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# System identification and reliability assessment of an industrial chimney under wind loading

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**Abstract.** This study presents the reliability assessment of a 100.5 m tall reinforced concrete chimney at a glass factory under wind loading by using vibration-based identified modal values. Ambient vibration measurements were recorded and modal values such as frequencies, shapes and damping ratios were identified by using Enhanced Frequency Domain Decomposition (EFDD) method. Afterwards, Finite Element Model (FEM) of the chimney was verified based on identified modal parameters. Reliability assessment of the chimney under wind loading was performed by obtaining the exceedance probability of demand to capacity distribution. Demand distribution of the chimney was developed under repetitive seeds of multivariate stochastic wind fields generated along the height of chimney. Capacity distribution of the chimney was developed by Monte Carlo simulation. Finally, it was found that reliability of the chimney is lower than code suggested limit values.

**Keywords:** industrial chimney; system identification; wind loading; reliability analysis

## 1. Introduction

In recent years, system identification and health monitoring of structures have experienced transition from an academic research field to an accepted way of condition assessment. The very basic definition of system identification is to collect vibration measurements and then identify dynamic parameters of structures such as frequencies, mode shapes, damping ratios. This allows both to understand actual dynamic characteristics of structures and decrease uncertainties in modeling. To obtain actual structural parameters, FEM updating can be carried out by minimizing the difference between modal parameters obtained from FEM and system identification.

On the other hand, wind loading has long been an issue for owners of industrial facilities and engineers. Almost all industrial facilities such as refineries and glass factories have tall chimneys. Chimneys are one of the main parts of an industrial facility. If malfunction occurs on the chimney, this creates significant economic loss. Furthermore, chimneys are affected by wind loading constantly during their service life. This highlights the priority of monitoring chimney performance under wind loading.

Some of the comprehensive literature reviews related with system identification are given in Doebling *et al*. (1996), Sohn *et al*. (2004), Carden and Fanning (2004), Brownjohn (2007). There are also studies on operational modal analysis of chimneys as follows: Ruscheweyh and Galemann (1996) presented full-scale measurements of a chimney under wind-induced vibrations. Pallares *et al.* (2009) presented operational modal analysis and FEM updating of a masonry chimney considering soil flexibility effect. Brownjohn *et al.* (2010) carried out system identification and FEM updating of a reinforced concrete chimney. Breuer *et al.* (2015) measured horizontal displacements and identified modal values of a chimney under different environmental conditions. Gorski (2017) identified dynamic characteristics of an industrial chimney by GPS measurements and compared these values with the ones obtained from FEM. Sancibrian *et al.* (2017) presented FEM updating of a brick chimney based on vibration-based identified modal values.

In addition to monitoring efforts on chimneys, numerous papers can be found related with analytical formulation of wind loading. Wind loading is composed of mean and fluctuating part which may numerically be generated using stochastic methods. Simulation of random processes was developed and applied by researchers in the literature (e.g., Shinozuka 1972). Typically, Monte Carlo based approaches are used for simulation of wind velocity that range from multi-variate to multi-dimensional cases involving Gaussian, non-Gaussian, stationary, non-stationary, conditional and unconditional (Kareem 2008). Digital simulation of a stochastic process of wind velocity at different points in space requires decomposition of the Power Spectral Density matrix. On the other hand, fluctuating part of wind may also be generated stochastically in time domain. To do this, wind field simulation procedure of n-variate wind velocity vectors are generated to obtain structure response in a time-domain. Studies that present simulation techniques for some types of structures have been carried out (e.g., Yang *et al*. 1997).

Dynamic responses of tall buildings subject to stochastic

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wind loading were investigated by using different probabilistic methods (Zhang *et al.* 2008). They generated stochastic wind field along a tall building, applied wind loading on the structure by using probability density evolution method (PDEM), and found that PDEM is applicable and efficient in the reliability analysis of wind-excited tall building. Besides, the results of the reliability analyses also suggest that the consideration of the uncertainty in structural parameters such as the fundamental period of vibration and the damping ratio is very important for serviceability limit states (Hong *et al.* 2001). Consequently, uncertainties in structural properties may cause response of structure to deviate from actual response.

