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Dynamic behavior investigation of scale building renovated by repair mortar

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Abstract. The objective of this study was to examine the effect of repair mortar on the dynamic properties such as natural frequencies, mode shape and damping ratios of two story single span scale reinforced concrete building. To this end, two story single span scale reinforced concrete building having dimensions of 150 cm (width), 150 cm (length) and 135 cm (height) was constructed. Workmanship defects such as separation of material, faulty vibration application and bad gradation of the structure were properly evaluated. Dynamic properties of damaged structure were experimentally determined using Operational Modal Analysis (OMA). Detected defects in the structure were fixed by plastering with repair mortar. Dynamic properties of repaired structure were reevaluated by using the OMA method. Finite element software called Abaqus was used to numerically determine dynamic properties of the structure. Structure modeled as solid was subjected to Linear Perturbation Frequency Method. The changes in dynamic properties of structure after the repair process were comparatively studied by evaluating experimental and numerical results.

Keywords: dynamic properties; operational modal analysis; abaqus; concrete building; repair

1. Introduction

Concrete gaps are one of the main workmanship defects observed in concrete buildings. These defects may be attributed to separation of material, faulty vibration application, bad gradation and pouring concrete from too high location. Moreover, concrete gaps may originate from punctures and breaks in certain areas of structural elements. Commercial repair mortars are frequently used in filling and plastering concrete gaps. However, there have been controversial ideas as to how these structures are repaired and what kind of materials is used (Can and Tankut 1989, Can and Tankut 1991). The main purpose of the repair is to enable the structure to retain its original shape. Therefore, workmanship defects observed in these structures and changes in the dynamic properties of the structure due to repair must be closely followed (Demir 1999, Öztürk and Kocabeyler 1993). Fig. 1 shows concrete gaps, which may occur in concrete buildings and the way of fixing these gaps.

Dynamic analyses of structures are very complex. Moreover, since parameters affecting dynamic behavior are not definitive, realistic determination of dynamic behavior is very difficult.

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Fig. 1 Gaps of reinforced concrete structure elements renovated by repair mortar

By defining dynamic behavior of structural systems more realistically, we may be able to find exact solutions. Thus, natural frequencies, modal shapes and damping ratios called dynamic properties of structures need to be experimentally determined enabling to reach more realistic description of dynamic behavior of these structures. By evaluating modal behavior of a structure, rigidity distribution and the presence or absence of torsional disturbance can be obtained. All these reasons can lead to a conclusion that vibration tests are very much needed in accurately determining dynamic behavior of structures (Morgan and Oesterle 2013, Bayraktar *et al.* 2010). Moreover, by using dynamic parameters, the location and level of damage can be estimated. In fact, the evaluation of the dynamic parameters is not exhaustive, a subsequent update of the numerical model is required in order to match the experimental results. This model can then be used to perform, for example, seismic analysis. Some examples of such procedure can be find in the references (Betti *et al.* 2011, Diaferio 2015, Oliveira *et al.* 2012, Diaferio *et al.* 2014, Ramos *et al.* 2010, Diaferio *et al.* 2007, Tomaszewska and Szymczak 2012, Diaferio *et al.* 2014).

Damage detection methods can be studied under four different categories based on their level of development. They are as follows:

1) Methods detecting the presence of damage
2) Methods detecting the location of damage
3) Methods detecting the level of damage
4) Methods detecting the life span of the damaged structure

Methods detecting the presence of damage cannot be used in determining the location and level of damage, which can be done by method #2 listed above. Methods listed above as #3 can detect not only the location, but also the level of damage. To determine the life span of the damaged structure, methods listed above as #4 are employed (Park 1997). To detect structural damages by using natural frequencies, the change in natural frequencies of the structure should not exceed 5%. However, uncontrolled environmental effects, temperature fluctuations and changes in frequencies due to instantaneous loading should be regarded as damages (Aktan *et al.* 1994). Some studies regarding the damage detection techniques are available (Salawu 1997, Moaveni *et al.* 2009, Amani *et al.* 2007).

Currently, experimental modal analysis and operational modal analysis have been widely employed in determining dynamic parameters of structures or objects. To get acceleration values, vibration must be applied to structures in experimental modal analysis. This is very difficult especially for large structures. Therefore, operational modal analysis has received more attention. In this analysis, vibrations in structures caused by environmental effects were recorded by accelerometers and dynamic parameters were obtained by analyzing these records (Aras *et al.* 2011, Altunışık *et al.* 2011, Foti *et al.* 2012, Foti 2013, Foti *et al.* 2014, Osmancılı *et al.* 2012, Júlio *et al.* 2008, Bartoli *et al.* 2013, Gentile and Saisi 2013, Gattuli 2013, Giraldo 2009). There have been several recent studies on the use of OMA in determining dynamic properties of engineering structures (Ventura *et al.* 2002, Kohler *et al.* 2005, Ren *et al.* 2004, Zivanovic *et al.* 2007, Wang and Li 2007, Oliveira and Faria 2006, Dooms *et al.* 2006, Reynolds *et al.* 2004, Gentile and Saisi 2007, Mamaghani 2006, Ceballos *et al.* 1998). In theoretical analysis of structures, loads taken into account are earthquake, wind and snow. Structures are designed to be resistant to these loads. However, most of the structures are damaged, or even destroyed by external effects. This damaged may be caused by workmanship defects, cracks, fatigue and support collapse due to extensive loading on the structure (Bayraktar *et al.* 2007).

