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Effect of Rotational Components of Strong Ground Motions on the Response of Cooling Towers Based on Dense Array Data (A Case Study: Kazeron Cooling Tower)

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ABSTRACT: The effect of earthquake rotational component (torsional and rocking ones) on the structures, has attracted the attention of many researchers in recent years. The impact of the rocking and torsional components of the ground motion, particularly on high-rise and height-wise irregular structures, is significant. In this paper, the rotational components of earthquake record were computed employing the acceleration gradient method, using the data obtained from a dense accelerometer array, and the behavior of the cooling towers under the influence of these rotational components was investigated. To this end, three distinct loading combinations were applied to the tower, and the results were examined and compared. The loading combinations include 1) three translational components of earthquake record, 2) applying rotational and translational components of the earthquake simultaneously, and 3) applying translational and rocking components concurrently. The response of the tower under the two latter loading combinations was compared with that of the first one. The results indicate that in the case of simultaneous action of translational and rocking components, displacements and support reactions, on average, increase by 5% in comparison with the case of applying solely translational component. Furthermore, including the torsional component, in addition to the rocking one, leads to a rise of nearly 6% in the displacements and supports reaction in comparison with the first loading combination results.

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1- Introduction

The rotational (rocking and torsional) components can be determined using the translation components of strong ground motion. Newmark [1], for the first time, presented a relationship between the torsional and translational components of the ground motion. Ghafory-Ashtiany and Singh [2] proposed a simple relationship to calculate the rotational component of ground motion. Moreover, the finite difference method has been employed in several studies [3, 4]. By applying databases of several stations in an accelerometer array, and applying a geodetic procedure, Spudich et al. computed the rotational component with high precision [5].
In order to improve the measurement accuracy and reduce the amount of error in the computation of rotational components, in terms of translational ones, a novel procedure known as the acceleration gradient method was developed by Basu et al. [6], Falamarz-Sheikhabadi [7] and Falamarz-Sheikhabadi and Ghafory-Ashtiany [8] indicated that the contribution of the earthquake rocking components to the rotational response of multi-storey buildings is highly sensitive to the structural irregularity, the height of the structure, and the type of seismic excitation. Height-wise irregularities in a structure can magnify the effect of the rocking component of the earthquake. They demonstrated that the contribution of the rocking component to the storey shear can be as much as one-third that of the horizontal component, and this should be accounted for in the seismic design codes. Furthermore, they concluded that five percent eccentricity considered in many seismic design codes, to the factor in the effect of accidental torsion, is not a conservative approximation of the actual accidental eccentricity generated by the torsional component. This is, particularly, significant in regular, torsionally rigid, and multi-storey buildings. Sarokolai et al. [9] examined the effect of rocking component on the response of a water tower, and observed the significant effect of the rocking component on the shear force and on the horizontal displacement, while no impact was felt on the vertical reaction force.
Although building codes introduce a design eccentricity, the effect of rocking component on structures is taken into account only in the Eurocode (Eurocode 8, part: 6) for the structures above 80 m in height [10]. Cooling towers are the biggest shell structures in their own right, and owing to the role they play in power plants, they are categorized as specific structures. Rao and Rao [11] explored the stress distribution in the shell and supporting base of hyperbolic cooling towers subjected to foundation settlement using the discrete finite element method. Chaojin and Spyrakos [12] investigated the effect of soil-structure interactions as well as foundation uplift for a tower structure and demonstrated that uplift significantly reduces the flexural moment and foundation rotation in the case of hard soil and cylindrical tower, while for short towers, it increases the shear force. Nasir et al. [13] conducted a survey in order to identify how the shell response is affected by parameters such as the height, thickness, and curvature of the shell. They suggested that the natural period of the structure increases, as its curvature increases, while for very high curvature values, this trend reverses. Noorzaei et al. [14] undertook a study on the physical modeling and material type of soil-foundation system. Their results revealed that the soil-tower interaction has a considerable effect on the stress values.

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In this paper, the rotational components of strong ground motions using the data of the highly dense accelerometer array of Chiba by the second-order acceleration gradient method were determined. Also, the effect of rotational components on the shell and columns supporting cooling tower by nonlinear time history analysis were studied. A case study is Kazeroon cooling tower.

