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On the wind and earthquake response of reinforced concrete chimneys

Erdem Türkeli[*1], Zeki Karaca[2a] and Hasan Tahsin Öztürk[3b]

[1]*Vocational School of Technical Sciences, Construction Department, Ordu University, Ordu, Turkey*
[2]*Department of Civil Engineering, Faculty of Engineering, Ondokuz Mayıs University, Samsun, Turkey*
[3]*Department of Civil Engineering, Faculty of Technology, Karadeniz Technical University, Trabzon, Turkey*

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Abstract. Slender structures like reinforced concrete (RC) chimneys are severely damaged or collapsed during severe wind storms or strong ground motions all over the world. Today, with the improvement in technology and industry, most factories need these slender structures with increasing height and decreasing in shell thickness causing vulnerable to winds and earthquakes. Main objectives in this study are to make structural wind and earthquake analysis of RC chimneys by using a well-known international standard CICIND 2001 and real recorded time history accelerations and to clarify weak points of these tall and slender structures against these severe natural actions. Findings of this study show that maximum tensile stress and shear stress approximately increase 103.90% and 312.77% over or near the openings on the body of the RC chimneys that cause brittle failure around this region of openings.

Keywords: wind; earthquake; reinforced concrete; industrial; opening; chimney; stack

1. Introduction

All over the world, so many RC chimneys suddenly collapsed during severe wind storms or strong ground motions causing loss of lives and loss of properties. Some of these incidents are: 275 meters high RC chimney located at thermal power plant of Bharat Aluminium Company (BALCO) in Korba, India collapsed in 2009 causing loss of 45 people because of extreme weather conditions (URL-1, 2016). 210 meters high RC chimney at the Paricha Thermal Power Plant in Jhansi, India collapsed in 2010 during strong winds causing loss of 4 people (URL-2, 2016). In 1999 M_w 7.4 Kocaeli, Turkey Earthquake, 115 meters high Tüpras Refinery RC stack (Fig. 1) collapsed (Aliyazıcıoğlu 2004, Tabeshpour 2012).

An approximate analytical approach is presented which makes it possible to consider soil properties and footing embedment in the analysis of the response of structures to external excitation such as wind and earthquake (Novak 1974). İpekçi (1987) dealt with RC chimneys and designing principles of these structures.

Aydoğan and Hasgür (1988) dealt with the general information about RC chimneys and made structural earthquake and wind analysis of selected RC chimneys without using finite element method (FEM). Waldeck (1992) in his study dealt with the across-wind response of 300 m. concrete chimney. The along-wind moments in RC chimney are estimated with the prevailing international codal recommendations by Menon and Rao (1997). Scawthorn and Johnson (2000) provided a preliminary report about Kocaeli (İzmit) Earthquake of 17 August 1999. Wilson (2003) dealt with earthquake response of tall RC chimneys by using the results from an experimental program. Aliyazıcıoğlu (2004) dealt with the structural analysis and design of industrial RC chimneys by using different methods. Two main methods were presented on the equivalent static wind actions on vertical structures like RC structures by Repetto and Solari (2004). Sezen and Whittaker (2004) dealt with the performance of industrial facilities during the 1999, Kocaeli, Turkey Earthquake. Gould *et al*. (2004) dealt with the nonlinear analysis of a collapsed heater stack in August 17, 1999, located at the Tüpras Refinery. Danış and Görgün (2005) studied about 17 August 1999 Kocaeli Earthquake and fire occurred in Tüpras Refinery. The structural analysis and design of industrial RC chimneys by using linear and non-linear

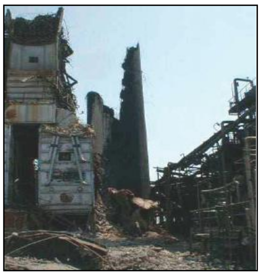

Fig. 1 115 meters high collapsed Tüpras Refinery RC Chimney

∗Corresponding author, Assistant Professor
E-mail: erdem18turkeli@hotmail.com
[a]Associate Professor
E-mail: zekikrc@omu.edu.tr
[b]Assistant Professor
E-mail: htozturk@gmail.com