Two story, single span scale reinforced concrete building was constructed in this study. Concrete cracks in the structure caused by workmanship defects were repaired with repair mortar. The effect of this repair on the dynamic behavior of structure was experimentally determined using OMA. Dynamic behavior of structure was also numerically evaluated using Abaqus finite element software. Numerical and experimental results were compared.

2. Material and methods

2.1 Operational modal analysis

Two types of modal analysis method are currently employed to determine dynamic parameters of the structures in solving engineering problems. These are Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). EMA is used to validate numerical analysis. However, EMA cannot be applied to very large structures such as bridges and buildings. Therefore, the focus has been shifted to the use of OMA. In the OMA method, vibrations caused by external effects were recorded by accelerometers and dynamic modal parameters were determined by analyzing results. OMA is a special modal analysis method and is applied by collecting real time data from the structure. Effects needed for OMA are external factors such as vehicle load, wind and machine vibration (Nohutcu *et al.* 2015). Modal parameters are obtained from experimental modal analysis utilizing different algorithms since environmental effects cannot be explicitly determined. A widely- cited technique called “The Stochastic Subspace Identification (SSI) technique” has been employed in this study.

SSI describing modal parameters through measured raw time responses is a parametric model. SSI is an output only time domain method that directly works with time data, without the need to convert them to correlations or spectra. The model of vibration structures can be defined by a set of linear, constant coefficient and second order differential equations.

$$\mathrm{M\ddot{U}(t) + C_2\dot{U}(t) + KU(t) = F(t) = B_2u(t)} \tag{1}$$

where M, C_2, K are the mass, damping and stiffness matrices, $F(t)$ is the excitation force and $u(t)$ is the displacement vector depending on time t. Observe that the force vector $F(t)$ is factorized into a matrix B_2 describing the inputs in space and a vector $u(t)$. Although Eq. (1) represents quite closely the true behavior of a vibrating structure, it is not directly used in SSI methods. So, the equation of dynamic Eq. (1) will be converted to a more suitable form: the discrete-time stochastic state-space model (Peeters 2000, Bayraktar *et al.* 2010). SSI method estimates both harmonic components and structural modes and is based upon the stochastic state space model described by

$$\begin{aligned} x_{t+1} &= [A]x_t + w_t \\ y_t &= [C]x_t + v_t \end{aligned} \tag{2}$$

where x_t is the state vector at time t, $[A]$ is the state matrix, y_t is the response vector at time t, and $[C]$ is the observation matrix. The natural frequencies and damping ratios can indirectly be obtained from state matrix A and the mode shapes from the observation matrix C. The response is generated by two stochastic processes w_t and v_t called the process noise and the measurement noise respectively. The technique is presented detail in the literature (Van Overschee and De Moor 1996, Peeters 2000, Peeters and De Roeck 1999, Bayraktar *et al.* 2009).

2.2 Definition and repair of structure

Two story, single span scale concrete building used in the experiments are shown in Fig. 2.

