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Vibration measurement and vulnerability analysis of a power plant cooling system

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Abstract. During the service life of a structure, design complications and unexpected events may induce unforeseen vibrations. These vibrations can be generated by malfunctioning machinery or machines that are modified or placed without considering the original structural design because of a change in the intended use of the structure. Significant vibrations occurred at a natural gas plant cooling structure during its operation due to cavitation effect within the hydraulic system. This study presents findings obtained from the in-situ vibration measurements and following finite-element analyses of the cooling structure. Comments are made on the updated performance level and damage state of the structure using the results of these measurements and corresponding numerical analyses. An attempt was also made to assess the applicability of traditional displacement-based vulnerability estimation methods in the health monitoring of structures under vibrations with a character different from those due to seismic excitations.

Keywords: vibration; finite element method; cooling structure; accelerometers; vulnarability analysis

1. Introduction

It is not possible to predict loads and their possible effects on structures with absolute certainty during the design phase. Thus, there is always a possibility that the design loads will be exceeded during the service life. In order to avoid failure or disruptions in the intended purpose, engineers traditionally include an amount of conservativeness during the design stage by increasing the predicted loads and decreasing the material strength parameters. However, unexpected behavior can be observed or even failure at extreme cases can still be encountered at some civil engineering structures. A large portion of unsatisfactory performance cases results from the difficulty in predicting some special loading effects such as those due to earthquake and wind, along with those arising in extraordinary situations which have not been considered during the design stage. It is also possible to include impact loads due to explosives, effects of collision of a vehicle to a structure and the unpredicted vibration due to an equipment installed to an industrial production facility in this group. Significant amount of studies investigating the effects of unpredicted loads on various engineering structures were encountered during a literature survey (Farar *et al*. 1997, Ni *et al*. 2001, Sohn *et al*. 1999, Tamura 2001, Kim *et al*. 2009). Extreme deformations, undesired

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vibrations and various amount of structural damage have been reported to occur due to these load effects. The majority of these studies focus on measurement of vibrations or deformations and interpretation of these acquired measurements for bridges and multi-storey structures (Farar *et al*. 1997, Ni *et al*. 2001, Sohn *et al*. 1999, Tamura 2001, Kim *et al*. 2009, Michelis *et al*. 2012, Ni *et al*. 2011, Shakib and Parsaeifard 2011, Nikitas *et al*. 2011).

Due to the reasons stated above, inclusion of monitoring systems for continuous observation of the performance of important infrastructure components such as bridges, multi-storey buildings, dams and nuclear power plants during their complete operation life has started to become widespread. Measurement of the response of structures to wind, earthquake, explosion or other random and extraordinary effects with various wired or wireless sensors and observation of any corresponding damage clearly have significant benefits (Lynch *et al*. 2004, Doebling *et al*. 1996, Lynch 2002, Straser and Kiremidjian 1998, Kosmatka and Riles 1999, Michelis *et al*. 2012, Ni *et al*. 2011, Shakib and Parsaeifard 2011, Nikitas *et al*. 2011).

Operational vibrations that had not been predicted during the design stage are not uncommon for structures such as industrial cooling plants where significant open or closed conduit fluid intake and discharge systems are present. These structures are under the effect of variable dynamic loads such as those due to the cavitation within fluid transfer pipes that are externally connected to them, which are very difficult to assess accurately during the design stage. In case continuous health monitoring is not available, in certain cases, it becomes necessary to estimate risk levels of these structures with instant measurements.

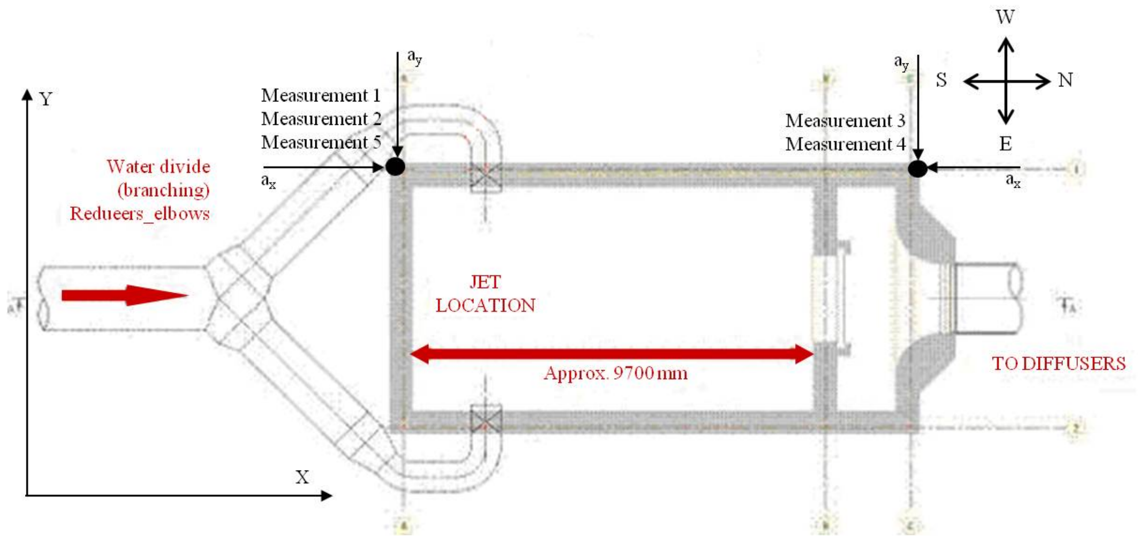
This study presents a major structural health monitoring example that involves the detailed measurement and characterization of unforeseen vibrations and the assessment of their effects on a combined natural gas power plant cooling structure. First, detailed acceleration measurements were conducted, to examine and analyze the irregular pattern of vibrations. Then, finite element analyses of the structure were performed by utilizing the acquired measurements to determine the variations in the forces and moments on critical sections as a result of these unpredicted vibrations. Expected damage state and the change in the performance level of the structure as a result of the modified shear force and moment values were analyzed. More importantly, an attempt was made to estimate the vulnerability of the power plant cooling structure using simplified criteria developed mainly for earthquake-induced vibrations. Within the framework of structural health monitoring, the applicability of the available displacement-based criteria is discussed for cases that involve vibrations with a character significantly different from those due to earthquakes.