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methods were studied by Öz (2007). Huang and Gould (2007) dealt with 3-D pushover analysis of a collapsed 115 m high RC chimney located at the Tüpras Refinery during the İzmit (Kocaeli) Earthquake of August 17, 1999. During the construction of the concrete towers, the effect of wind loads was studied by Abdullah (2011). Vaziri *et al*. (2011) studied the behavior and residual structural capacity of RC chimneys subjected to an uncontrolled fire. Karaca and Türkeli (2012) dealt with the determination and comparison of wind loads according to different international codes. Liu *et al*. (2013) dealt with the earthquake responses for the tall flexible structures when the vertical eccentricities between the discrete nodes and the corresponding centroids of investigated lumps are considered. Takabatake and Ikarashi (2013) proposed a new vibration control device to effectively prevent the collapse of slender structures subjected to strong earthquakes. Jisha *et al*. (2014) presented 3-D soil-structure interaction (SSI) analyses of tall RC chimneys with annular raft foundation subjected to wind loads. In the study, different ranges of height and slenderness ratios of the chimneys and different ratios of external diameter to thickness of the annular raft are selected for the parametric study. Jayalekshmi *et al*. (2014) dealt with a numerical 3-D SSI of annular raft of tall slender chimney structures using FEM incorporating the effect of openings in the structure and the effect of soil flexibility. Jayalekshmi *et al.* (2015a) dealt with the numerical analysis of tall RC chimneys with piled raft foundation subjected to along-wind loads considering the flexibility of soil. Jayalekshmi *et al.* (2015b) carried out SSI of tall RC chimneys with piled raft foundation subjected to wind loads according to IS: 4998 (Part 1)-1992. Arunachalam and Lakshmanan (2015) presented a semi-empirical method for predicting across-wind response of a circular chimney due to vortex shedding during lock-in region. Elias *et al.* (2016) dealt with the effectiveness of distributed tuned mass dampers for multi-mode control of chimneys under earthquakes.

2. Research significance

Today, with the improvement of technology, the industrial factories need higher chimneys with the decrease in shell thickness causing them to become irremediable against winds, earthquakes or any other destructive action. From literature survey, it becomes clear that there are a few studies dealing with 3-D structural analysis of these structures considering all body forces acting on them. The incidents given in the introduction part of the study compel us to revise our knowledge about the structural analysis of industrial RC chimneys. Therefore, it is inevitable to make such a research study on tall and slender RC chimneys.

3. Materials used in the study

The structural analysis and design of industrial RC chimneys are generally carried out by using specific codes in the area of expertise. One of the well-known international standards is CICIND 2001 “Model Code for Concrete Chimneys” (CICIND 2001). In this study, wind and earthquake analyses of RC chimneys are executed by using the procedures cited in this specific standard.

3.1 Wind load calculation procedure

There are two components of wind forces namely *along-wind* and *across-wind (vortex shedding phenomena)* that should be calculated for these type of slender and vertical structures whose aspect ratios (*i.e., ratio of height to width of the structure*) are high.

In this part of the study, it is aimed to give only brief information about the wind loading procedure given in CICIND 2001 due to the reason that this cited wind loading standard is open to the use of the public. Therefore, there is no need to give detailed calculation procedures of the standard for the purpose of the volume limitation of the study.

3.1.1 Along-wind forces

In CICIND 2001, total wind on unit height is given by the combination of the mean wind load on unit height and the wind load according to instantaneous wind effect given in Eq. (1)

$$w(z) = w_m(z) + w_g(z) = 0{,}5 \cdot \rho_a \cdot [v(z)]^2 \cdot C_D \cdot d(z) + \frac{3 \cdot (G-1)}{h^2} \cdot \frac{z}{h} \cdot \int_0^h w_m(z) \cdot z \cdot dz \tag{1}$$

In Eq. (1), $w_m(z)$ and $w_g(z)$ is denoting the mean wind load on unit height and equivalent static wind load calculated according to instantaneous wind effect on unit height, respectively. The mean speed at height z which is found from basic wind speed as the hourly mean wind speed at 10 meters height from the ground at open terrain countries is used while calculating the mean wind load on unit height. Moreover, instantaneous wind parameter has an important role in the calculation of the wind according to instantaneous wind effect. Instantaneous wind parameter is the combination of some parameters namely maximum peak factor, turbulence intensity, theoretical turbulence parameter, energy intensity spectrum and size reduction parameter. The other parameters used in the along-wind force calculation procedure are detailed given in CICIND 2001.

3.1.2 Across-wind forces

CICIND 2001 emphasizes that if the equation given in Eq. (2) is satisfied for all sections considered, there is no need to analyze the across-wind forces (*formed from vortex separated from the across-wind surface of chimney*)

$$\frac{G}{V} \geq 2.0 \ \text{kN/m}^3 \tag{2}$$

In Eq. (2), G is denoting the weight of the chimney above the section that is considered and V is denoting the volume of the chimney for the height that the section considered. Also it is stated in CICIND 2001 that if Eq. (2) is not satisfied for the sections considered, then the procedures given in ACI 307/98 "Design and Construction of Reinforced Concrete Chimneys" (ACI 1998) should be used for the calculation of across-wind forces. In ACI 307/98, the peak base moment due to across-wind forces, M_{emax} can be calculated from Eq. (3)

$$M_{e\max} = \frac{G}{g} \cdot S_s \cdot C_L \cdot \frac{\rho_a}{2} \cdot V_{cr}^{\ 2} \cdot d(u) \cdot h^2 \cdot \left[\frac{\pi}{4(\beta_s + \beta_a)} \right]^{1/2} \cdot S_p \cdot \left[\frac{2 \cdot L}{\left[\frac{h}{d(u)} + C_E \right]} \right]^{1/2} \quad (3)$$