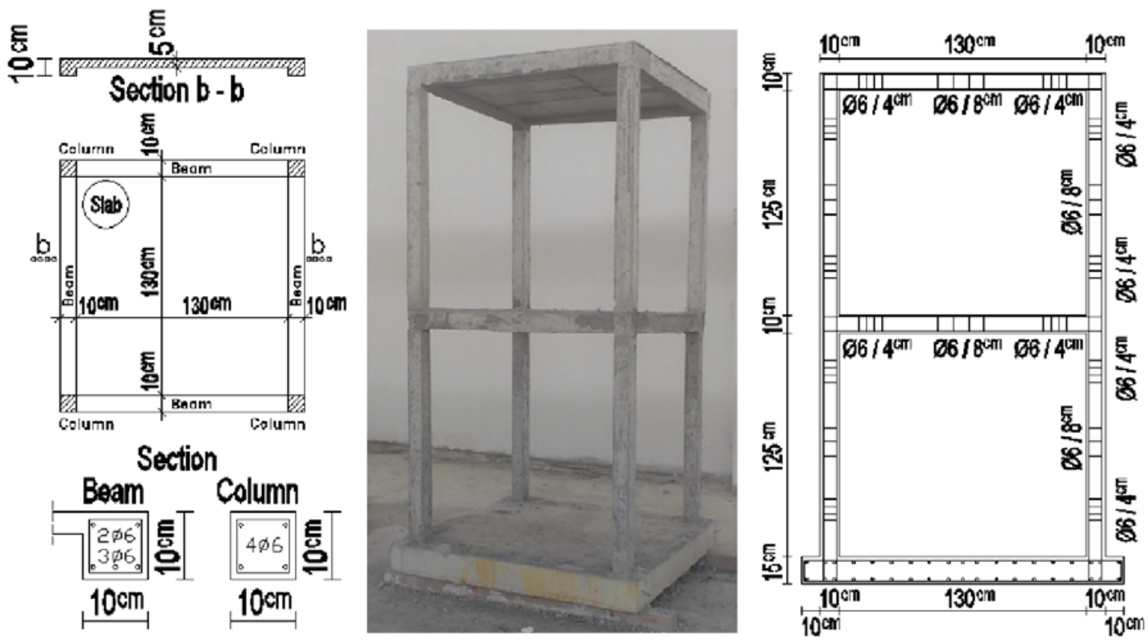


Fig. 2 Scaled concrete structure

Columns and beams are 10×10 cm, floor thickness 5 cm, story height 135 cm, and overall dimensions of structure 150×150 cm. Raft foundation, whose thickness was 15 cm was anchored to the base of ground floor columns. Longitudinal reinforcement of 4Ø6 was applied to columns, 3Ø6 to the bottom and 2Ø6 to the top of beams. Stirrup Ø6/8-4 was applied to columns and beams.

Table 1 Mechanical properties of concrete samples

	Compressive Strength (MPa)	Elastic Modulus (MPa)
Sample-1	32.8	32452
Sample-2	29.8	31112
Sample-3	27.8	30423

Fig. 3 Workm anship defects and their repair

Table 2 Mechanical properties of repair mortar

Compressive Strength (MPa)	15
Flexural Strength (MPa)	3
Adhesion strength (MPa)	1
Ambient Temperature (C^0)	+5 / +30
Turkish Standard	TS EN 1504-3

Floors were arranged in both directions as Ø6/10. Ribbed S420 reinforcement steel was used in the structure. Mechanical properties of concrete samples complying with Turkish Standard (TS - EN206) used in building construction are shown in Table 1.

Tested structure has eight nodal points and columns. The vibration was not applied to column-beam junction on the first floor and was not also applied to the middle of column, thus honeycomb structure was formed. These defects were repaired using commercial repair mortar. The ratio of commercial repair weight to the structure's weight was 0.003. Damages formed in the structure and their location and how the fixing was made are depicted in Fig. 3.

There are studies on the strengthening of the structures with repair mortar in the literature (Foti and Vecca 2013, Foti and Romanazzi 2011). Concrete gaps in the structure were repaired using cement based polymer modified commercial repair mortar having the mechanical properties shown in Table 2.

2.3 Experimental setup of operational modal analysis

OMA method was used in determining dynamic characteristic of the structure. SENSEBOX - 7021 accelerometers were used in measurements. Signals received from accelerometers were processed in a 4-channel TESTBOX-651 data collection unit and were transferred to a computer

Fig. 4 Data processing unit and accelerometers

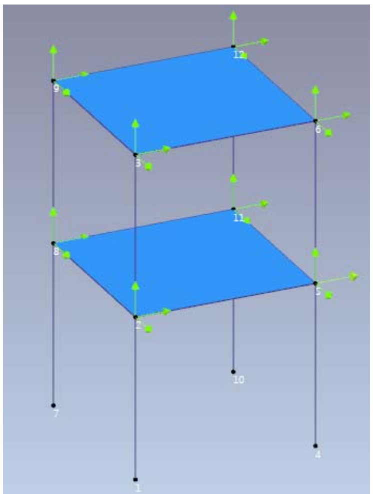


Fig. 5 Locations and directions of accelerometers

using TESTBOX software (Fig. 4). Then, dynamic characteristics were obtained by ARTEMIS Modal Pro (AMP) software using the SSI technique.

To accurately measure vibration modes of the structure, accelerometers were placed in 8-nodal points. For each direction, three accelerometers were used in each nodal points. Measurements were carried out in two steps. In the first step, 12 accelerometers were placed into 4 different locations on the first floor. In the second step, acceleration was measured at four different locations on the second floor. To account for environmental changes and temperature fluctuations, tests were carried out in the structure on two different dates. However, since the testing environment was a lab, environmental effects were considered minimum. Test done on a given day lasted for 6 hours and were repeated. Approximate model of the structure was drawn using ARTEMIS Modal Pro (AMP) software and exact location of accelerometers is shown in Fig. 5.