2- Ground motion data

2- 1- Chiba accelerometer array and estimation of rotational component of strong ground motion

A unique 3D mass seismometer array system was installed in Chiba Experiment Station of Institute of Industrial Science, the University of Tokyo in 1982. In this array, seismometers and accelerometers are densely placed, both on the ground surface and in the boreholes. The Chiba station is located around 30 km east of Tokyo. The array system is comprised of 15 boreholes with 44 three-component accelerometers. Eight surface accelerometers are densely arranged, four of which are located just 5 m from C0, and the other four are 15 m from C0. A big triangular network exists with each of the three sides being about 300 m around C0 borehole. Time steps to record the data of all the seismometers and accelerometers are 0.005 s [15]. Figure 1 shows the location of Chiba accelerometer array and layout of stations, and Table 1 lists the characteristics of the earthquakes recorded at this accelerometer array.

Based on the previous research and given the layout of the stations as well as the ratio of noise to earthquake signals, the database of this array is capable of accurately estimating the rotational components [4, 16]. Bodin et al. [17] showed that to obtain array-gradient estimates accurate to within ~90% of true gradients, the array dimensions must be less than one quarter-wavelength of the dominant energy in the wave train. Later, Langston [18]- [19] indicated that the accuracy order of finite difference approximation depends also on the geometry of the array. He found that the station spacing must be ~10% of a horizontal wavelength to obtain %90 accuracy, and these finite difference estimates are in first- and second-order of accuracy for irregular and regular arrays, respectively. Regarding estimated large-wave velocity (Katayma et al. [15]) and the very closely spaced instruments in the Chiba array, the torsional motions can be accurately evaluated for the two closely spaced rings (C0, C1-C4) and (C0, P1-P4) up to the high-frequency range (< 11 Hz). Spudich et al. introduced a geodetic method that can estimate torsional motion using multiple stations with a higher precision. In the framework of classical elasticity, and further assuming infinitesimal deformations, displacement of a point r is related to that of a neighboring point *r+δr*:

$$u(r+\delta r) = u(r) + G\delta r = u(r) + \varepsilon\delta r + \omega \times \delta r \quad (1)$$

where *G, ε, ω* are the displacement-gradient matrix, strain, and rotation, respectively. Using the displacement-gradient matrix *G*, one can compute strains and rotations. The *G* matrix is given by

$$G=\begin{pmatrix} \partial_x u_x & \partial_y u_x & \partial_z u_x \\ \partial_x u_y & \partial_y u_y & \partial_z u_y \\ \partial_x u_z & \partial_y u_z & \partial_z u_z \end{pmatrix} \quad (2)$$

The relation between rotational and translational motions is obtained through the application of the curl operator (∇×) to the displacement by:

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \frac{1}{2}\nabla\times u(r) = \frac{1}{2}\begin{pmatrix} \partial_x u_z - \partial_z u_y \\ \partial_z u_x - \partial_x u_z \\ \partial_x u_y - \partial_y u_x \end{pmatrix} \quad (3)$$

where ω_x, ω_y, ω_z are rotations about x, y and z axes.

The rotational components computed using the GM do not necessarily characterize free-field motion, but rather are inputs to a rigid foundation with a footprint described by the spatial distribution of the recording stations in the array.

The physical interpretation of the solution vector computed using Equation (3) (the GM) is a planar surface best-fit through the measured dataset at every time step. The curvature of the distribution surface must be computed to enable a comparison