Considering the uncertainties in structural systems, probabilistic assessment approaches are preferable than deterministic ones. Uncertainties due to the parameters of the calculation model and the inherent randomness of the wind load effect are considered to obtain demand distribution. Kareem (1998) determined resisting factor for probability-based design of the tubular reinforced concrete sections. Kareem and Hsiesh (1986) investigated the reliability of a reinforced concrete chimney under wind loading. Tessari *et al.* (2017) obtains reliability of a steel tower considering uncertainties in material strength and wind loading

In this study, a 100.5 m reinforced concrete chimney at a glass factory was instrumented with twelve acceleration sensors. Vibration measurements were recorded and system identification of the chimney was carried out in order to determine modal parameters such as modal frequencies, shapes and damping ratios. These parameters were identified by using Enhanced Frequency Domain Decomposition (FDD) method. FEM of the chimney was developed in accordance with design drawings and verified based on the modal identification results.

Wind velocity fields were simulated by using multivariate stochastic process. And, demand distribution in terms of over-turning moment was obtained by performing linear time history analyses. In accordance with CICIND (2001), linear time history analyses can be used to obtain base overturning moment for serviceability limit state. Capacity distribution of the chimney's base section was developed by using Monte Carlo method to simulate the randomness in structural parameters. Afterwards, reliability estimation of the chimney was performed and it was found that reliability of the chimney is lower than code suggested limit values.

The suggested approach in this paper, i.e., vibration-based modal identification, validation or updating of FEM, wind simulation and reliability estimation of the chimney can be carried out over years. This will allow owner to quantify the risk when there is deterioration or damage on the chimney. Without obtaining failure probability of the chimney under wind loading, any possible change in the identified modal values would not mean a lot to the owner. Especially, change in modal frequencies over years may put the chimney in resonance regime with applied loading. Such pronounced effects should be quantified in terms of failure probability.

Fig. 1 Overall view of the chimney

## 2. Chimney characteristics and experimental set-up

The chimney is located in Bozuyuk, Turkey. It is 100.5 m tall and its outer diameter is 9700 mm at base and 5750 mm at top. The wall thickness starts from 30 cm at the base and decreases to 20 cm at the top. It was constructed by ENDEM Construction Co. in 2012 .The concrete class used in construction is C 30 (fc'=30 MPa). Fig. 1 presents overall view of the chimney.

Twelve accelerometers were mounted on the chimney to measure the vibration response. The chimney has eight access elevations for the refractory brick liner along the height of chimney. Appropriate location of accelerometers was selected to obtain largest modal displacements. Sensors were located at foundation level and elevations at 25 m, 58 m, 91 m. Fig. 2 shows accelerometers and recorder.

For each elevation, accelerometers were located both along x and y directions. Five accelerometers were mounted at the foundation level. Three of them were mounted vertically to monitor rocking mode during a potential earthquake. An additional sensor along x direction was located at elevation +91 m to monitor torsional mode of the chimney. Data acquisition system was monitored by remote control via internet. Fig. 3 shows the sensors locations along the height of the chimney.

Kinemetrics made sensors (Episensor) with the dynamic range of 155 dB, bandwidth of DC-200 Hz and full-scale range of +/- 2g were used.

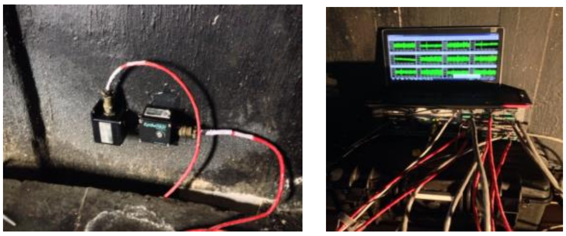

Fig. 2 Accelerometers and recorder

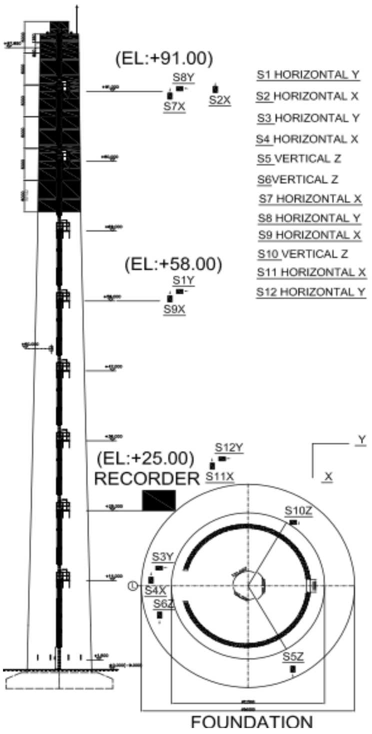


Fig. 3 Sensor layout

## 3. System identification

Different techniques were developed in recent years in order to obtain dynamic properties of structures from ambient vibration responses. In this study, Enhanced Frequency Domain Decomposition (EFDD) method (Brincker *et al.* 2001) was used to identify modal parameters.