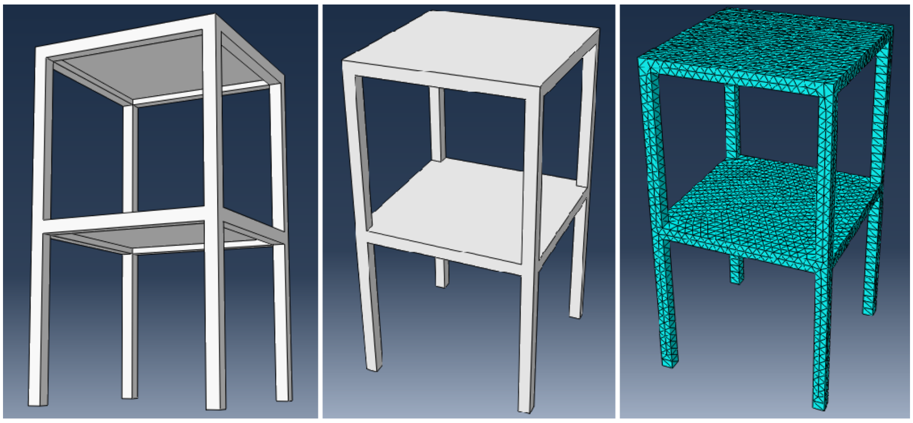
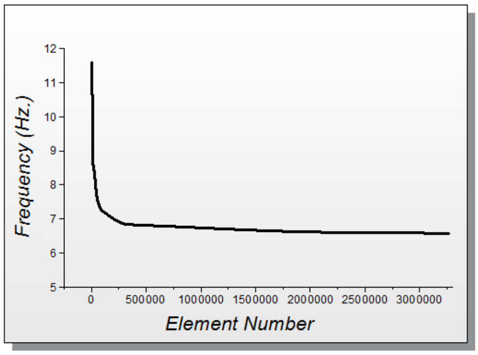


Fig. 6 Three dimensional model of structure and meshes

Table 3 Frequency values, number of elements and convergence graph of different mesh sizes

Mesh Size (m)	1. Mod Freq. (Hz.)	Element Number	Convergence graph
0.1	11.59	4322	
0.09	11.13	5388	
0.08	10.47	7042	
0.07	9.69	10200	
0.06	8.61	14853	
0.05	8.41	24061	
0.04	7.65	49930	
0.03	7.23	102394	
0.02	6.84	329915	
0.01	6.61	2392158	
0.0095	6.59	2900924	
0.009	6.58	3264105	

2.4 Numerical model

ABAQUS software was used in the finite element model of the structure. Concrete used in the numerical model had elasic modulus of 31000 MPa, poission's ratio of 0.2 and mass density of 24 kN/m^3. Solid elements were used in the finite element model. Moreover, 3264105 4-nodal tetrahedral (C3D4) solid element was used to accurately determine dynamic behavior of structure. The structure was anchored from the base of columns. Linear Perturbation- Frequency Module which allows us to carry out eigenvalue and eigenvector analysis was employed in this study. Three dimensional modeling of structure and its meshes obtained from ABAQUS software is depicted in Fig. 6.

Convergence analysis was performed to determine the optimum mesh range to be used in the model. Meshes ranging from 0.009 m to 0.1 m in size were taken in the convergence analysis of the model. Frequency analysis was done for each mesh size and obtained frequency values, number of elements and convergence graphs are given in Table 3.

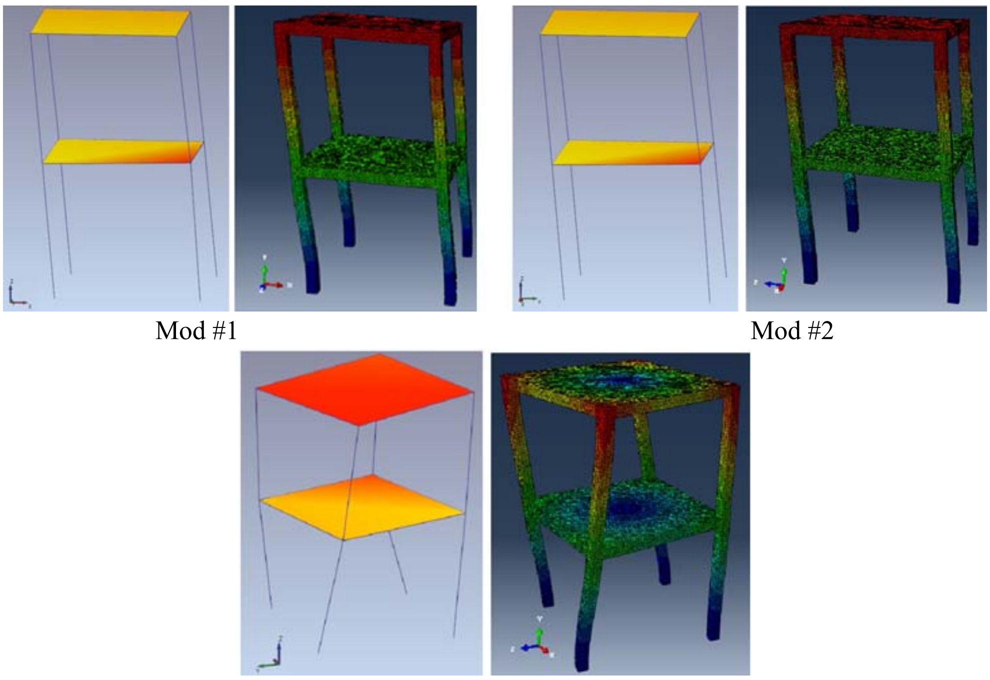
The optimum mesh size was found to be 0.009 m from convergence analysis. The first 6 modes of structure are given in Table 4.

3. Experimental results

By using experimental values, modal parameters of damaged and repaired structure were obtained using the SSI method in the AMP software. Stabilization diagram was also acquired by the SSI method. Numerical and experimental modal shapes are given in Fig. 7.