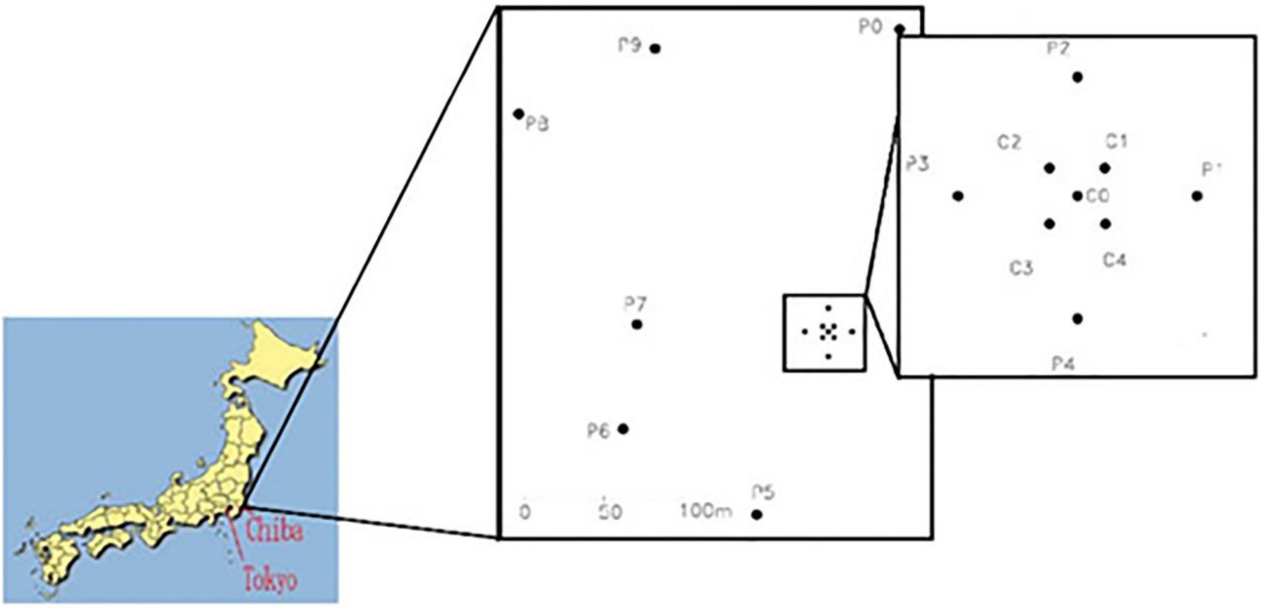

Fig. 1. Chiba array configuration and reference system [16]

Table 1. Characteristics of selected earthquakes from Chiba accelerometer array [4]

NO.	Event No.	Focal Depth (Km)	Distance (Km)	PGA (cm/s²)		M_{JMA}*
				NS	EW	
1	33	73.3	104.5	52.29	59.61	6.5
2	36	56.5	62.4	45.47	29.39	4.9
3	37	57.9	44.7	400	292.51	6.7
4	38	58	42.4	18.23	30.28	4.4
5	40	40	52.3	34.48	28.27	4
6	41	42	37.4	48.45	52.56	4.2
7	42	47.6	37.9	117	79.18	5.2
8	43	32	16.9	37.41	27.39	4.1
9	45	55.3	47.7	57.3	70.39	5.6
10	47	55.7	55.2	31.95	34.13	6
11	48	44.5	51.8	28.01	48.66	4.9
12	81	96	42.2	71.35	86.38	9
13	82	69	62.4	38.17	51.02	5.3
14	84	50	40.2	90.63	121.17	5.4
18	85	50	69.6	40.7	46.57	5.2
16	86	81	7.9	29.74	31.1	4.9
17	87	82	52.4	91.3	93.73	5.9

*Japan Metrological Agency

of rotational motions with estimates obtained using single station procedure. Basu et al. established the curvature of the surface using a second-order Taylor expansion of the displacement field about the reference station. The second-order method is denoted as acceleration gradient method 2 (AGM2).

The rotational components were measured using the translational one recorded at Chiba accelerometer array by employing second-order acceleration gradient method [6] for the stations of the internal and external rings with the maximum accelerometer spacing of 15 m. A sample response spectrum obtained for the rocking (SRSS combination of rocking component about X and Y axis) and torsional components at the station C0 for the event No.37 are illustrated in Figure 2.

2- 2- Selected earthquake records for time history analysis

A study of the tower performance was carried out using the SAP 2000 software, employing the nonlinear time history analysis. To do this end, four earthquakes numbered 36, 37, 38, and 87, recorded at the Chiba accelerometer array, were used. The specification of the events was listed in Table 1. Also, peak ground acceleration of each event was scaled to 0.35g. Translational and computed rotational motions were applied to the tower in three cases and the results were compared:

a) Applying solely the three translational components of earthquake record,

b) Applying rotational components (including torsional and rocking ones) and translational components of the earthquake simultaneously,

c) Applying translational and only rocking components concurrently.

It must be mentioned, torsion due to accidental eccentricity was not considered in the analysis of cooling tower.