Fig. 4 presents a sample ambient vibration data recorded at elevation 25 m and 91 m, respectively.

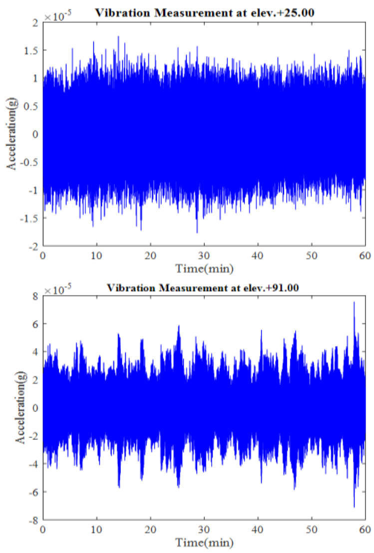


Fig. 4 Vibration measurements at elevation 25 m and 91 m

In FDD method, cross spectral density matrix is generated from vibration data Y(t) and is decomposed by singular value decomposition with Eq. (1)

$$S_{YY}(\omega) = U(\omega)\sum(\omega)U^{H}(\omega) \tag{1}$$

where,

$\sum(\omega)$ is diagonal matrix of singular values,

$U(\omega)$ is unitary matrix of the singular vectors,

$H$ is complex conjugate and transpose.

Here, singular values present modal frequencies and singular vectors present modal shapes. Fig. 5 presents power spectral density of various responses recorded during a single day. From the figure, it is observed that the frequencies of the first, second, third modes are 0.59 Hz, 2.54 Hz, 6.01 Hz, respectively. The peak at 3.90 Hz is related with crude/vacuum heater unit in the main facility located very near the chimney that generates vibration when system is on.

Fig. 6 presents the identified modal damping ratio for one of the data sets. Similar damping identification was performed for the first three modes and amplitude dependency of damping ratio was investigated for all recorded signals at the top the chimney. The damping ratio identified for each data set was plotted with respect to amplitude as shown in Fig. 7; clear increase in modal damping ratio was observed. Eq. (3) presents estimation of the first three modes damping ratio with respect to amplitude.

$$\begin{aligned} DR_1 &= 587\ VA + 0.95 \\ DR_2 &= 108\ VA + 0.68 \\ DR_3 &= 226\ VA + 0.57 \end{aligned} \tag{3}$$