2. Vibration measurements at the cooling structure

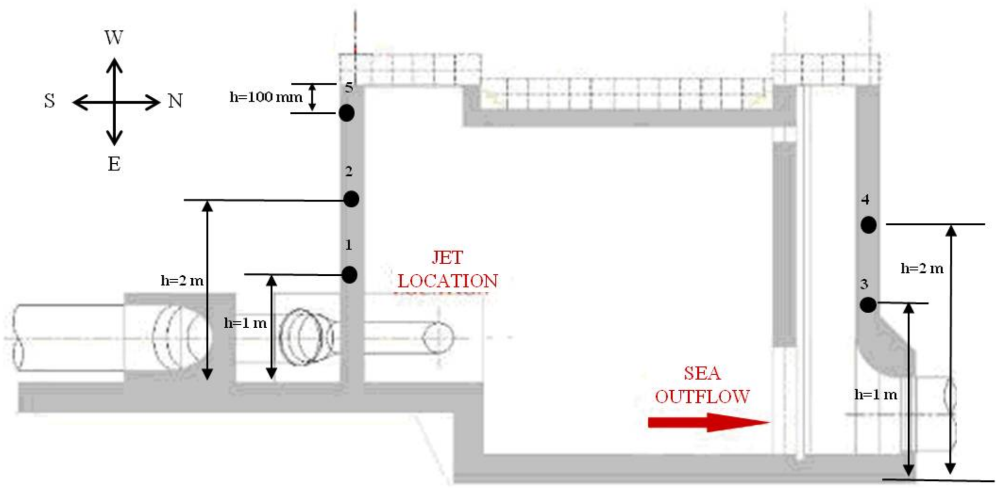
The cooling structure is a 12 m × 4 m building composed of reinforced concrete shear walls. The water processed at the combined cycle natural gas power plant, which is required to be cooled, is transferred to the cooling structure from its southern end with a 1 m diameter pipe, and then discharged to sea with a 0.5 m diameter pipe after its treatment. The transferred water is divided into two branches with a "V" shaped connection to facilitate collision within a basin at the cooling structure. Water settled at this basin is then transferred to a smaller one for final discharge to sea.

Significant vibrations were reported during the operation of the cooling structure, characteristics and operation mode of which summarized above. Thus, utilization of accelerometers was considered to be necessary for the measurement and the interpretation of these vibrations. Since the considered structure has a rectangular shape, and it’s longer and more rigid in the north-south direction, acceleration measurements in both the north-south and the east-west directions were taken at five different points on the structure. As the cooling structure has a height of three meters, the measurement points were chosen to be at different elevations. This enables the estimation of the most critical acceleration-time profile which may occur on the structure. Layout of the structure and locations of the acceleration measurement points are given in Fig. 1 both in section and plan views.

ICP type accelerometers with model number 353B02, manufactured by PCB Group were utilized for acceleration measurements of the cooling structure. A 003A20 model special cable, manufactured by PCB Group, was used for transmission of measurements acquired from the



(a) Cooling structure plan layout

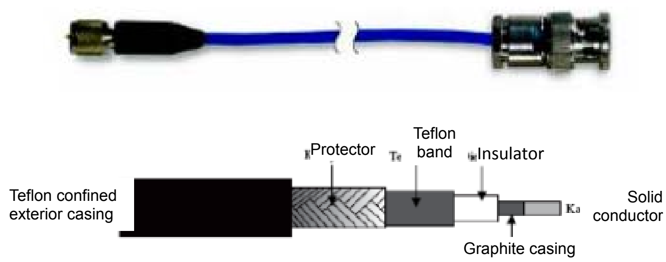


(b) Cooling structure section layout

Fig. 1 Cooling structure acceleration measurement locations accelerometers to data logger without data loss. These are low noise, coaxial cables that are suitable for operation at high temperatures and for transmission of high or low impedance voltage signals with ICP sensors. The diameters of the cables are 2 mm and operation temperature range is between –90 and +260°C. Impedance of the cable is 50 ohm. N1 9233-USB-9162 model data logger manufactured by National Instruments Company was used for collection of measurements and transmission to the computer in the field. This data logger is a four channel dynamic signal acquisition unit and is composed of IEPE sensors which can acquire measurements with high accuracy. The data logging device is composed of two independent modules. The first module is the data logger to which the measurement devices are also connected. The second is the signal transmission module, which transmits the signal from the first module to computer. Data transferred to computer from data logger is stored after conversion to the required type via Labview Signal Express 3.5 software, developed by National Instrument Company. Calibrations of the measurement devices are performed using this software as well. Diadem 10.1 software, also developed by National Instruments, was used for necessary editing operations during data processing.

The accelerometer, cable and data logger used in measurements are shown in Fig. 2. Also, several examples from the photographs taken during field measurements are presented in Fig. 3. Acceleration measurements were taken at the locations on the cooling structure shown in Figure 1 in both directions for 500 sec. The duration of the measurements was determined by several trial measurements taken prior to the actual measurements, and this duration was kept long enough to ensure that the vibration profile of the cooling structure is accurately determined. A total of 15