Table 4 Frequency values from numerical analysis

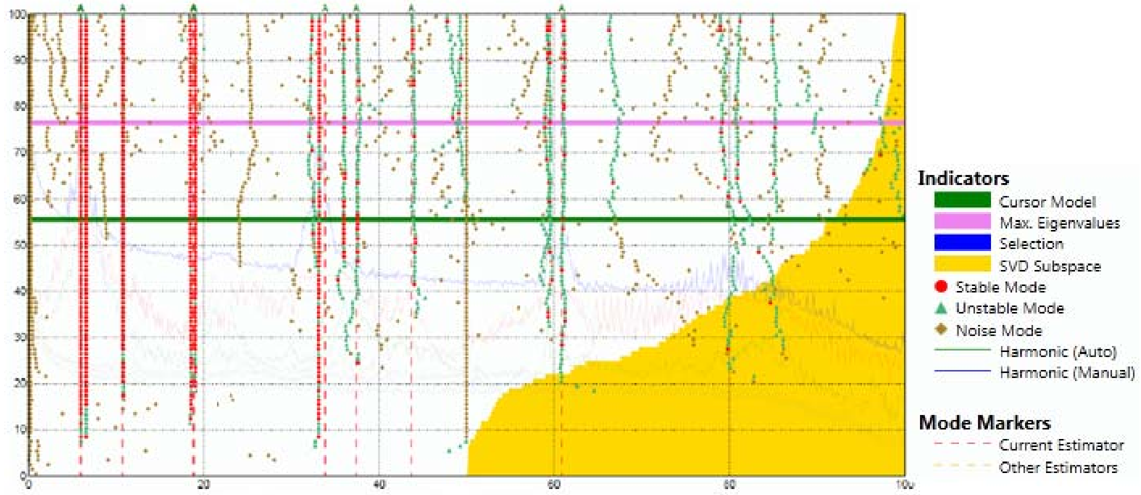
Mod	Frequencies (Hz)	Modal Participation Coefficients	
		X	*Y*
1	6.586	0.91144	0.91144
2	6.586	0.911471	0.911471
3	11.795	0.911471	0.911471
4	19.935	0.911471	0.911471
5	19.935	0.996498	0.996498
6	30.366	1	1



Mod #1 Mod #2

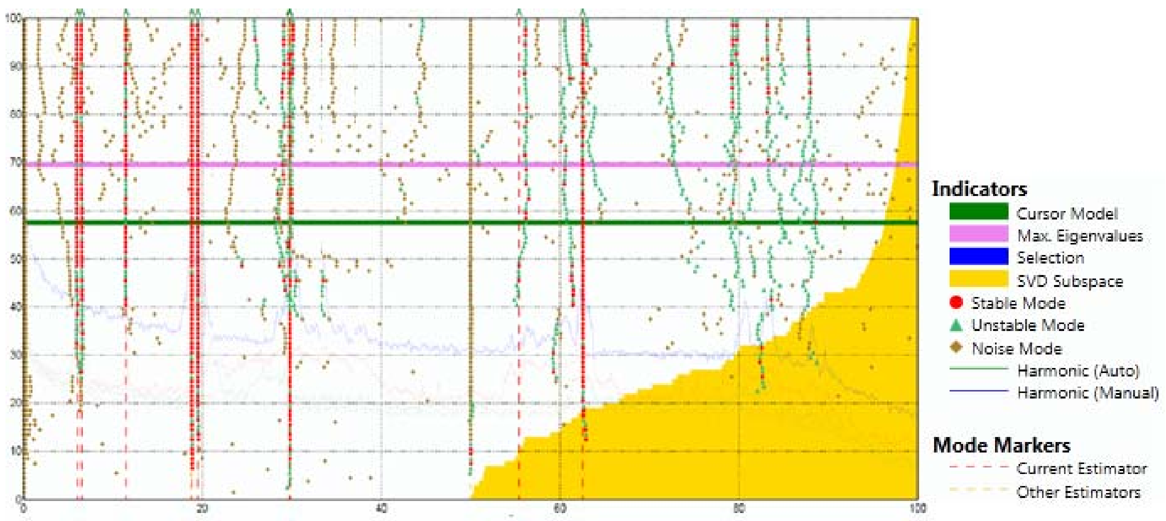
Mod #3

Fig. 7 Experimental and numerical first, second, and third modal shapes of structure



Mod	Frequencies (Hz)	Mod	Frequencies (Hz)
1	5.861	4	18.060
2	6.228	5	18.402
3	10.754	6	28.252

Fig. 8 Dynamic modal parameters and stabilization diagram of structure before repair



Mod	Frequencies (Hz)	Mod	Frequencies (Hz)
1	6.528	4	19.096
2	6.581	5	19.485
3	11.549	6	30.525

Fig. 9 Dynamic modal parameters and stabilization diagram of repaired structure

Table 5 Numerical and experimental dynamic properties of the structure

Mod	Frequencies with FEM	Frequencies with SSI					
		Before Repair			After Repair		
		Frequencies (Hz.)	Damping Ratios %	Difference %	Frequencies (Hz.)	Damping Ratios %	Difference %
1	6.586	5.861	0.825	11	6.528	1.854	0.88
2	6.586	6.228	0.910	5.44	6.581	1.464	0.075
3	11.795	10.754	0.395	8.83	11.549	0.598	2.08

Modal shapes obtained by the two methods (experimental and numerical) were in good harmony. The first mode of structure was in *X* direction, the second in *Y* direction and the third was seen as torsional for both experimental and numerical analysis. The following three modes were also similarly oriented. Fig. 8 depicts dynamic modal parameters and stabilization diagram of structure before repair.