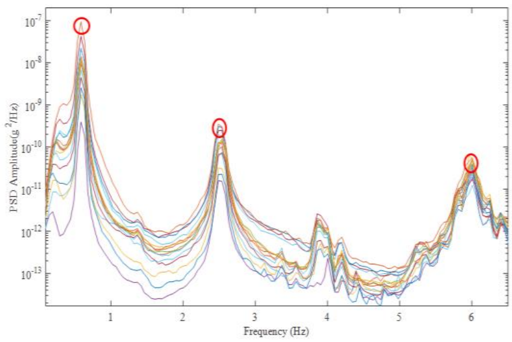


Fig. 5 Modal frequencies

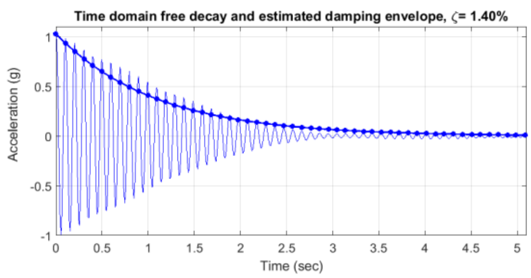


Fig. 6 Modal damping ratio

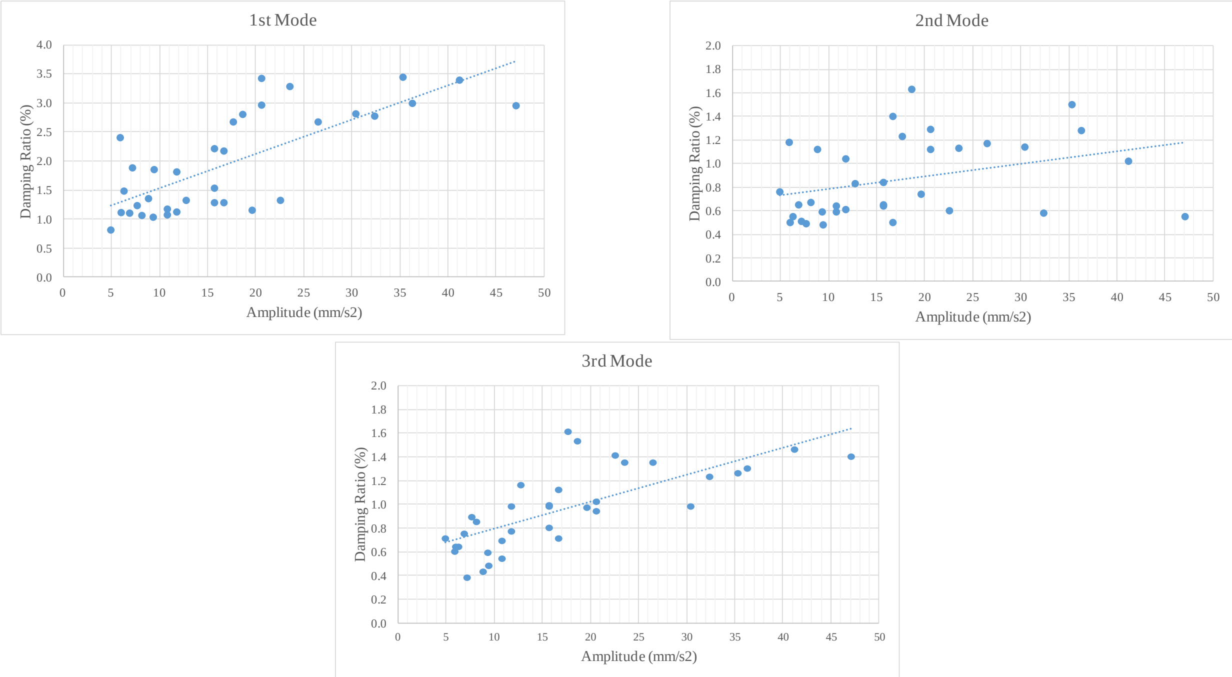


Fig. 7 Variation of damping ratio

Table 1 Damping ratio estimations

| Damping Ratio (%) | | | |
|---|---|---|---|
| CICIND | Eurocode | Niemann and Lupi | Gorski |
| 1.51 | 1.11 | 0.73 | 0.56 |

where;
*DR* is damping ratio
*VA* is vibration amplitude at top level in g

Table 1 presents the estimated damping values for a lined reinforced concrete chimney with foundation on gravel in the literature (Niemann and Lupi 2013, Gorski 2015). It can be seen that the identified damping ratios are in good agreement with the ones in literature; however, Eq. (3) also presents an estimation of damping with respect to vibration amplitude. Therefore, different damping values may be considered based on the location i.e., average wind speed.

## 4. Finite element model of the chimney

Finite element model (FEM) of the chimney based on design drawings was developed in SAP2000. 18000 shell elements were used in the model including foundation with soil springs as shown in Fig. 8. Refractory brick liner masses were assigned on the shell as additional mass. Young's Modulus was computed in accordance with American Concrete Institute (ACI) Code (ACI 318, 2008) and found as 25743 MPa for C30 concrete class. The soil spring coefficient was taken as 20000 kN /m in accordance with soil site investigation report. Total additional mass due to liner were calculated 340 tons along the height of the chimney.

Table 2 shows that vibration frequencies obtained from FEM and vibration measurements agree well.

Furthermore, Fig. 9 illustrates the first, second and third mode shapes from FEM and vibration measurement. Modal Assurance Criteria (MAC) was calculated to evaluate the correlation between mode shapes obtained from system identification results and the FEM simulation. MAC values for the first three modes are 0.992, 0.986, 0.610; respectively.

The first three modes were used in comparisons because mass participation ratios; namely 0.62, 0.23, 0.06 suggest that total dynamic behavior can be represented considering the first three modes.