(a) ICP Model 353B02 accelerometer

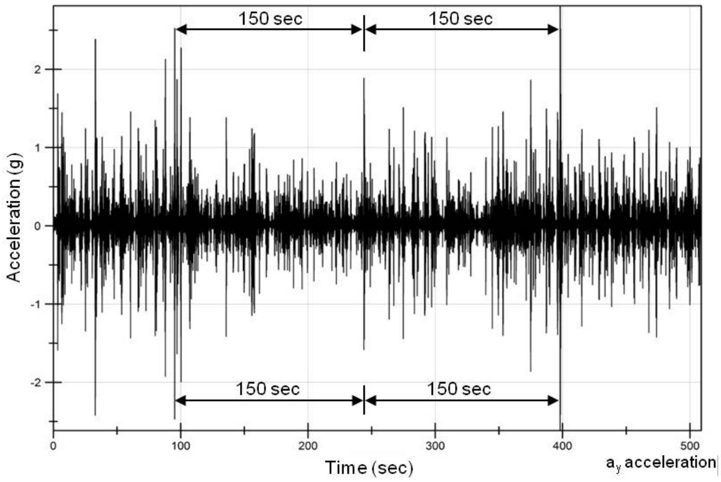


(b) 003A20 model cable

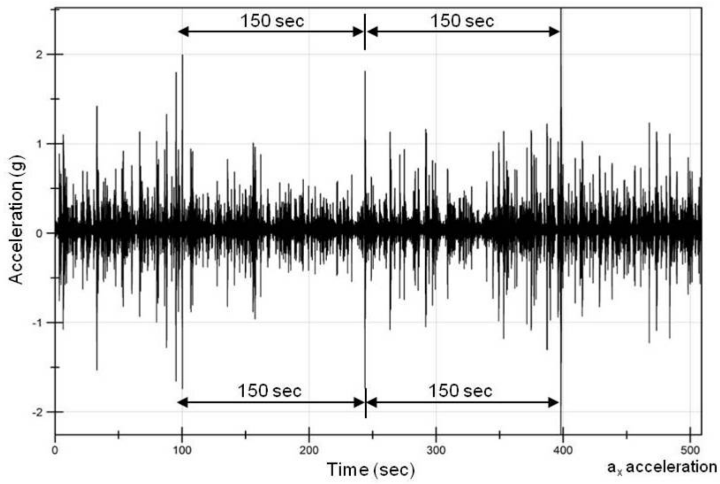
(b) NI 9233-USB-9162 data logger

Fig. 2 Measurement devices

Fig. 3 A photo of field acceleration measurements



(a) East-west acceleration measurement of point 5



(b) South-north acceleration measurement of point 5

Fig. 4 Acceleration measurements of point 5 million data were collected during this period. The time histories of accelerations measured at measurement location number 5 for both directions are shown in Fig. 4. Note that Fig. 4 presents a sample time history of acceleration, which is only a portion of a much longer duration measurement.

An inspection of the measurements enables to reach at several general judgments regarding the characteristics of acceleration on the structure. The maximum acceleration values reach up to about 2.5 g. Although a segment of acceleration pattern at a constant frequency somewhat repeats itself with time on the structure, these segments are not completely identical to each other. This observation indicates that the effect that creates the vibrations on the structure is itself not periodic and thus induces irregular vibrations, unlike those that results from operating engine systems or machinery, which generally create a regular and recurring acceleration-time behavior. Although

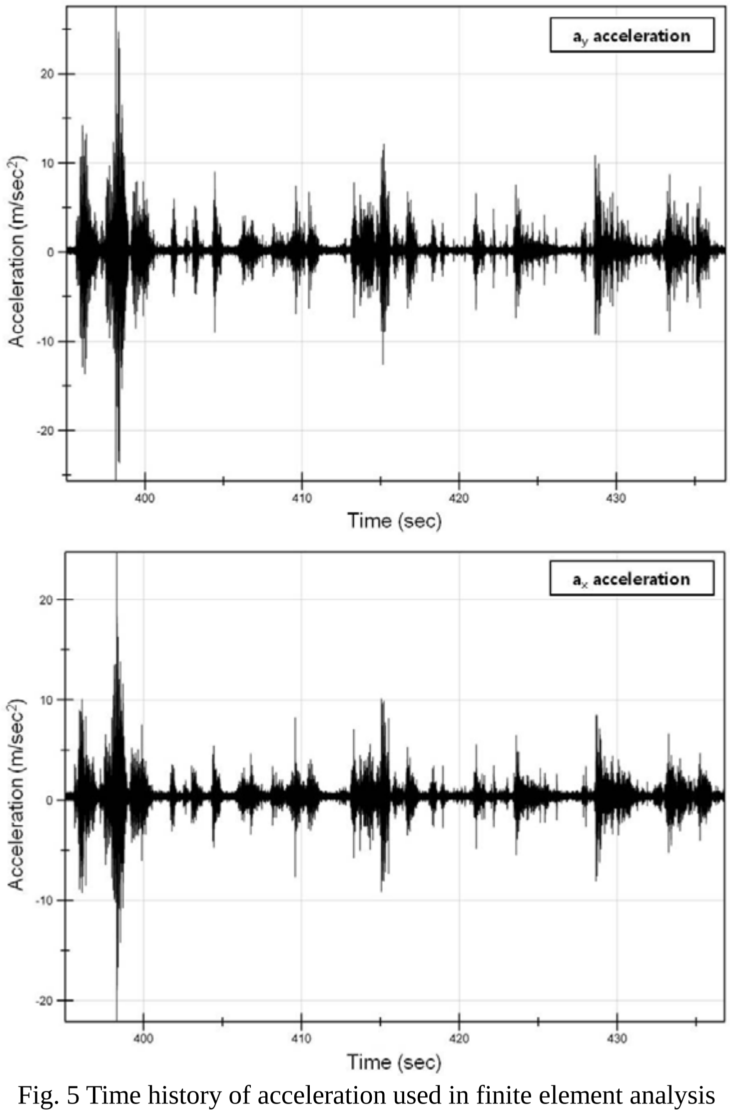


Fig. 5 Time history of acceleration used in finite element analysis

there are no acceleration-time segments that are completely identical, sections with somewhat recurring acceleration-time behavior at about every 150 second could be identified as the measurements are carefully analyzed.

For example, when the acceleration-time graphs from measurement point 5 are analyzed, segments that approximately repeat themselves 3 times within the 500-second record duration can clearly be observed. Although there is a minor variation at the maximum value of acceleration, the acceleration-time behavior in these three sections is similar in general. This observation is valid for all measurements in both directions. This finding significantly indicates that, although the effect creating the acceleration changes with time, it is an influence which recurs and which affects the structure in a manner that creates a similar acceleration-time behavior within a certain time period.

The results of above mentioned acceleration measurements were used in finite element analyses of the structure and in the determination of the effects of vibrations on the structure that are unaccounted for at the design stage. The natures of the acquired measurements and the observations have supported the idea that the source of vibrations is the cavitation formed at the pipes that transmit the water to the cooling structure. Although a somewhat recurring acceleration behavior was observed, the presence of small changes in the pattern and at the maximum acceleration value is an indication that the effect causing the vibration is a time-varied and unstable event such as cavitation.

Since the source of vibrations is the cavitation formed at the pipes that transmit the water to the cooling structure, the acceleration measurements taken at the connection of the pipes with the cooling structure, i.e., at measurement point number 5, were used as the acceleration–time history that is applied on the cooling structure for finite element analyses. This acceleration time history represents the source of the external excitation that is applied to the structure by the pipe. Hence, the analysis considered in the current study can be considered as a problem of transmission of accelerations between two connected structures. The acceleration time history that is used as the excitation input, which is the part that repeats itself in about every 150 seconds with minor variations, is shown in Fig. 5 for both x and y directions. The results of Fast Fourier Transform (FFT) analyses performed on these measurements are given in Fig. 6 where the dominant frequency and the corresponding values of acceleration are also shown.