In Eq. (3), $d(u)$ is denoting average outer diameter of upper 1/3 part of the chimney, G is maximum multiplier (taken as 4.0), g is gravitational acceleration (taken as 9.81 m/s^2), S_s, mode shape factor (taken as 0.57 for 1st mode), C_L is uplifting force parameter, ρ_a is air density (1.25 kg/m^3), L is correlation length factor (taken as 1.20), C_E is end factor (taken as 3.0), h is total height of the chimney, V_{cr} is critical wind speed at $\frac{5}{6} \cdot h$ of the chimney, β_a is aerodynamic damping, β_s is critical damping quantity, S_p is spectral parameter.

3.1.3 Combining along-wind forces with across-wind forces

Across-wind actions should be combined with the along-wind actions occurring at the same time by using Eq. (4)

$$M_w(z) = \left\{ \left[M_{e\max}(z) \right]^2 + \left[M_1(z) \right]^2 \right\}^{0,5} \quad (4)$$

In Eq. (4), M_{emax} is denoting maximum base moment due to across-wind forces given by Eq. (3) and $M_1(z)$ is denoting the moment occured due to average along-wind actions.

3.2 Earthquake load calculation procedure

Two dynamic methods namely elastic response spectrum analysis given in CICIND 2001 for different types of soils and time history analysis of real ground motions (two components of 1999 M_w 7.4 Kocaeli Earthquake) were selected and used for the dynamic seismic analysis.

3.2.1 Design spectrum analysis according to CICIND 2001

In CICIND 2001, the design spectrum analysis is performed for three different types of soils. Moreover, for the purposes of this study, $R_a(T_r)$, earthquake reduction factor, A_0, maximum ground acceleration factor and I structural importance factor is determined as 2.5, 0.4 and 1.0, respectively. By using 0.01 seconds time interval steps, the dimensionless calculated and drawn design response spectrum for different types of soils is shown in Fig. 2 (CICIND 2001).

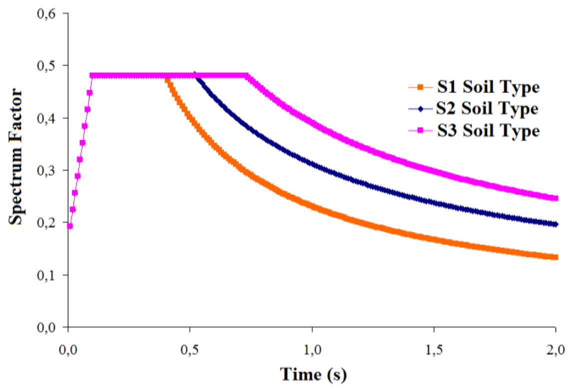


Fig. 2 The design response spectrum curves for different soil types

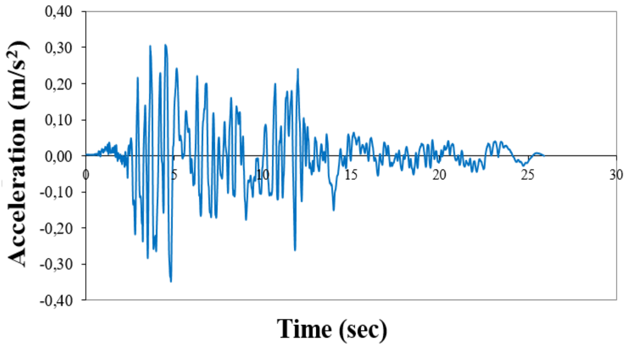


Fig. 3 DZC180 component of 1999 Kocaeli earthquake

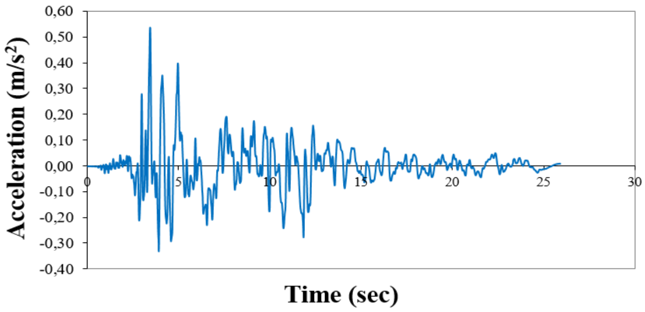
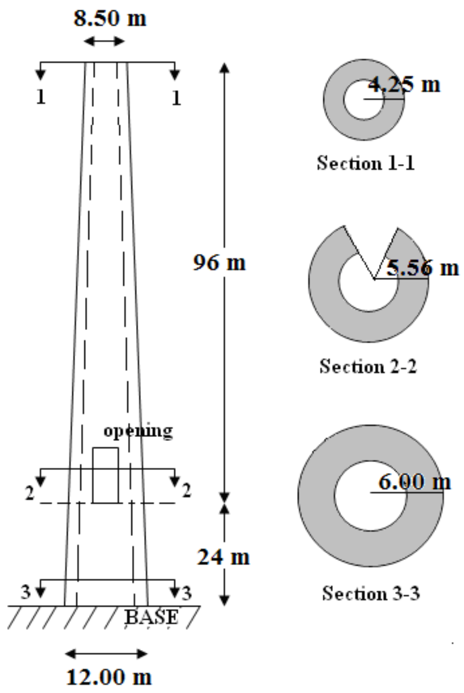