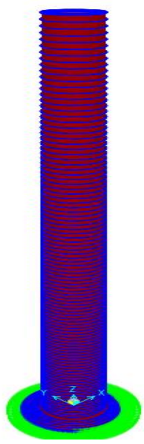

Fig. 8 FEM of the chimney

Table 2 Frequencies from FEM and Vibration Measurement

| Mode Number | Frequencies of Vibration (Hz) | |
|---|---|---|
| | FEM | Experimental |
| 1 | 0.59 | 0.59 |
| 2 | 2.69 | 2.54 |
| 3 | 6.54 | 6.01 |

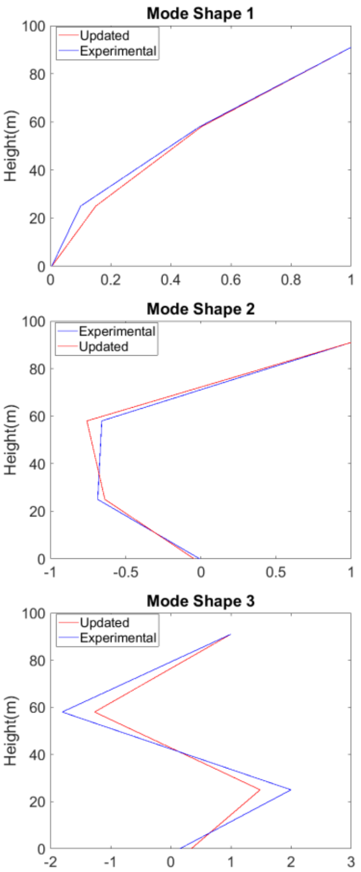


Fig. 9 Mode shapes from FEM and vibration measurement

## 5. Generation of wind loading

Wind field can be simulated as a stochastic process. Wind velocity comprises two parts as mean and fluctuation (gust) part. In this study, the fluctuation part was simulated as a Gaussian ergodic stationary multivariate stochastic process. After generating wind velocity field, wind pressure distribution along the height of the chimney was obtained. And, linear time history analysis of the chimney under wind loading was carried out.

### *5.1 Wind profile and characterization*

Wind field can be characterized by mean velocity profile and fluctuation part. Wind velocity can be defined as in Eq. (4). (Simiu and Scanlan 1996).

$$U(z,t) = \overline{U}(z) + u(z,t) \tag{4}$$

where;
*U (z,t)* is wind velocity
$\overline{U}(z)$ is mean velocity at height z
*u (z,t)* is fluctuation velocity at height z

The mean wind velocity profile is given in Eq. (5).

$$U(z) = \frac{1}{k} u_* \ln\frac{z}{z_o} \qquad \kappa = \frac{k}{\ln(10/z_o)} \qquad u_* = \sqrt{\frac{\kappa}{V_b^{\,2}}} \tag{5}$$

where;
$k$ is Von Karman constant, equal to 0.4
$z_o$ is terrain toughness taken as 0.03 for the location of open terrain
$z$ is height
$u_*$ is shear velocity
$\kappa$ is surface drag coefficient
$V_b$ is basic wind speed measured at 10 m elevation

In order to generate wind data, the mean velocities measured at 10 m above the ground in 10 min period that has probability of exceedance at least once in 50 years, was taken as 30 m/sec in accordance with wind report given by local administration.

### *5.2 Simulation of wind fluctuation*

Wind velocity fluctuation fields were simulated by using multivariate stochastic process. The spectral representation method first proposed by Shinozuka and Jan, (1972). Shinozuka (1974) used Fast Fourier Transform (FFT) technique to reduce computation time drastically. Furthermore, Li and Kareem (1991) used FFT technique to generate multivariate stochastic process. Deodatis and Shinozuka (1989) developed a technique to simulate stochastic waves. Shinozuka *et al*. (1989) built a method to simulate ergodic multivariate stochastic processes by using the concept of double-indexing the frequencies. However, sample functions simulated by using this technique were not ergodic. Later, the spectral representation method was further developed by Deodatis (1996) and was used to successfully simulate ergodic multivariate stochastic processes.

In this paper, wind velocity fluctuations were simulated along the height of the chimney at 100 points. The results for the first 600 seconds at elevation 35 m, 40 m and 100.5 m were presented in Fig. 10.