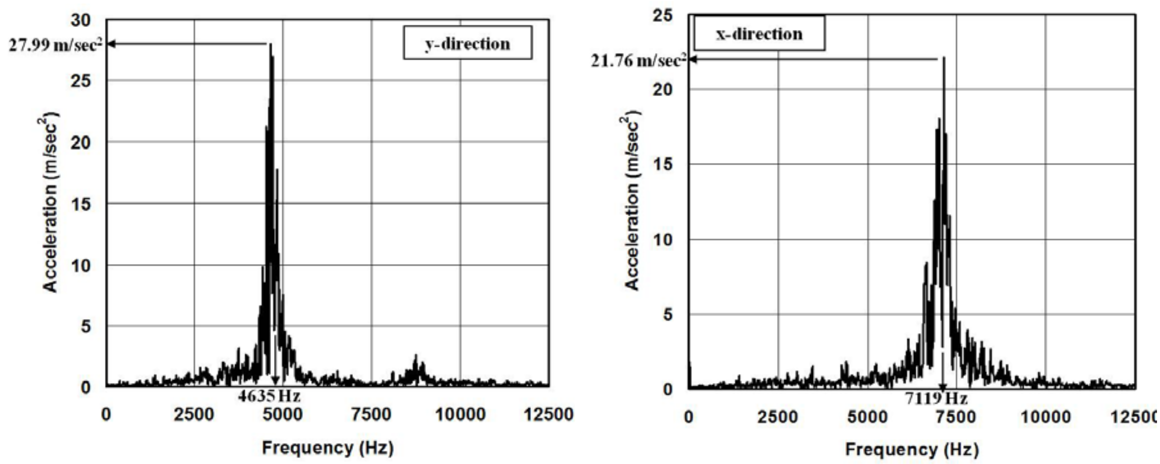


Fig. 6 FFT (Fast Fourier Transform) analysis results of acceleration time history

3. Finite element analysis of the cooling structure

3.1 Finite element modeling

The SAP 2000 software developed by Computers & Structures Company, which is general purpose finite element software, was chosen for performing the finite element analysis of the cooling structure. This software is commonly used for civil engineering applications including dynamic analyses.

SAP 2000 software had also been used during the design of the cooling structure, during which load combinations that involve static vertical loads, dynamic loads such as earthquake and fluid pressures inside the structure, active and passive earth pressures as well as temperature effects had been considered. Along with these, some operational loads such as those that exist at the connection point of water transmission pipes to the structure had also been taken into account during the design stage. However, the aforementioned vibration occurring during the operation of the structure had not been predicted during the design stage. Thus, the vibration profile measured after the structure has been commissioned is externally applied to the structure as a dynamic load through the acceleration-time history measured at measurement point number 5. The vibration effect is superposed to the loads that were used for the calculation of member stresses that are considered during project design phase of the structure. Thus, internal member forces were calculated in the most conservative manner.

As the cooling structure is composed of reinforced concrete shear walls, it was modeled by four-node rectangular elements that are available in the library of SAP 2000 software. The finite element mesh of the structure as viewed from different axes is given in Fig. 7. The acceleration-time history having the largest peak acceleration value acquired from the measurements was applied on the structure. The acceleration profile measured at the fifth