Fig. 4 DZC270 component of 1999 Kocaeli earthquake

3.2.2 Time history analysis (1999 M_w 7.4 Kocaeli Earthquake)

Two components of 1999 M_w 7.4 Kocaeli Earthquake are selected for the time history analysis due to the fact that so many industrial facilities including RC chimneys are heavily damaged or collapsed in this earthquake. An example of these calamities is cited in the introduction part of the study. Two components of 1999 Kocaeli Earthquake namely DZC180 and DZC270 are obtained from Peer Strong Motion Database Records (URL-3 2016). These two components of ground accelerations are shown in Figs. 3 and 4.

4. Wind and earthquake analysis of RC chimneys: Case study



Note: The chimney and the sections are not in scale and ratio.

Fig. 5 General structural properties of modeled chimney

4.1 General Information about the Chimney

A 120 m. high RC chimney is selected for the structural wind and earthquake analysis. The outer diameter at base and top are 12.0 and 8.50 m., respectively. Also, the wall thickness at bottom and top of the chimney are 60 and 26 cm, respectively. The chimney is constructed from RC whose unit weight, the module of elasticity and Poisson ratio is 25 kN/m^3, 30.000.000 kN/m^2 and 0.2, respectively. The base of the modeled chimney is assumed as fixed to the ground. The presence of a nearby structure influences the pressures on a high-rise building due to interference (Ahuja *et al.* 2005). Therefore, the modeled chimney is evaluated considering that there are no chimneys near or around the modeled chimney. The interference effect is not in the scope of this study. Moreover, the modeled chimney is assumed as constructed on open areas that have low vegetation and fewer obstacles. The modeled chimney has a rectangular duct opening whose bottom is about 24 meters high from the base. This rectangular opening is used for flue duct that circumscribed an arc of about 30° and has approximately 2.9 m×6.0 m. dimensions in width and height, respectively. Moreover, the chimney has four inspection slabs with 0.20 meters in thickness and at elevations of 24, 60, 96 and 120 m. These inspection slabs are used for making control or maintenance operations of the chimney. These inspection slabs and the opening on the shell of the chimney are also included in the FEM of the chimney. The general structural properties of the modeled chimney are given in Fig. 5.

4.2 FEM of the chimney

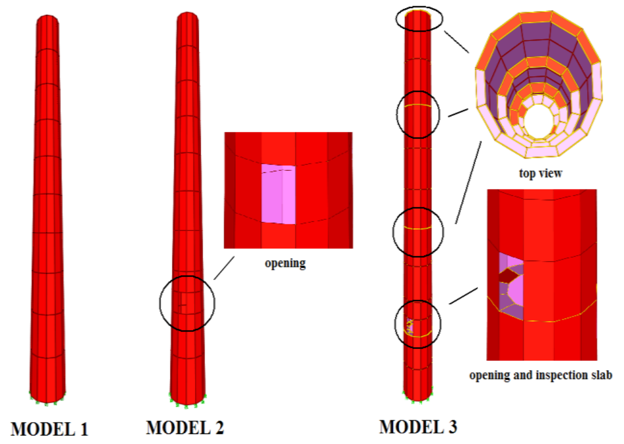


Fig. 6 Three dimensional FEM of the modeled RC chimney

Three FEMs' of the modeled RC chimney is developed in Sap2000 V.11 structural analysis program (Wilson EL 2000) given in Fig. 6.

The first FEM of the chimney has no rectangular opening on the body and it has no inspection slabs. The second model has a rectangular opening whose elevation is about 24 m. from the base and has approximately 2.9 m×6.0 m. dimensions in width and height, respectively. Moreover, this rectangular opening that is used for flue duct is circumscribing an arc of about 30°. Same with the first model, second model has no inspection slabs. The third model has a rectangular opening that has same dimensions and location with the second model. Additionally, the third model has inspection slabs with 0.2 meters in thickness and at elevations of 24, 60, 96 and 120 m. In the construction of the body of the chimney, 120 thin shell elements with the heights of 12 meters are used. Moreover, four inspection slabs at the specified heights is constructed from 12 thin plate elements.