Fig. 11 presents the auto and cross correlation functions of the realizations at given points of the simulated multivariate stochastic process. In accordance with the plotted figure, the correlation between elevation 35 m and 40 m are strong since they are close to each other and a weaker correlation was seen between elevation 35 m and 100.5 m.

Fig. 12 presents the power spectral density check of the simulated wind velocity horizontal fluctuation fields. As can be seen in the figure, simulated spectra were in good match with target spectra.

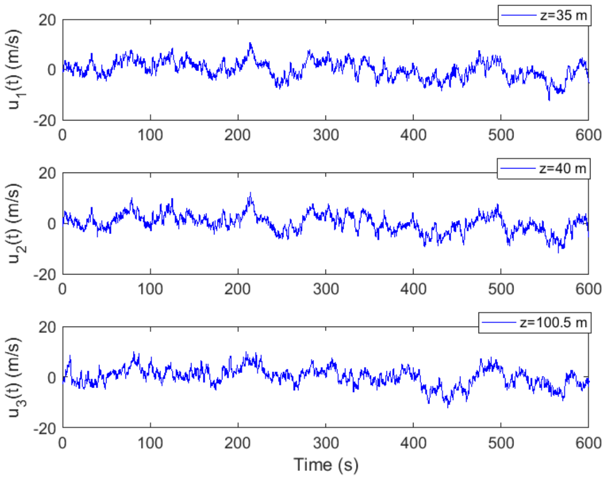


Fig. 10 Simulation of velocity fluctuation at three different heights

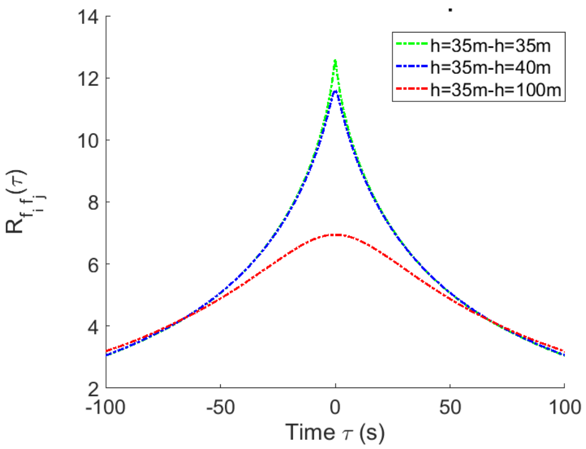


Fig. 11 Auto and cross correlation functions of simulated wind velocities

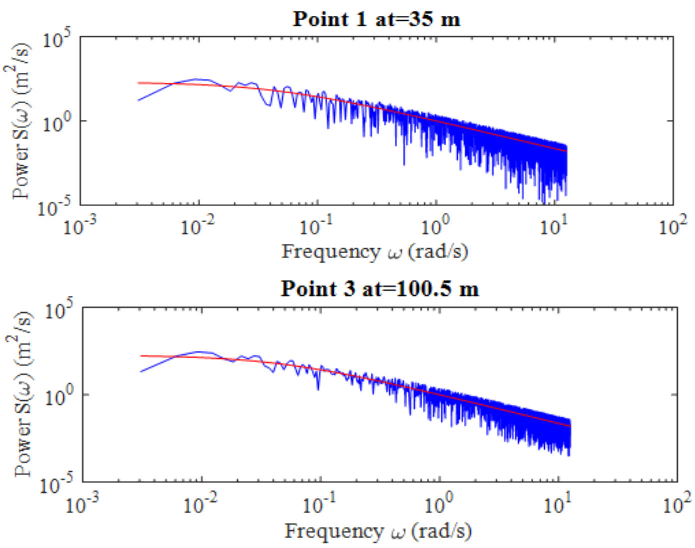


Fig. 12 Power spectrum of simulations and targets

### 5.3 Along-wind actions

Reinforced concrete chimneys are designed to resist the wind forces both in along-wind and across-wind directions. Across-wind actions are not primary concern for the chimney in this study because of the fact that the frequency of the chimney is far from the vortex shedding frequency which can be expressed as in Eq. (6). Therefore, across-wind actions were not calculated in this study.

$$f_s = \frac{SV_{cr}}{D} \tag{6}$$

where
$S$ is the Strouhal number,
$V_{cr}$ is the critical velocity,
$D$ is the diameter at the tip.