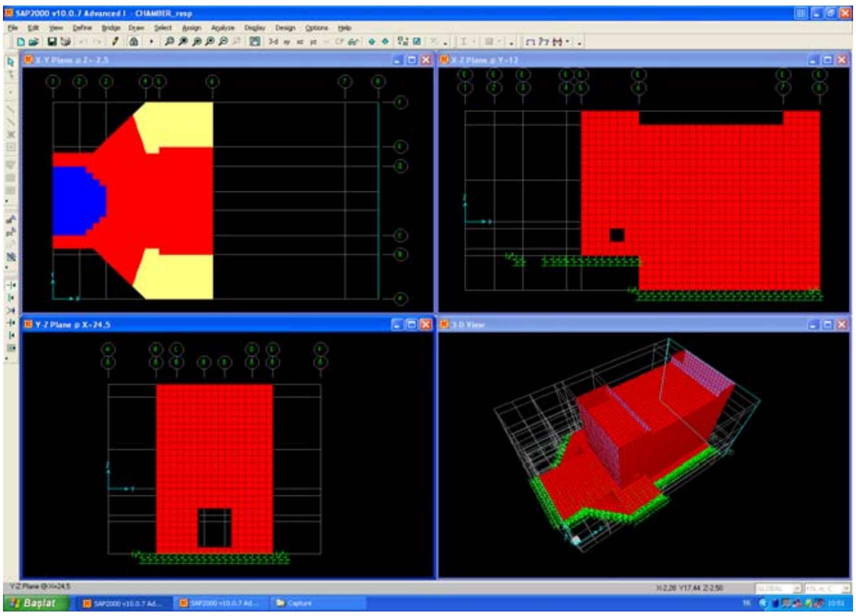


Fig. 7 SAP 2000 Finite element mesh of cooling structure

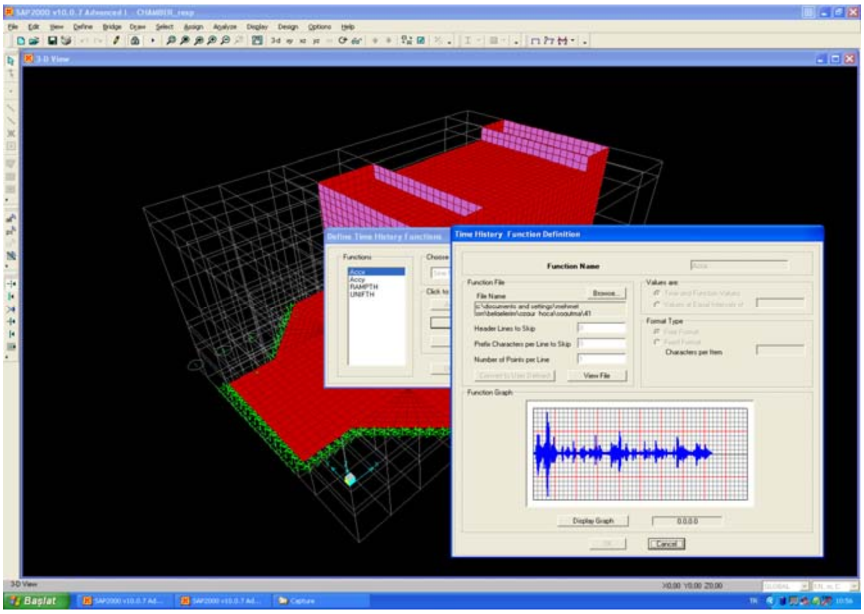


Fig. 8 Acceleration loading in SAP 2000 software

measurement point given in Fig. 4 have the largest peak acceleration value and the recurring acceleration-time sections were applied to the structure model, and member forces as well as displacement and stress distributions were analyzed. In these analyses, the acceleration-time histories measured in both directions have been loaded on the structure simultaneously. Along with this, for the worst-case scenario, the vibration and earthquake effects were considered to act on the cooling structure at the same time. The acceleration-time histories utilized in the analyses are given in Fig. 8. Note that the acceleration-time history loaded on the structure, which is given in Fi. 5, is a 40-second section which has the largest peak acceleration value among the self-repeating segments of measurement number 5, which has already been presented in Fig. 4.

3.2 Finite element results

The effect of unforeseen vibrations were analyzed by comparing the estimated moment and shear force distributions at the reinforced concrete walls (plates) of the cooling structure with and without the application of the measured acceleration time histories. Maximum computed moment and shear force values with and without the application of acceleration time histories due to vibration is presented in Table 1 for six main concrete walls that form the structure and for each principal direction. Fig. 9 presents examples of member force distributions for some of the reinforced concrete walls that form the cooling structure as obtained through the analysis that include vibration loading.

Due to the effects of vibration, the minimum and maximum moments and shear stresses are determined to increase between 2% and 60%, which corresponds to an average increase of 20% for all reinforced concrete wall sections composing the structure.

The analysis results also show that, as expected, there is a tendency for additional stress concentration at those sections where sharp edges or holes are present. It was observed that, the

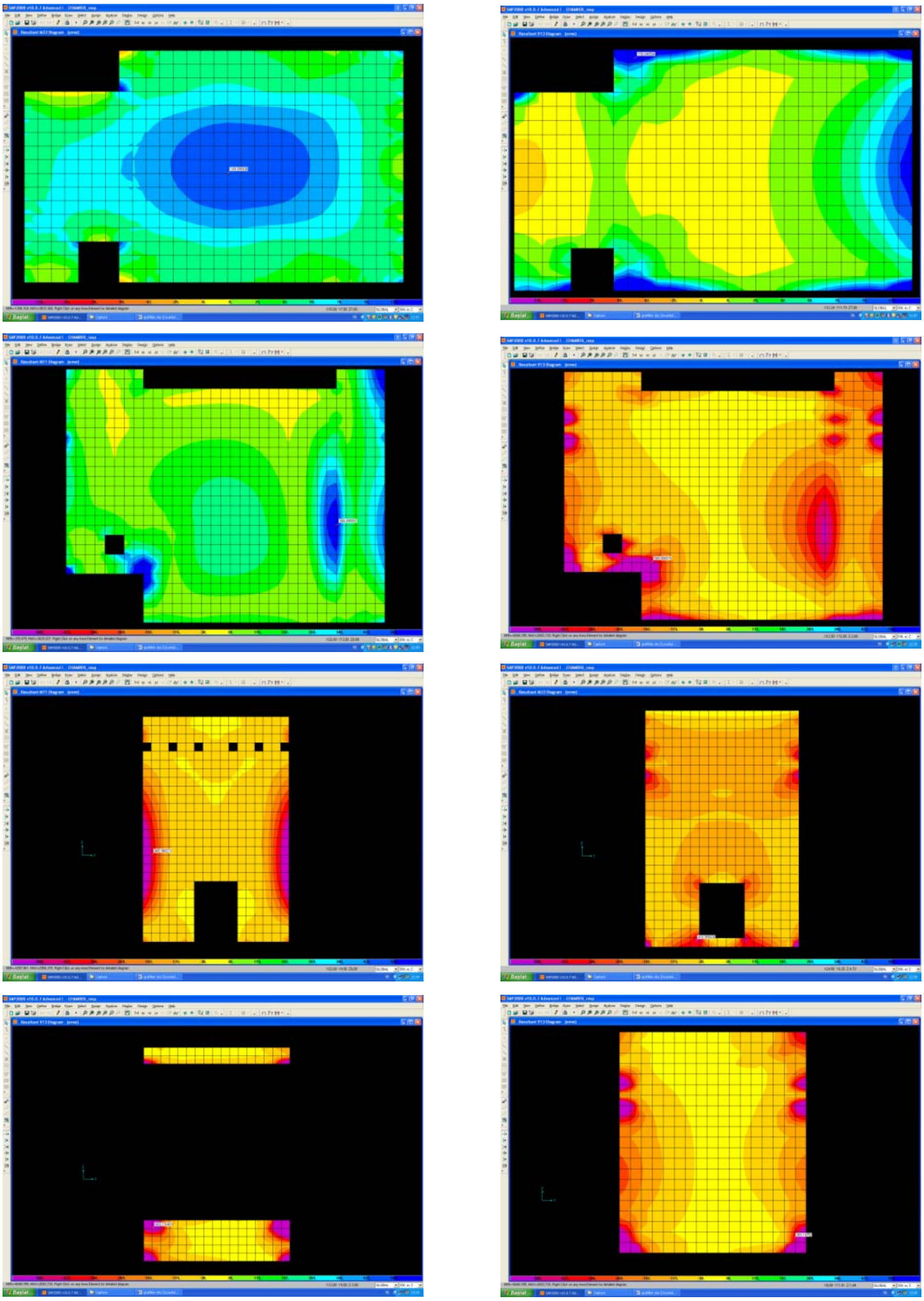


Fig. 9 Moment and shear force distribution example of cooling structure with vibration