4.3 Dynamic analyses of the chimney

The dynamic structural properties namely 1st mode periods of Model 1, Model 2 and Model 3 are obtained as 1.398399, 1.418935 and 1.471812 seconds in SAP2000, respectively.

4.4 Wind load calculation according to CICIND 2001

4.4.1 Along-wind load calculation

Total along-wind load on unit height is calculated by the combination of the mean wind load on unit height and the wind load according to instantaneous wind effect as given in Eq. (1). These are given in Table 1, Table 2 and Table 3 for Model 1, Model 2 and Model 3, respectively. In these calculations, basic wind speed is taken as 45 m/s. Although, the loads obtained from CICIND 2001 in Table 1, Table 2 and Table 3 are equivalent static loading which account for dynamic wind-structure interaction by "Gust Response Factor", the application of these loads to the models are statically. Therefore, in this study, the loading according to CICIND 2001 is called as static wind loading.

Table 1 1st Model along-wind calculation according to CICIND 2001

Section No	Height From Base (m)	V_b (m/s)	$w_m(z)$ (kN/m)	$w_g(z)$ (kN/m)	$w(z)$ (kN/m)
0-1	12.0	45.00	10.051	0.018	10.070
1-2	24.0	45.00	11.838	0.172	12.009
2-3	36.0	45.00	12.850	0.630	13.480
3-4	48.0	45.00	13.483	1.566	15.049
4-5	60.0	45.00	13.878	3.148	17.026
5-6	72.0	45.00	14.106	5.529	19.635
6-7	84.0	45.00	14.208	8.843	23.051
7-8	96.0	45.00	14.209	13.201	27.409
8-9	108.0	45.00	14.126	18.687	32.813
9-10	120.0	45.00	13.974	25.357	39.331

Table 2 2nd Model along-wind calculation according to CICIND 2001

Section No	Height From Base (m)	V_b (m/s)	$w_m(z)$ (kN/m)	$w_g(z)$ (kN/m)	$w(z)$ (kN/m)
0-1	12.0	45.00	10.051	0.018	10.070
1-2	24.0	45.00	11.838	0.173	12.010
2-3	36.0	45.00	12.850	0.633	13.483
3-4	48.0	45.00	13.483	1.574	15.057
4-5	60.0	45.00	13.878	3.164	17.042
5-6	72.0	45.00	14.106	5.558	19.664
6-7	84.0	45.00	14.208	8.889	23.097
7-8	96.0	45.00	14.209	13.269	27.478
8-9	108.0	45.00	14.126	18.784	32.910
9-10	120.0	45.00	13.974	25.488	39.462

Table 3 3rd Model along-wind calculation according to CICIND 2001

Section No	Height From Base (m)	V_b (m/s)	$w_m(z)$ (kN/m)	$w_g(z)$ (kN/m)	$w(z)$ (kN/m)
0-1	12.0	45.00	10.051	0.019	10.070
1-2	24.0	45.00	11.838	0.175	12.013
2-3	36.0	45.00	12.850	0.642	13.492
3-4	48.0	45.00	13.483	1.596	15.078
4-5	60.0	45.00	13.878	3.208	17.086
5-6	72.0	45.00	14.106	5.634	19.740
6-7	84.0	45.00	14.208	9.011	23.219
7-8	96.0	45.00	14.209	13.452	27.660
8-9	108.0	45.00	14.126	19.042	33.168
9-10	120.0	45.00	13.974	25.839	39.813

4.4.2 Across-wind base moment calculation

CICIND 2001 emphasizes that if the equation given in Eq. (2) is satisfied for all sections considered, there is no need to analyze the across-wind forces (*formed from vortex seperated from the across-wind surface of chimney*). A section at 108 meters height is selected to analyze whether at this section, the given equation is satisfied or not. For the section selected at 108 meters: the weight of the chimney above the section that is considered, G=2264.537 kN and also, the volume of the chimney for the height that the section considered, V=1607.531 m^3. The ratio of the weight to the volume of the section is found as 1.408 which is smaller than 2.0. It can be clearly seen that Eq. (2) is not satisfied. Therefore, across-wind actions on the chimney should be analyzed. The across-wind base moment calculation of the 1st model, 2nd model and 3rd model according to Eq. (3) is given in Table 4, Table 5 and Table 6, respectively.