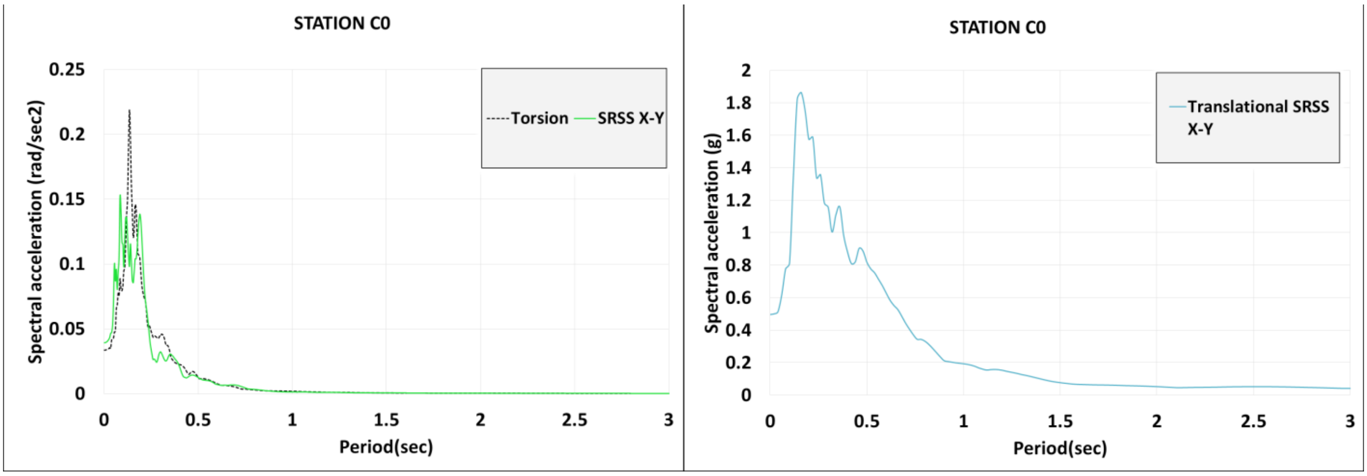

Fig. 2. A sample response spectrum for rotational and translational component at station C0 of Event No.37

3- Geometry of the cooling tower and modeling

The submitted papers to the journal should be in both the word The cooling tower is made of concrete and the columns connecting the shell to the foundation are made of steel. The mechanical properties of the materials and soil are shown in Tables 2 and 3, respectively. The geometry of the cooling tower is illustrated in Figure 3 [20]. The total height of the tower is 125 m, mounted on 36 cross-shaped columns. The shell thickness, at the bottom and at the top, is 120 cm and 18 cm, respectively (Figure 3). In Table 4, the mean radius and thickness of the shell at different heights are given. Translational and rotational springs and dashpots used to represent soil-foundation interaction. The specifications were introduced by Gazetas [21]. Spatial variation of strong ground motion is not considered in this paper. Time history analyses were conducted to estimate the response of the tower to the earthquake excitations.

Table 2. Physicomechanical properties of materials

	Concrete	steel
Young's modulus	34 GPa	210 GPa
Poisson's ratio	0.2	0.32
Unit weight	2400 kg/m^3	7800 kg/m^3

Table 3. Physicomechanical properties of soil

Shear wave velocity (m/s)	145
Soil type (according to Iranian code of practice for seismic resistant design of buildings)	III
Modulus of elasticity (GPa)	5
Shear modulus (MP)	375
Poisson's ratio	0.4

Table 4. Shell thickness and radius at different heights.

Thickness (cm)	Radius (m)	Height
18	31.76	125
18	31	105
18	32.14	80
30	38.567	35
120	40.66	24.16

4- Numerical results

As regards the significant effect of the earthquake rotational components on the structures, the simultaneous action of the translational component and the rotational one on the cooling tower were explored and compared with the results obtained under the sole excitation of the translational component. Investigated response parameters under the action of translational, torsional, and rocking earthquake components consist of the displacement at the top of the cooling tower and the support reactions.