Table 1 Comparison of moment and shear force values

Number	Remarks*	Without Vibration	With Vibration	Ratio**
1	M_{11} Max	60	68.05	1.14
2	M_{11} Min	-110	-117	1.06
3	M_{22} Max	105	109	1.04
4	M_{22} Min	-130	-149.51	1.15
5	V_{13} Max	150	159.54	1.06
6	V_{13} Min	-120	-145.57	1.21
7	V_{23} Max	160	163.54	1.02
8	V_{23} Min	-140	-149.27	1.07
9	M_{11} Max	400	566.48	1.41
10	M_{11} Min	-350	-436.01	1.25
11	M_{22} Max	500	799.79	1.60
12	M_{22} Min	-500	-711.12	1.42
13	V_{13} Max	450	702.64	1.56
14	V_{13} Min	-450	-548.06	1.22
15	V_{23} Max	460	641.66	1.40
16	V_{23} Min	-450	-464.74	1.03
17	M_{11} Max	170	234.73	1.38
18	M_{11} Min	-250	-268.55	1.07
19	M_{22} Max	320	350.02	1.09
20	M_{22} Min	-300	-311.30	1.04
21	V_{13} Max	350	401.53	1.15
22	V_{13} Min	-350	-383.15	1.28
23	V_{23} Max	370	400.97	1.08
24	V_{23} Min	-400	-541.31	1.35
25	M_{11} Max	400	550.45	1.38
26	M_{11} Min	-350	-360.17	1.03
27	M_{22} Max	450	506.15	1.12
28	M_{22} Min	-400	-455.26	1.14
29	V_{13} Max	550	665.82	1.21
30	V_{13} Min	-600	-669.12	1.11
31	V_{23} Max	550	722.80	1.31
32	V_{23} Min	-450	-697.80	1.55
33	M_{11} Max	350	377.57	1.08
34	M_{11} Min	-400	-465.08	1.16
35	M_{22} Max	260	328.85	1.26
36	M_{22} Min	-400	-462.93	1.16
37	V_{13} Max	450	500.70	1.11
38	V_{13} Min	-450	-501.68	1.12
39	V_{23} Max	350	472.58	1.35
40	V_{23} Min	-450	-505.18	1.12
41	M_{11} Max	400	423.09	1.06
42	M_{11} Min	-400	-411.96	1.03
43	M_{22} Max	300	319.97	1.07
44	M_{22} Min	-400	-410.96	1.03
45	V_{13} Max	400	593.32	1.48
46	V_{13} Min	-400	-447.69	1.12
47	V_{23} Max	400	516.51	1.29
48	V_{23} Min	-400	-406.08	1.02

* M: This symbol show moment values (kN-m), V: this symbol show shear force (kN)
** Ratios of moment and shear force with vibration to without vibration

increase in the shear forces and bending moments due to vibrations in regions where stress concentrations exist are significantly higher than those where the stress distributions are more homogeneous. Analyses on several reinforced concrete plate sections indicate that the average increase in member forces occurring as a result of vibrations is about 10% at locations where stress concentrations do not exist. Note that these analyses were performed for only a selected number of walls (plates). As the cooling structure is composed of many plates and these plates themselves are composed of numerous elements, averaging the member forces at numerous points is a time consuming and difficult process.

It was observed, in accordance with the results of the analyses, that the computed effect of vibration on the cooling structure is significant when the shear force and moment values are considered. The safety margin used during the design process might have prevented the failure or significant damage on the structure. However, it is clear that the structure in its current state is not at the original target safety level it was designed for, and its risk level has considerably elevated as a result of the increase in member forces.

5. Vulnerability analysis of cooling structure

This section presents the studies performed for determination of vulnerability or damage state of the cooling structure based on the analysis and field measurement results discussed in the previous sections. Many studies are available in the literature concerning the estimation of the probability of damage or the change in the vulnerability of the structures under vibration effects (e.g., Mosalam *et al*. 1997, SEAOC 1995, ASCE 2000, Rossetto and Elnashai 2003, Ghobarah 2004, Booth *et al*. 2004). However, almost all of these studies were concentrated on vibrations due to earthquakes, which affect very large areas and numerous structures at once.

It is considered that those approaches that have originally been developed for earthquake-related damage can also be used for estimating the vulnerability of structures under vibrations due to other causes. The main difference in the acceleration-time histories generated by earthquakes and those by accidental vibrations is that the duration of the significant part of the vibration is usually much larger in earthquakes. On the other hand, the maximum acceleration generated by blasts or various other sources can be significantly larger than those generated by earthquakes. Nevertheless, vulnerability prediction approaches that were developed for earthquakes were reviewed and their applicability to above mentioned vibration problem is investigated in this study. The maximum ground acceleration is one of the most influential vibration characteristics that correlate with the potential structural damage that may occur under earthquake influence. Mosalam *et al*. (1997) presented a relationship between the maximum ground acceleration and structural damage, which was divided into four classes (Fig. 10). However, due to the high peak acceleration and relatively short duration of the measured vibrations, it is considered that the relationship presented by Mosalam *et al*. 1997, which gives the damage state as a function of the peak acceleration only, cannot be utilized for the case herein. Therefore, it is considered that selection of interstorey or total drift ratios for the classification of structural damage would be more appropriate in the current case. For this purpose, the displacement due to unforeseen operational vibrations on the cooling structure was estimated through double integration of the measured acceleration-time history. Note that, double integration of acceleration may lead to unacceptable baseline displacements due to the amplification of low frequency errors of the recorded acceleration. In order to minimize this error, the accelerometers were selected to be capable of measuring low frequency signals with as high resolution as possible. Model 353B02 accelerometer has a resolution of 0.05 m/s^2 between 1 and 10000 Hz, as specified by the manufacturer. The calculated displacements as a function of time are presented in Fig. 11 for accelerations measured in two separate directions. An inspection of Fig. 11 indicates that the maximum displacements were calculated as 14.65 mm and 24.14 mm for the more rigid x and y directions, respectively.

These displacement values are considerably high for a structure with 3000 mm height. The corresponding maximum interstorey drift ratios of the structure were calculated to be 0.81% and 0.49% in x and y directions, respectively. Comments on the vulnerability or the damage state of the structure will be made based on these values.

Studies are available in the literature, where relationships between total or interstorey drift ratios and the potential structural damage were presented (SEAOC 1995, ASCE 2000, Rossetto and Elnashai 2003, Ghobarah 2004, Booth *et al*. 2004). Almost all of these presented relationships consider structural type and the amount of interstorey drift as basic parameters that determine the amount of damage, but none indicate a limitation on applicability based on the source of vibration.