In fact, the differences of Fig. 8 are expected due to the presence of damages that, as it is shown in Fig. 3, are not uniformly distributed along the two principal directions and in some positions appear to be a significant percentage of the area of the transversal section. Fig. 9 gives dynamic modal parameters and stabilization diagram of the repaired structure.

Frequency values for the first and second modes were symmetrical so were for the fourth and fifth modes. Moreover, experimental and numerical frequency values fit very well.

4. Discussion

In this study, the OMA method was used to experimentally determine dynamic properties of damaged (having concrete gaps) and repaired structure. Accelerometers placed in various locations on the structure were used to determine natural vibrations and these data were transformed to dynamic properties using the AMP software. Table 5 presents experimental and numerical values for dynamic properties.

Since the structure was symmetrical, modal frequencies for first and second mode were the same as seen in Table 4. The frequency values acquired by the SSI method for the first and second modes were not the same for the damaged structure (having concrete gaps). The difference between the numerical and experimental values was 11%, 5.44%, and 8.83% for the first, second, and third modes, respectively. Since the changes in frequencies were more than 5%, honeycomb defects rather than environmental effects, temperature changes and instantaneous loading were more likely responsible for these changes.

Since measurements were taken in the lab, environmental conditions, temperature fluctuations and instantaneous loading were effectively controlled. Therefore, differences in dynamic properties can solely be attributed to workmanship defects.

In the repaired structure, experimental first and second mod frequencies acquired by the SSI method were symmetrical. Moreover, the difference between experimental and numerical values was significantly reduced with 0.88%, 0.075% and 2.08% for the first, second, and third modes, respectively proving that repair process significantly improved dynamic properties of damaged structure.

From the numerical nodal shapes, the first mode of structure was in *X* direction, the second in *Y* direction and the third was seen as torsional. Modal shapes obtained for the damaged and repaired structure by the SSI method using the AMP software were correlated very well (Fig. 7).

5. Conclusions

In this study examined the effect of repair mortar on the dynamic properties such as natural frequencies, mode shape and damping ratios of two story single span scale reinforced concrete building. The solid modelling and linear perturbation frequency analysis of the structure were performed using the ABAQUS software. The optimum mesh size was found to be 0.009 m. Frequencies and modal shapes were obtained by numerical analysis. The OMA method was used to experimentally determine dynamic properties of defective (having concrete gaps) and repaired structure. The following conclusions can be drawn from this study.

Since the structure is symmetrical it is expected that the first and the second modes have same values. Due to gap effect in the defective structure, 6% difference in values for the first and second mode was seen. Moreover, up to 11% difference was observed between numerical and experimental values. Thus, workmanship defects can be said to negatively impact dynamic properties of the structure.

Defects in the structure were repaired utilizing repair mortar, whose weight ratio to structure's weight was 0.003. With the repair of structure, the fist and the second modes became symmetrical. Thus, the difference between numerical an experimental values was reduced to 0.075% indicating that repair process improved dynamic properties of the structure. After the repair, the fit between numerical and experimental values was much better.

In This study has proven that the OMA method can effectively be used in the detection of defects in the structure with great accuracy. However, further studies are needed to elucidate the relationship between the level of damage and the effectiveness of repair mortar.

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References

Can, H. and Tankut, T. (1989), "Betonarme kirişlerin eğilme için güçlendirilmesi", *Türkiye İnşaat Mühendisliği 10. Teknik Kongresi*, Cilt **II**, 559-573. (in Turkish)

Can, H. and Tankut, T. (1991), "Ağır hasar görmüş betonarme kirişlerin eğilme için onarımı", *IMO Teknik Dergi*, **23**, 309-317. (in Turkish)

Demir, H. (1999), "Depremden hasar görmüş betonarme yapıların onarım ve güçlendirilmesi", İTÜ Yayınları. (in Turkish)

Öztürk, A. and Kocabeyler, M.F. (1993), "Betonun onarımı", *DSİ Yayınları*, **MLZ.854**. (in Turkish)

Morgan, B.J. and Oesterle, R.G. (1994), "On-site modal analysis-a new powerful inspection technique", *Proceedings of the 2nd International Bridge Conference, Pittsburg, Pennsylvania,* 108-114.