Following procedures developed by Vickery and Basu (1983), vortex shedding frequency is obtained as $f_s$=1.39 Hz. Power spectrum of across-wind action can be also plotted by using Eq. (7).

$$S_{CL}(f) = \sigma_{CL}^2 \frac{1}{\sqrt{\pi} B_c f_s} \exp\left[ -\left( \frac{1-\frac{f}{f_s}}{B_c} \right)^2 \right] \tag{7}$$

where;
$B_c$ is bandwith of the spectrum
$f_s$ is dominant frequency of vortex shedding,
$\sigma_{CL}^2$ is mean square value of lift coefficient

Fig. 13 presents that frequency of the chimney (0.59 Hz) falls apart from effective band of across-wind action.

As described in the previous section, wind velocity profile was obtained as shown in Fig. 14.

For along-wind forces, a ‘strip’ assumption regarding the forces on a section of the structure with the flow condition upstream of the section was applied (Holmes 2001).

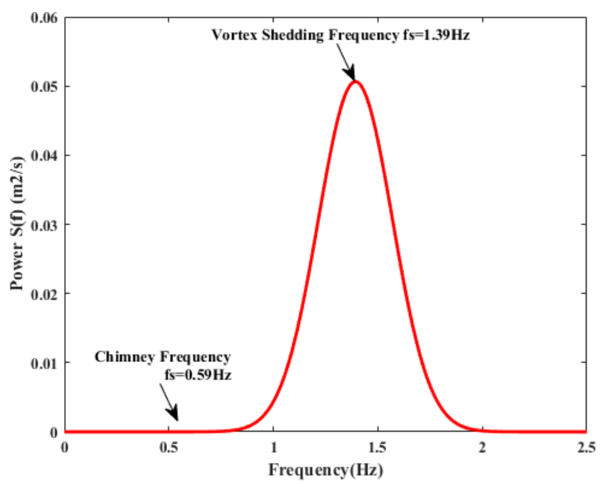


Fig. 13 Power spectrum of across-wind action

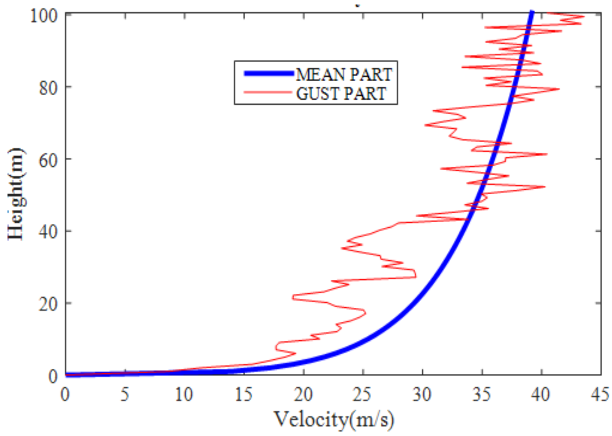


Fig. 14 Wind velocity profile

Along-wind aerodynamic actions were calculated by using obtained wind profile as in Eq. (8).

$$F(z,t) = \bar{F}(z) + f(z,t) \tag{8}$$

$\bar{F}(z)$ is the wind load value along the chimney height regarding mean part of wind profile defined as in Eq. (9).

$$\bar{F}(z) = \frac{1}{2}\rho C_d(z) D(z) \bar{U}^2(z) \tag{9}$$

and $f(z,t)$ is the wind load value regarding fluctuation part of wind profile is expressed in Eq. (10).

$$f(z,t) = \rho C_d(z) D(z) \bar{U}(z) u(z,t) \tag{10}$$

$C_d$ (z), is the drag coefficient taken as in accordance with (ACI 307-08) and given in Eq. (11).

$$\begin{aligned} C_d(z) &= 0.65, \; for z < z - 1.5d(z) \\ C_d(z) &= 1, \; for z = z - 1.5d(z) \end{aligned} \tag{11}$$

where,
$d(z)$ is the diameter of the chimney section at height z.

## 6. Reliability estimation of safe operation

Reliability estimation of the chimney was performed as presented in this section. Demand distribution of the chimney was developed in terms of overturning moment values under many seeds utilizing multivariate stochastic process. On the other hand, capacity distribution of the chimney was calculated in terms of ultimate moment capacity of chimney section at base by using Monte Carlo simulation.