Table 4 1st Model across-wind base moment calculation

$V(z_{120})$ (m/s)	V_{cr} (m/s)	C_L	β_s	S_p	β_a	M_{emax} (kN.m)
46,11	30,03	0,13	0,04	0,70	-0,02	1699,9

Table 5 2nd Model across-wind base moment calculation

$V(z_{120})$ (m/s)	V_{cr} (m/s)	C_L	β_s	S_p	β_a	M_{emax} (kN.m)
46,11	29,60	0,13	0,04	0,67	-0,02	1490,7

Table 6 3rd Model across-wind base moment calculation

$V(z_{120})$ (m/s)	V_{cr} (m/s)	C_L	β_s	S_p	β_a	M_{emax} (kN.m)
46,11	28,54	0,13	0,04	0,59	-0,01	1057,2

The moments occurred from the application of along-wind forces are combined with the across-wind base moments by using Eq. (4). The combined moments are 187493.3 kN.m, 187945.7 kN.m and 189152.6 kN.m for Model 1, Model 2 and Model 3, respectively.

4.5 Application of wind and earthquake loads to the models

Combined along-wind and across-wind moments and dynamic accelaration loads (*i.e., spectrum and time history analysis loads*) are applied to the models on the direction passing through the axis that is dividing the opening into two equal arcs that is circumscribing an angle of 15° given in Fig. 7.

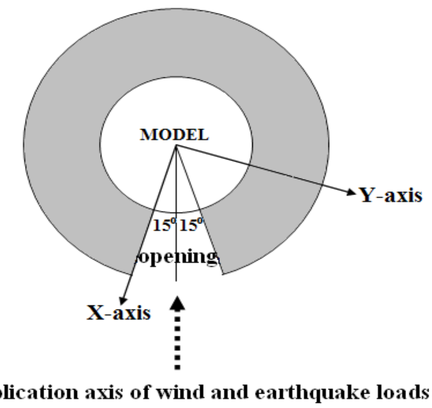


Fig. 7 Application of the loads to the models

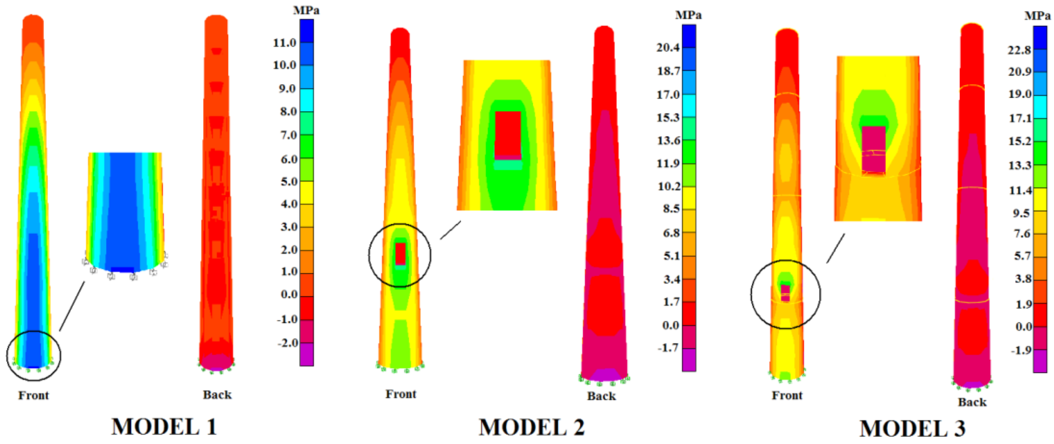


Fig. 14 Maximum tensile stress (S_{max}) distribution over modeled chimneys (in MPa)

Table 7 Maximum top joint displacements obtained from models under different loadings

Load\Model No	Model 1		Model 2		Model 3	
	X (cm)	Y (cm)	X (cm)	Y (cm)	X (cm)	Y (cm)
WIND	8.30	2.22	8.51	2.28	8.50	2.28
CICIND S1	14.70	3.93	14.90	3.99	15.32	4.10
CICIND S2	20.60	5.54	21.00	5.63	21.75	5.83
CICIND S3	25.80	6.92	26.20	7.03	27.17	7.28
DZC 180	22.20	5.94	22.30	5.97	25.83	6.92
DZC 270	44.10	11.81	43.30	11.59	44.85	12.02

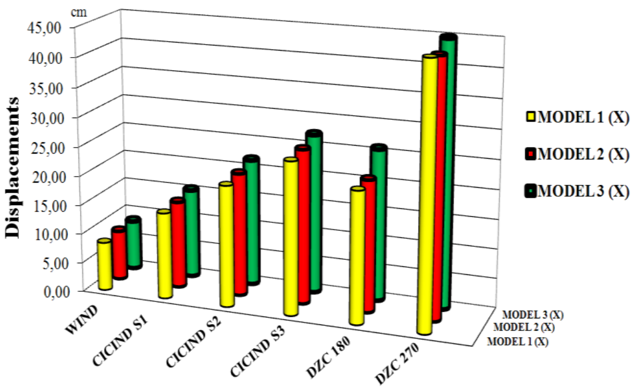


Fig. 8 Top joint displacements in X direction under different loadings

5. Structural wind and earthquake load analysis results

The analysis results are obtained and evaluated under three main categories namely top joint displacements, stress analysis and base reactions. Also, the explanations of the abbreviations about the loadings shown in the following tables are given as follows: WIND (*The equivalent static*