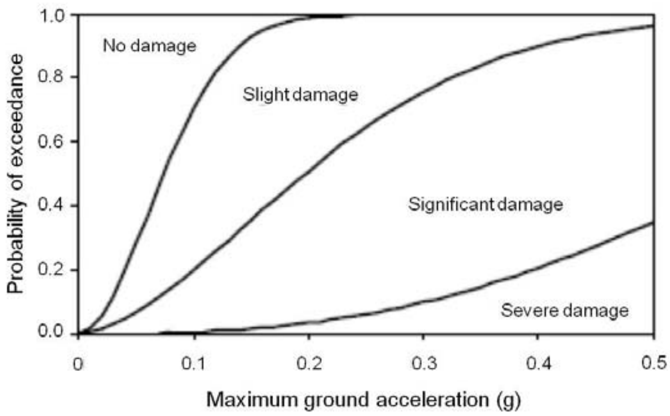
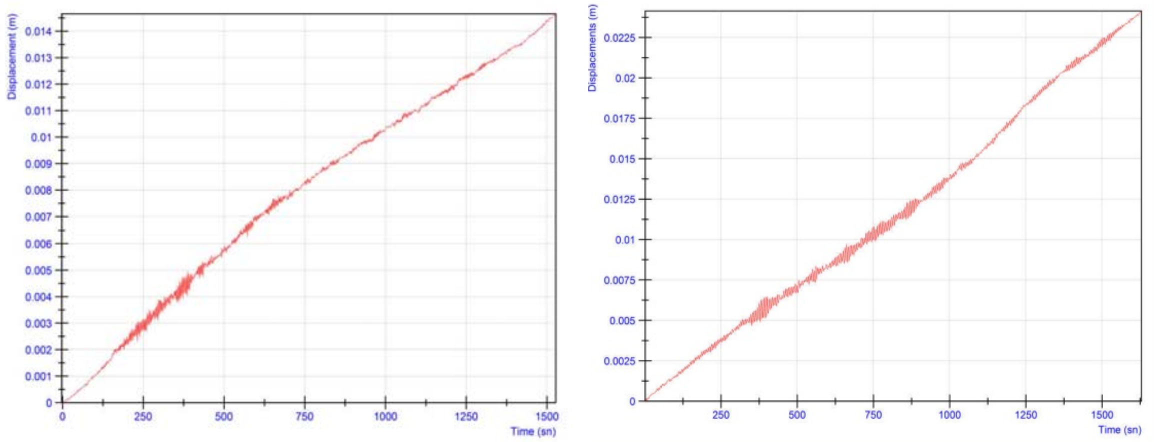


Fig. 10 Fragility Curves of Brick Infilled RC Structures (Mosalam *et al*. 1997)



(a) Displacement-time graph of x direction (b) Displacement-time graph of y direction

Fig. 11 Displacement of cooling structure due to vibration

Table 2 Performance level in terms of interstorey drift as suggested by SEAOC, 1995 and FEMA 273

Performance Level	Building Damage	Transient Drift
Fully Operational	Negligible	Interstorey Drift <0.2%
Operational	Light	0.2%< Interstorey Drift<0.5%
Life Safe	Moderate	0.5%< Interstorey Drift<1.5%
Near Collapse	Severe	1.5%< Interstorey Drift<2.5%
Collapse	Complete	2.5%< Interstorey Drift

Table 3 Limit values of interstorey drift defining the HRC-damage scale (Rossetto and Elnashai 2003)

HRC Limit State	Interstorey Drift
No damage	0.00%
Slight	0.32%
Light	0.43%
Moderate	1.02%
Extensive	2.41%
Partial collapse	4.27%
Collapse	>5.68%

Table 4 Drift limits associated with different damage states (Ghobarah 2004)

Limit State	Ductile MRF	Nonductile MRF
No damage	<0.2%	<0.1%
Repairable damage		
a) Light	0.40%	0.20%
b) Moderate	<1.0%	<0.5%
Irreparable	>1.0%	>0.5%
Severe-Partial Collapse	1.80%	0.80%
Collapse	>3.0%	>1.0%

Thus, it is considered that these relationships can reasonably be used for estimating the damage state of the cooling structure under the vibration effect investigated herein. Tables 2, 3, 4 and 5 present some of the commonly used structural damage criteria based on the interstorey drift ratio.

Performance level and building damage was classified into five categories as a function of interstorey drift in the studies performed by SEAOC and FEMA 273 (SEAOC 1995, ASCE 2000). The interstorey drift ratios in the analyzed cooling structure were calculated as 0.81% and 0.49% in x and y directions, respectively. According to the criteria presented by SEAOC and FEMA 273 (SEAOC 1995, ASCE 2000), these values correspond to the Life Safe performance level and moderate building damage state as can be seen from Table 2.

Rosetto and Elnashai (2003) defined a seven-class homogenized reinforced concrete (HRC) damage scale according to the limit values of interstorey drift (Table 3). The interstorey drift ratios of the analyzed cooling structure correspond to light damage according to HRC scale.

Ghobarah (2004) presented total drift limits associated with six different limit states for ductile and non-ductile structures. If the analyzed reinforced concrete cooling structure is assumed to fall

Table 5 Drift ranges for different damage states (Booth *et al*. 2004)

Damage State	Drift Value
None	0-0.5%
Low	0.5%-0.9%
Moderate	0.9%-1.7%
Extensive	1.7%-4.5%
Complete	>4.5%

within the ductile class, the calculated drift ratios indicate it to have experienced moderate repairable damage (Table 4).

According to Booth *et al*. (2004) classification, which also considers the drift value as the main damage indicator, the analyzed cooling structure lies within low damage state (Table 5).

The assessment of the damage state of the analyzed cooling structure using available classification systems that utilize the total or interstorey drift ratio as the main parameter indicates that the displacements caused by the unforeseen vibrations may result in light to moderate damage. Considering the reported damage state of the building as obtained by the field observations, which indicate no significant damage in the building, it can be stated that the assessment provided by the investigated classification systems are conservative. However, it is clear that, for the modeled building, the performance level is decreased and the risk of damage is increased as a result of the measured vibrations, even without the consideration of fatigue.

6. Conclusions

Measurement and analysis of significant vibrations at a combined natural gas power plant cooling structure which were not foreseen during the design stage is presented in this study. First, accelerations due to these vibrations were measured. Then, the measured acceleration-time history was dynamically loaded on the cooling structure and structural analyses were performed using finite element modeling. The results were used to estimate the damage level of the structure. The results reached at the end of this study are summarized below.