To be able to obtain the distribution of the demand, ten different simulation wind field along the height of the chimney was performed. Afterwards, linear time history analyses were carried out and the maximum values in terms of over-turning moment were obtained. Normal distribution was fitted to these maximum results as shown in Fig. 15.

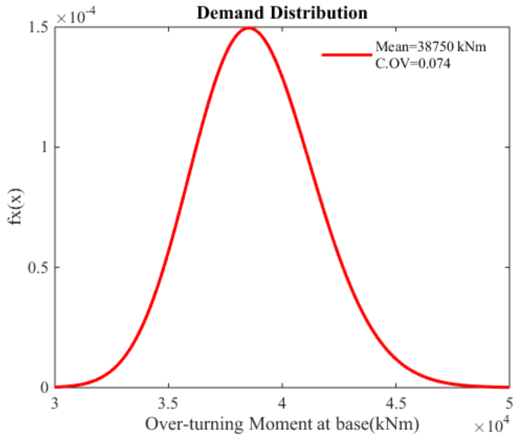


Fig. 15 Demand distribution

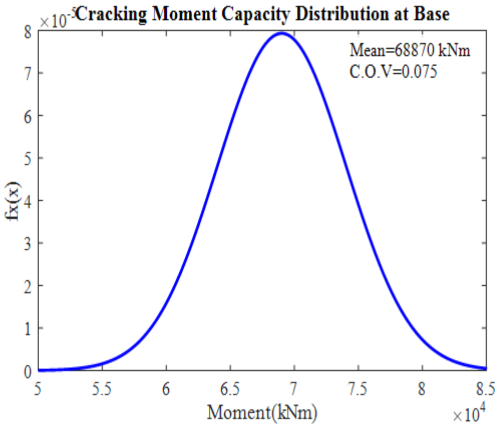


Fig. 16 Capacity distribution

Table 3 Statistics of basic variables

| Variables | Mean | COV | PDF |
|---|---|---|---|
| $E_s$ | 201188 MPa | 0.033 | Normal |
| $f_{ck}$ (C30) | 27.75 MPa | 0.15 | Normal |
| $f_{yk}$ (S420) | 489 MPa | 0.093 | Lognormal |
| $\varepsilon_c$ | 0.003 | 0.16 | Normal |

Cracking moment capacity was obtained for serviceability limit state condition under wind loading (CICIND, 2001). Monte Carlo simulation was used to estimate the mean and coefficient of variation (c.o.v) of cracking moment capacity of the chimney at its base. Random variables were digitally simulated with specified probability distribution function which has mean and c.o.v. values shown as Table 3 (Ellingwood 1980, Mac Gregor *et al.* 1979, Mirza and Mac Gregor 1979).

Closed form equations expressed in CICIND 2001 were used to obtain cracking moment capacity. The number of samples was selected as 30000 and the corresponding capacity distribution was developed for wind loading presented in Fig. 16.

On the basis of the theoretical principles of reliability analysis, failure probability of a system is the cumulative probability that demand is greater than capacity. Failure probability of the chimney was calculated to be $2.10^{-6}$. The target probability of failure for this type of chimney is suggested as $10^{-4}$ (CICIND, 2001) and $10^{-5}$ (Eurocode 2002). The estimated failure probability is below this limit.

## 7. Conclusions

This paper presents reliability assessment of a 100.5 m tall reinforced concrete chimney at a glass factory under wind loading. In this study, modal parameters such mode shapes, frequencies and damping were identified using ambient vibration measurements. Afterwards, FEM of the chimney was verified based on identified parameters.

Reliability of the chimney was estimated as the exceedance of demand distribution to capacity distribution. Demand distribution of the chimney in terms of overturning moment values was obtained by simulation of wind field utilizing multivariate stochastic process. And, capacity distribution was developed with Monte Carlo simulation.

Following conclusions in the context of this study can be drawn as follows:

• Modal frequencies and shapes obtained from FEM are close to ones obtained from system identification. This indicates that construction details of the chimney are well represented by FEM. Single comment related with system identification would be on the low MAC number of the third mode; authors believe that this may be due to insufficient identification of the exact mode shape.

• Damping ratio was obtained as a function top level vibration.

• The target probability of failure for this type of chimney is suggested as $10^{-4}$ (CICIND, 2001) and $10^{-5}$ (Eurocode, 2002). The estimated value is below code-suggested values.

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