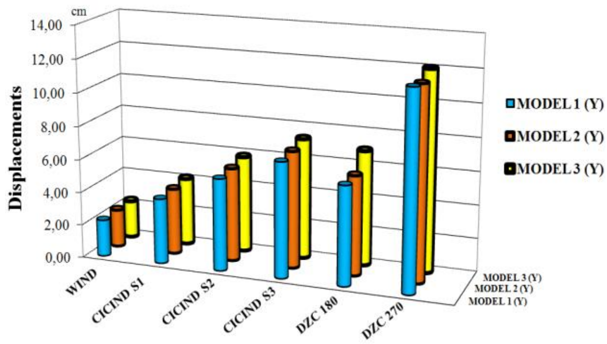


Fig. 9 Top joint displacements in Y direction under different loadings

loading according to CICIND 2001), CICIND S_n (*The design spectrum analysis for three different types of soils according to CICIND 2001*) and DZC (*The real recorded two components of 1999 M_w 7.4 Kocaeli Earthquake*).

5.1 Top joint displacements

The maximum absolute displacement values obtained on top of the models for X and Y directions are given in Table 7. Also, these values are shown in Figs. 8 and 9 schematically.

5.2 Stress analysis

The maximum tensile (S_{max}) and shear stress distribution (*in MPa*) over the modeled chimneys is analyzed under DZC270 loading at the time of maximum response in which maximum displacement values occur in X and Y directions for all modeled chimneys (Figs. 14 and 15).

5.3 Base reactions

The base reactions of the modeled chimneys are analyzed under DZC270 loading in which maximum displacement and maximum stress values occur in X and Y directions. The results are given in Table 8.

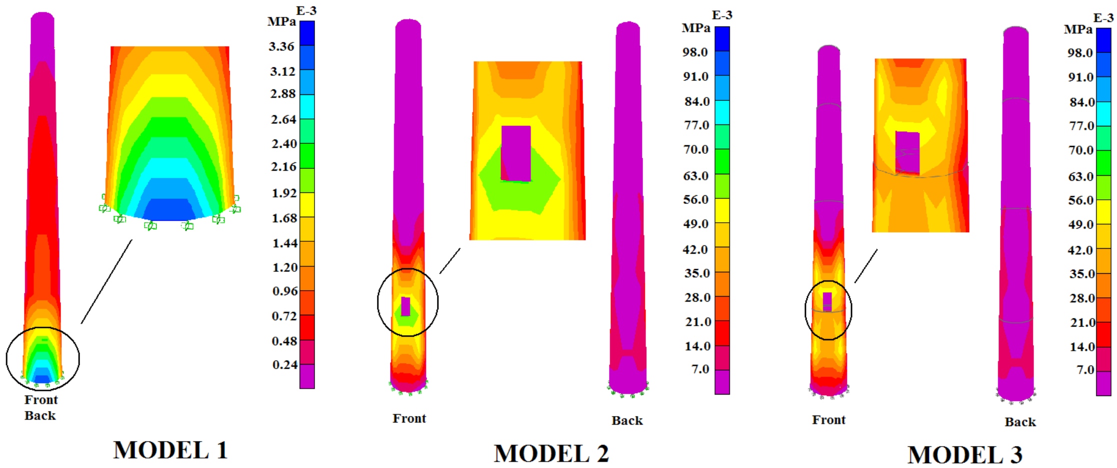


Fig. 15 Maximum shear stress distribution over modeled chimneys (in MPa)

Table 8 Base reactions of modeled chimneys under DZC270 loading

Model No\Base Reaction	X Direction (kN)	Y Direction (kN)
Model 1	14471.66	3694.17
Model 2	14568.81	3724.40
Model 3	17340.48	4549.8

6. Discussion of the results

6.1 Joint displacements

For all modeled chimneys, the top joint displacement has an increasing tendency from the loading WIND to DZC270 i.e., WIND < $CICINDS_1$ < $CICINDS_2$ < $CICINDS_3$ < DZC180 < DZC270. This shows that real recorded earthquake loading creates maximum displacement response (44.85 cm. in X direction for Model 3) when compared with the static and dynamic spectrum loadings. Moreover, the displacement response of Model 3 is greater than Model 2 and Model 1. This is due to the differences that Model 3 contains an opening different from Model 1 and four inspection slabs different from Model 2. Also, adding inspection slabs to the system has the effect of increase in the mass of the structure which has the reverse effect on earthquake and displacement response.