Bayraktar, A., Türker, T., Altunışık, A.C., Sevim, B., Şahin, A. and Özcan, D.M. (2010), "Binaların dinamik parametrelerinin operasyonal modal analiz yöntemiyle belirlenmesi", *IMO Teknik Dergi*, 5185-5205. (in Turkish)

Betti, M., Orlando, M. and Vignoli, A. (2011), "Static Behaviour of an Italian Medieval Castle: Damage Assessment by Numerical Modelling", *Comput Struct.*, **89**(21-22), 1956-1970.

Diaferio, M. (2015), "Dynamic analysis of a historical fortified tower", *Key Eng. Mater.*, **628**, 178-184.

Oliveira, C.S., Çakti, E., Stenge, D. and Branco, M. (2012), "Minaret behavior under earthquake loading: the case of historical Istanbul", *Earthq. Eng. Struct. D.*, **41**, 19-39.

Diaferio, M., Foti, D., Giannoccaro, N.I. and Ivorra, S. (2014), "Optimal model through identified frequencies of a masonry building structure with wooden floors", *J. Mech.*, **8**, 282-288.

Ramos, L., Marques, L., Lourenco, P., De Roeck, G., Campos-Costa, A. and Roque, J. (2010), "Monitoring historical masonry structures with operational modal analysis: two case studies", *Mech. Syst. Signal Pr.*, **24**(5), 1291-1305.

Diaferio, M., Foti, D. and Sepe, V. (2007), "Dynamic identification of the tower of the provincial administration building", *Proc. of the Eleventh International Conference on Civil, Structural and Environmental Engineering Computing*, Malta.

Tomaszewska, A. and Szymczak, C. (2012), "Identification of the vistula mounting tower model using measured modal data", *Eng. Struct.,* **42**, 342-348.

Diaferio, M., Foti, D. and Giannoccaro, N.I. (2014), "Non-destructive characterization and identification of the modal parameters of an old masonry tower", *IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems*, Italy.

Park, S. (1997). "Development of a methodology to continuously monitor the safety of complex structures", Ph.D. Thesis, Texas A&M University, College Station, Texas.

Aktan, A.E., Lee, K.L., Chuntavan, C. and Aksel, T. (1994), "Modal testing for structural identification and condition assessment of constructed facilities", *12th International Modal Analysis Conference, Honolulu, Hawaii*, **1**, 462-468.

Salawu, O.S. (1997), "Dection of structural damage through changes in frequency: a review", *Eng. Struct.*, **19**(9), 718-723.

Moaveni, B., Conte, J.P. and Hemez, F.M. (2009), "Uncertainty and sensitivity analysis of damage identification results obtained using finite element model updating", *Comput-Aided Civ. Inf.*, **24**(5), 320-334.

Amani, M.G., Riera, J.D. and Curadelli, O. (2007), "Identification of changes in the stiffness and damping matrices of linear structures through ambient vibrations", *Struct. Health Monit.*, **14**, 1155-1169.

Aras, F., Krstevska, L., Altay, G. and Tashkov. L. (2011), "Experimental and numerical modal analyses of a historical masonry palace", *Constr. Build. Mater.*, **25**(1), 81-91.

Altunışık, A.C., Bayraktar, A., Sevim, B. and Birinci, F. (2011), "Vibration-based operational modal analysis of the mikron historic arch bridge after restoration", *Civ. Eng. Environ. Syst.*, **28**(3), 247-259.

Foti, D., Diaferio, M., Giannoccaro, N.İ. and Mongelli, M. (2012), "Ambient vibration testing, dynamic identification and model updating of a historic tower", *NDT E. Int.*, **47**, 88-95.

Foti, D., Ivorra, S., Bru, D. and Dimaggio, G. (2012), "Dynamic Identification of a Pedestrian Bridge using OMA: Previous and Post-Reinforcing", *Proceedings of the Eleventh International Conference on Computational Structures Technology,* Dubrovnik, Stirlingshire.

Foti, D. (2013), "Dynamic identification techniques to numerically detect the structural damage", *Open Constr. Build. Tech. J.*, **7**, 43-50.

Foti, D., Gattulli, V. and Potenza, F. (2014), "Output-only modal identification in unfavourable testing conditions and finite element model updating of a seismically damaged building", *Comput-Aided Civ. Inf.*, **29**(9), 659-675.

Osmancılı, G., Uçak, Ş., Turan, F.N., Türker, T. and Bayraktar, A. (2012), "Investigation of restoration effects on the dynamic characteristics of the hagia sophia bell-tower by ambient vibration test", *Constr. Build. Mater.*, **29**, 564-572.

Júlio, E.N.B.S., da Silva Rebelo, C.A. and Dias-da, D.A.S.G. (2008), “Structural assessment of the tower of the university of coimbra by modal identification”, *Eng. Struct.*, **30**(12), 3468-3477.

Bartoli, G., Betti, M. and Giordano, S. (2013), “In situ static and dynamic investigations on the “torre grossa” masonry tower”, *Eng. Struct.*, **52**, 718-733.

Gentile, C. and Saisi, A. (2013) “Operational modal testing of historic structures at different levels of excitation”, *Constr. Build. Mater.*, **48**, 1273-1285

Gattulli, V. (2013), “Advanced applications in the field of structural control and health monitoring after the 2009 L’Aquila earthquake”, Ed. Dr Sebastiano D’Amico, *Engineering Seismology, Geotechnical and Structural Earthquake Engineering*.