- Identical acceleration time history segments could not be identified, although a similar acceleration pattern on the structure somewhat repeats itself with time. This finding indicates that acceleration is induced by a time-varying but recurring effect, thus creating an acceleration-time behavior that can be approximately classified as periodic.
- The results indicate an increase that ranges between 2% and 60% in the minimum and maximum moments and shear stresses due to vibration effect in all reinforced concrete wall sections composing the structure. This corresponds to an average increase of about 20% in the maximum and minimum moments and shear forces. The analysis results also show that, as expected, stress concentration is amplified due to vibrations at those sections where sharp edges or holes are present. It was observed that, the increase in the shear forces and bending moments due to vibrations in regions where stress concentrations exist are significantly higher than those where the stress distributions are more homogeneous. At locations where stress concentrations do not exist, an average increase of 10% was determined in the member forces as a result of vibrations.

• It was concluded that the vibrations measured on the cooling structure have resulted in a significant increase in member forces. As a result of the analyses, it can be stated that the safety level and reserve resistance of the structure has decreased, and level of risk of the structure has increased.
• The results of the measurements and the finite element analyses indicate that the load carrying units of the cooling structure are under the influence of higher member forces than they were designed for. Although it can be observed that the structure has been capable of carrying these extra loads without significant amount of damage, the fatigue effects should also be considered due to the constant nature of measured accelerations.
• The displacements due to unforeseen operational vibrations on the cooling structure were estimated through double integration of the measured acceleration-time history. The maximum displacements were calculated as 14.65 mm and 24.14 mm for the x and y directions, respectively, which are considerably high values for a structure with 3000 mm height. Light to moderate damage is anticipated due to unforeseen vibrations by available classification systems. Based on the field observations, this is a conservative assessment.
• It is important to keep in mind that the results of the analyses are based on the acceleration measurements taken on the structure. The operation conditions and capacity of the facility at the time of measurement may have an effect on the measured accelerations. Thus, it is important to install the necessary measurement systems for continuous structural monitoring in order to detect and prevent unsatisfactory performance or failure.

References

ASCE (American Society of Civil Engineers) (2000), NEHRP Guidelines for the Seismic Rehabilitation of Buildings. FEMA 273, Washington D.C.

Booth, E., Spence, R. and Bird, J. (2004), "Building vulnerability assessment using pushover methods - a Turkish case study", *Proceedings of the International Workshop on Performance–Based Seismic Design Concepts and Implementation Bled Slovenia*.

Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W. (1996), *Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review*, Report No. LA-13070-MS, Los Alamos National Laboratory, Los Alamos, NM.

Farrar, C.R., Doebling, S.W., Cornwell, P.J. and Straser, E.G, (1997), "Variability of modal parameters measured on the Alamosa Canyon Bridge", *Proceedings of the 15th Int. Modal Analysis Conf., Society of Engineering Mechanics*, Bethel, CT, 257-263.

Ghobarah, A. (2004), "On drift limits associated with different damage levels", *Proceedings of the International Workshop on Performance-Based Seismic Design Concepts and Implementation Bled Slovenia*.

Kim, J.Y., Dae, E.Y., Kim, Y. and Kim, S.D. (2009), "Calibration of analytical models to assess wind-induced acceleration responses of tall buildings in serviceability level", *Eng. Struct*., **31**(9), 2086-2096.

Kosmatka, J.B. and Ricles, J.M. (1999), "Damage detection in structures by modal vibration characterization", *J. Struct. Eng*., **125**(12), 1384-1392.

Lynch, J.P., Law, K.H., Kiremidjian, A.S., Carryer, E., Farrar, C.R., Sohn, H., Allen, D.W., Nadler, B. and Wait, J.R. (2004), "Design and performance validation of a wireless sensing unit for structural monitoring applications", *Struct. Eng. Mech*., **17**(3-4), 393-408.

Lynch, J.P. (2002), *Decentralization of wireless monitoring and control technologies for smart civil structures*, Ph.D. Thesis, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.

Mosalam, K., Ayala, G. and White, R. (1997), *Chapter 7.c: Development of Fragility Curves for Masonry Infill – Concrete Frame Buildings, Loss Assessment of Memphis Buildings*, Technical Report NCEER.

Michelis, P., Papadimitriou, C., Karaiskos, G.K., Papadioti, D.C. and Fuggini, C. (2012), "Seismic and vibration tests for assessing the effectiveness of GFRP for retrofitting masonry structures", *Smart Struct. Syst*., **9**(3), 207-230.

Ni, Y.Q., Wang, B.S. and Ko, J.M. (2001), *Simulation studies of damage location in Tsing Ma Bridge deck*, SPIE Nondestructive Evaluation of Highways, Utilities, and Pipelines IV, SPIE, 3995, 312-323.

Ni, Y.Q., Li, B., Lam, K.H., Zhu, D.P., Wang, Y., Lynch, J.P. and Law, K.H. (2011), "In-construction vibration monitoring of a super-tall structure using a long-range wireless sensing system", *Smart Struct. Syst*., **7**(2), 83-102.

Nikitas, N., Macdonald, J.H.G. and Jakobsen, J.B. (2011), "Identification of flutter derivatives from full-scale ambient vibration measurements of the Clifton Suspension Bridge", *Wind Struct*., **14**(3). 221-238.

Rossetto, T. and Elnashai, A.S. (2003), "Derivation of vulnerability functions for european type RC structures based on observational data", Eng. Struct., **25**(10), 1241-1263.

SEAOC (1995), Performance Based Seismic Engineering of Buildings. Vision 2000 Committee, Structural Engineers Association of California, Sacramento, California.

Shakib, H. and Parsaeifard, N. (2011), "Ambient vibration tests on a 19 - story asymmetric steel building", *Struct. Eng. Mech*., **40**(1), 1-11.

Sohn, H., Dzwonczyk, M., Straser, E.G., Kiremidjian, A.S., Law, K.H. and Meng, T. (1999), "An experimental study of temperature effect on modal parameters of the Alamosa Canyon Bridge", *Earthq. Eng. Struct. D*., **28**(9), 879-897.

Straser, E.G. and Kiremidjian, A.S. (1998), *A modular, wireless damage monitoring system for structures*, Report No. 128, John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.

Tamura, K. (2001), Instrument systems of major bridges in Japan. Proceedings of Instrumental Systems for Diagnostics of Seismic Response of Bridges and Dams, Consortium of Organizations for Strong-Motion Observation Systems, Richmond, CA, 10-18.