6.2 Stress analysis

The interpretation of Fig. 14 shows that for Model 1, the maximum tensile and maximum shear stress distributions seem to be in expected manner that is decreasing from bottom to top of the chimney. However, for Model 2 and Model 3 (*contains an opening on the body of the shell*), the maximum tensile and maximum shear stress distributions are piled up on the areas near and over the opening. From Fig. 14, it can be clearly seen that, from Model 1 to Model 2, the percentage increment in maximum tensile stress near or over the opening is 103.90%. This means a brittle and sudden failure from this region (*opening region*) without showing any ductile behavior. This behavior is observed in 1999 M_w 7.4 Kocaeli Earthquake in RC chimneys as indicated in the previous sections of this study. Also, from Fig. 14, from Model 2 to Model 3, the percentage increment in maximum tensile stress near or over the opening is only 7.43% which is in tolerable limits. It can be clearly said that the RC chimneys that contains opening on the body should be analyzed carefully from the regions of openings. Another stress type to be analyzed is the shear stress on the body of the chimneys. From Fig. 15, from Model 1 to Model 2, it can be clearly identified that the percentage increment in maximum shear stress near or over the opening is 312.77%. In the same manner, from Model 2 to Model 3, the percentage increment in maximum shear stress near or over the opening is only 2.41%. Exactly as maximum tensile stress distribution, this dramatic increase in shear stress near or over the openings causes a brittle and sudden failure of the chimney.

6.3 Base reactions

From Table 8, it can be clearly seen that base shear reactions have an increasing tendency from Model 1 to Model 3 i.e., Model 1 < Model 2 < Model 3. Also, the maximum base shear reactions occurred under DZC270 loading in which maximum displacement and shear responses observed. Moreover, as can be seen from Table 8, from Model 1 to Model 2, the percentage increment in base shear reactions in X direction is 0.67%. In the same manner, from Model 2 to Model 3, this percentage increment is 19.02% which is due to the reason that the mass of inspection slabs increase the base shear reactions.

7. Conclusions

In this study, structural wind and earthquake analysis of an industrial RC chimney is performed by using the procedures of CICIND 2001, a currently world-wide used standard. In order to verify and compare the acceptability degree of the analysis results obtained from the application of static wind and dynamic earthquake spectrum loads obtained from CICIND 2001, the real time history of the two components of ground movements experienced in 1999 M_w 7.4 Kocaeli Earthquake are also applied. This earthquake is selected because of the reason that so many industrial facilities are damaged or destructed in this fatal disaster. The overall results derived from the findings of this study are summarized below.

- The openings on the body of RC chimney and the inspection slabs added to the inner part of the chimneys significantly change the overall dynamic response of the chimney. From the dynamic analysis performed, it can be seen that there is a tendency to increase in the 1st mode periods i.e. from Model 1 to Model 3 (1.39 s. to 1.47 s.). This change in the period affects the overall response of the chimney.
- The along-wind and across-wind forces calculated from the procedures of CICIND 2001 have an increasing and decreasing tendency from Model 1 to Model 3, respectively. This is because of the reason that the along-wind and across-wind load calculations according to CICIND 2001 are based on the dynamic properties (*1st mode period or frequency of the chimney*) of chimney which is strictly connected to the structural properties (*i.e., opening on the body or the inspection slabs added to inner part of the chimney*) of the chimney explained before.
- The maximum top joint displacements obtained from the models show that static wind loading analysis according to CICIND 2001 underestimates the overall response of the modeled RC chimneys when compared with the results of dynamic spectrum and time history analysis.
- The structural performance of the currently standing RC chimneys should be checked by using the dynamic earthquake methods (*i.e., spectrum or time history analysis*) cited before.
- From the interpretation of the maximum tensile and shear stress analysis of the modeled chimneys, it is evident that the tensile and shear stress increases rapidly and abnormally over or near openings. By adding only one opening on the shell of the modeled chimney, the maximum tensile stress increases 103.90% and maximum shear stress increases 312.77% which is very high for a relatively small thickness shell element. This dramatic increase in tensile or shear stress over or near the openings is the main reason for the brittle failure or destruction of industrial RC chimneys without showing any ductile behavior. Therefore, for the region of openings, extra tensile and shear steel should be occupied in order to maintain the ductility and prevent brittle failure. Also, in the region of openings, lap splicing of longitudinal steel bars should be avoided.
- From the base shear reaction analysis of the modeled chimneys, it is evident that the additional mass to the structural system (*by adding inspection slabs*) of the chimney dramatically increase the base shear reactions as seen in Model 2 to Model 3.

In summary, this study showed that extra precautions should be taken over or near openings which cause the brittle failure of the RC chimneys. In order to generalize the results obtained from this study, it is considered as beneficial that similar studies should be made on different chimneys with different standards.

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