Giraldo, D.F., Song, W., Dyke, S.J. and Caicedo, J.M. (2009), “Modal identification through ambient vibration: comparative study”, *J. Eng. Mech.*, ASCE, **135**(8), 759-770

Ventura, C.E., Lord, J.F. and Simpson, R.D. (2002), “Effective use of ambient vibration measurements for modal updating of a 48 storey building in Vancouver”, *Proceedings of the 3rd international conference on structural dynamics modeling-test, analysis, correlation and validation,* Madeira Island, Portugal.

Kohler, M.D., Davis, P.M. and Şafak, E. (2005), “Earthquake and ambient vibration monitoring of the steel-frame ucla factor building”, *Earthq. Spectra.*, **21**(3), 715-736.

Ren, W.X., Zhao, T. and Harik, I.E. (2004), “Experimental and analytical modal analysis of steel arch bridge”, *J. Struct. Eng.*, ASCE, **130**(7), 1022-1031.

Zivanovic, S., Pavic, A. and Reynolds, P. (2007), “Finite element modelling and updating of a lively footbridge: the complete process”, *J. Sound Vib.*, **301**, 126-145.

Wang, H. and Li, D. (2007), “Experimental study of dynamic damage of an arch dam”, *Earthq. Eng. Struct. D.*, **36**, 347-366.

Oliveira, S. and Faria, R. (2006), “Numerical simulation of collapse scenarios in reduced scale tests of arch dams”, *Eng. Struct.*, **28**, 1430-1439.

Dooms, D., Degrande, G. and Roeck, G.D. (2006), “Finite element modelling of a silo based on experimental modal analysis”, *Eng. Struct.*, **28**, 532- 542.

Reynolds, P., Pavic, A. and Ibrahim, Z. (2004), “A remote monitoring system for stadia dynamics, proceedings of the institution of civil engineers”, *Struct. Build.*, **157**, 385-393.

Gentile, C. and Saisi, A. (2007), “Ambient vibration testing of historic masonry towers for structural identification and damage assessment”, *Constr. Build. Mater.*, **21**, 1311-1321.

Mamaghani, I.H.P. (2006), “Analysis of masonry bridges by discrete finite element method”, *J. Tran. Res. Board*, DOI: 10.3141/1976-04.

Ceballos, M.A., Car, E.J., Prato, T.A., Prato, C.A. and Alvarez, L.M. (1998), “Experimental and numerical determination of the dynamic properties of the reactor building of atucha II NPP”, *Nucl. Eng. Des.*, **182**, 93-106.

Bayraktar, A., Türker, T., Altunışık, A.C. and Sevim, B. (2007), “Düzlem kafes taşıyıcı sistemlerin operasyonal modal analizi”, *2. Çelik Yapılar Ulusal Sempozyumu, Eskişehir*, 273-281. (in Turkish)

Nohutcu, H., Demir, A., Ercan, E., Hokelekli, E. and Altıntas. (2015), “Investigation of a historic masonry structure by numerical and operational modal analyses”, *Struct. Des. Tall Spec.*, **24**(13), 821-834.

Peeters, B. (2000), “System identification and damage detection in civil engineering”, PhD Thesis, K.U, Leuven, Belgium.

Bayraktar, A., Altunışık, A.C., Sevim, B. and Türker, T. (2010), “Ambient vibration tests of a steel footbridge”, *J. Nondestruct. Eval.*, **29**(1), 14-24

Van Overschee, P. and De Moor, B. (1996), *Subspace Identification for Linear Systems: Theory, Implementation and Applications*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Peeters, B. and De Roeck, G. (1999), ‘‘Reference based stochastic subspace identification in civil engineering’’, *Proceedings of the 2nd International Conference on Identification in Engineering Systems,* Swansea, UK.

Bayraktar, A., Sevim, B., Altunışık, A.C. and Türker, T. (2009), “Analytical and operational modal analyses of turkish style reinforced concrete minarets for structural identification”, *Exp. Techniq.*, **33**(2), 65-75.

Foti, D. and Vacca, S. (2013), “Comportamiento mecánico de columnas de hormigón armado reforzadas con

mortero reoplástico/Mechanical behavior of concrete columns reinforced with rheoplastic mortar", *Mater. Constr.*, **63**(310), 267-282
Foti, D. and Romanazzi, A. (2011), "Experimental analysis of fiber-reinforced mortar for walls in rectified brick blocks/Analisi sperimentale di malte fibrorinforzate per pareti in blocchi di laterizio rettificati", C+CA Ceramurgia + Ceramica Acta, Anno XXXXI, **41**(2) 109-118.
ARTeMIS Extractor Pro software (2009), Issued by Structural Vibration Solutions ApS, NOVI Science Park, Niels Jernes Vej 10, DK 9220, Aalborg East, Denmark.
Abaqus software is a product of Dassault Systemes Simulia Corp, USA.

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