.1	
8	2.0142	1.9000	6.0	
9	2.1841	1.9700	10.9	
10	2.8891	2.6900	7.4	
Average absolute error (%)			7.7	
Average abs. error excluding torsional modes (%)			5.1	

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