4- 1- Tower displacement

To make a comparison between the results, the displacement response under the single translational component was compared with its counterpart under the translational-rotational, and the translational-rocking components at the upper points of the tower. The ratio of the displacement

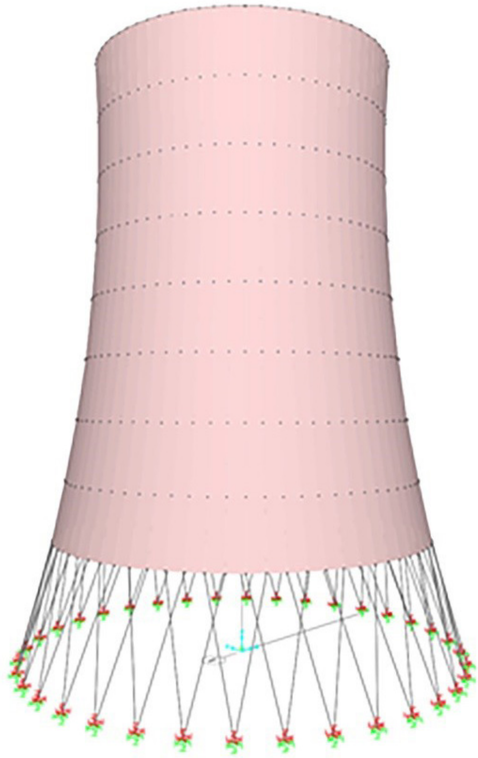

Fig. 3. Cooling tower model

difference under the two latter loading combinations divided to the displacement under the effect of translational components was computed for all the aforementioned points, and an average ratio was calculated for all the points. These displacement ratios along X and Y directions are represented by DR-X and DR-Y, respectively, in Table 5. The analysis results indicate that the simultaneous action of the translational and the rotational components leads to a nearly 6% increase in the tower displacement response. The displacement of the tower under the earthquake record No.36 along the X and Y axes is shown in Figures 4-a, and 4-b, respectively.

Table 5. Displacement ratio of the cooling tower for different loading cases

Loading conditions	Difference ratio in percentage	
	DR-Y	DR-X
translational and rotational in comparison with only translational	6	5.8
translational and rocking in comparison with only translational	5.0	5.7

4- 2- Support reaction of the tower

Support reactions are calculated at the base of the tower, under the three aforementioned loading combinations. The same ratio, which is computed for the displacement, is calculated to compare the support reaction under the single translational component with its counterpart under the two other loading combinations. As seen in Table 6, the simultaneous action of translational and rotational components increases the tower base reactions.

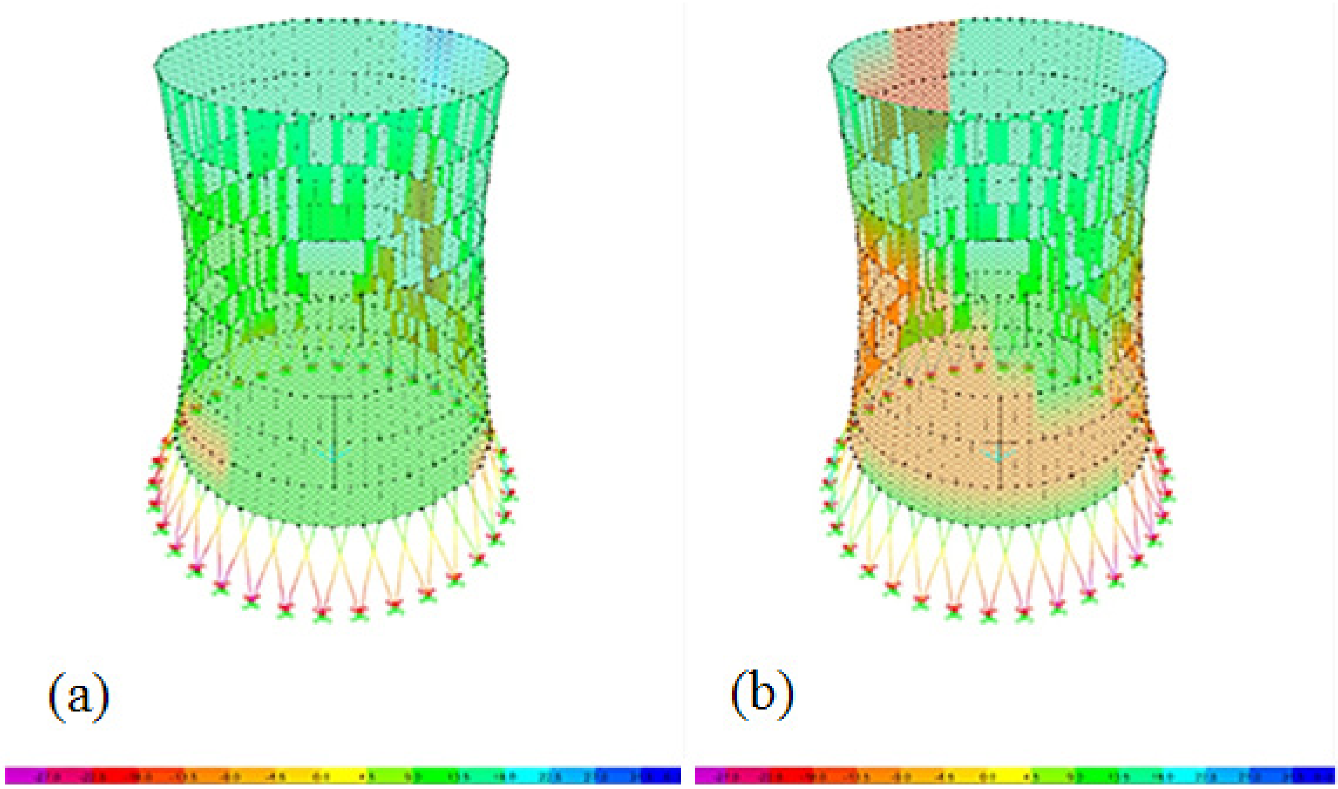

Fig. 4. Tower displacement under translational-rotational component of earthquake No.36; a) X direction and b) Y direction

Table 6. Ratio of the support reaction of the cooling tower

Loading conditions	Difference ratio (in percent)					
	Moments			Forces		
	M_Z	M_Y	M_X	R_Z	R_Y	R_X
Response under translational & rotational components divided by the response under sole translational component	6.9	3.9	8.3	2.0	5.0	6.1
Response under translational & rocking components divided by the response under sole translational component	3.8	8.2	2.0	4.7	6.1	5.7

The concurrent action of translational and rotational components results in 6.1%, 5.0%, and 2% increase in support reaction along X, Y, and Z directions, respectively. The flexural moment at the base of the tower under this loading combination, experiences about 8.3%, 3.9%, and 6.9% rise about X, Y, and Z directions, respectively. The stress distribution in tower columns under this load combination is illustrated in Figure 5.

In addition, support reaction under the translational and rocking components increases roughly by 5.7%, 6.1%, and 4.7% in X, Y, and Z directions, respectively in comparison with its counterpart under the single translational components. Furthermore, for a moment, this rise is 2.0%, 8.2%, and 3.8% about X, Y, and Z axes, respectively.

5- Conclusion

In this paper, the data obtained from the dense accelerometer array were used to derive the earthquake rotational components, including the torsional and rocking components, by employing the acceleration gradient method. The effect of translational and rotational components on the response of the cooling tower was investigated. The displacement at the top of the tower, as well as the support reactions, were

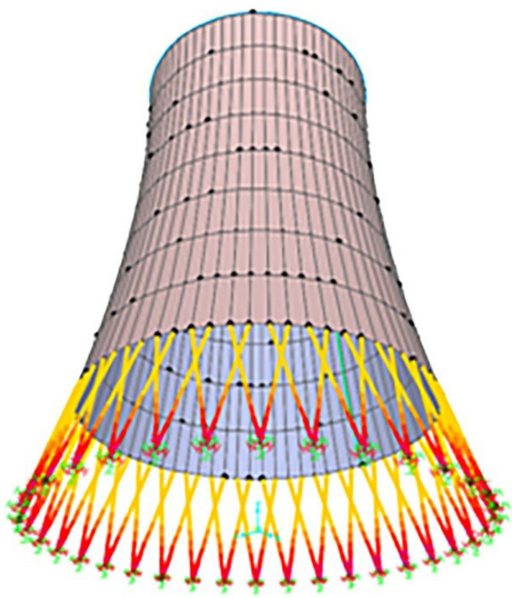

Fig. 5. Stress distribution in columns under the translational-rotational components of earthquake No.36.

compared in different loading combinations. Main findings of this research are as follows.It must be mentioned these results are for the case study model and it may need more studies to introduce some general criteria.

1. The tower experiences, on average, 5.8% increase in the displacement under the loading combination of translational and rotational components in comparison with single translational component action.
2. The displacement at the top of the tower under the simultaneous loading of translational and rocking components increases by about 5.7% compared to the sole translational component action.
3. In comparison with single translational component action, the support reaction in a horizontal direction, on average, increases by 6.1% when the tower is subjected to the translational-rotational components and by 5.7% when the tower is subjected to the translational-rocking ones.

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