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ORIGINAL ARTICLE

The effect of rotational component of earthquake excitation on the response of steel structures

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Abst ract

This work is on the influence of the rotational component of earthquake excitations to the response of steel structures. In most studies, seismic input is being modeled only using the translational component of the ground acceleration, while the rotational one is ignored. This was due to the observation that the rotational component had minimal effect on low-rise buildings. Hence, the accelerometers used would not measure it, leading to a lack of records. Nowadays, technology provides such instruments and relative records are made available. Indicative of that is that elastic design response spectra for rotational components are int-roduced to the design codes. In this paper, the results on structural response and internal forces due to the rotational component of a seismic excitation on the steel structures are examined. Dynamic time history analysis and response spectrum analysis of different steel structures are performed (a) considering the rotational component of the excitation and (b) without it. From the numerical results it is shown that the impact of rotational component in structural response and internal forces of the steel structures is significant and should not be ignored during structural design.

Keywords

Rotational component, seismic design, earthquake engineering, steel structures, EC8 part 6.

1 Introduction

Time history analysis of structure involves exclusively fully descrip-tion of ground-motion along the three dimensions of space. In order to fully describe the ground motion, translational and rotations also need to be considered, which results in a total of six components, three for translation and three for rotation. The luck of rotational component to the analysis was firstly because they were considered as negligible and secondly rotation sensors were not available to di-rectly measure rotations during an earthquake. The rotational com-ponents data history can be measured directly in a free field with special accelerometers or can be extracted from measured transla-tional recordings. Many earthquake and seismology scientists focus on rotational records over the last decades. Droste and Teisseyre [1] derived rotations from an array of seismographs. Rotational mo-tions observed during an earthquake in April 1998 ιν Japan was measured with a gyro -sensor, and an inertial angular displacement sensor, by Takeo [2]. Advances in rotational seismology about in-strumentation, theory and observations are presented in the work of Igel et al. [3]. The application of compact and cheaper sensors ba-sed on electrochemical magnetohydrodynamic technology, used from Liu et al. [4] and Wassermann et al. [5].There are a lot of proce-dures that calculate rotational time series from translational recor-dings. A Single Station Procedure (SSP), is one of them. A number of researchers such as Lee and Trifunac, [6], Castellani and Boffi [7], Li et al. [8] and Basu et al.[9], presented their work base on SSP. An ex-tension to the SSP method is the use of data from a number of closely spaced, spatially distributed stations, this procedure is called Mul-tiple Station Procedures, denoted as MSP, Niazi [10]. An expansion of MSP is the Geodetic Method, GM, Spudich et al.[11],[12], work on this method. Basu et al. [13], point out some limitations of GM, and propose the Acceleration Gradient Method, AGM, which is capable of extracting the free-field rotational time series from the three-component strong motion data recorded at surface stations in a dense array. However, the AGM fails to capture the frequency con-tent above a limit and this limit reduces as the physical dimension of the array increases. The drawback of AGM is overcoming using an alternative procedure, the Surface Distribution Method, SDM, Basu et al. [14].

Falamarz-Sheikhabadi et al. [15],[16], work on the effects of both time delay and loss of coherency in order to derive simple mathematical expressions for generating the middle-field rocking acceleration component and its corresponding response spectra. They revi-sed the seismic intensity parameters in order to account for the combined action of horizontal and rocking seismic motion on struc-tures. Links between rotational ground motion and site soil conditi-ons are proposed in the work of Sbaa et al. [17] and Perron et al. [18]. They show that the coupling of translational and rotational measu-rements appears to be useful, not only for direct applications of en-gineering seismology, but also to investigate the composition of the wavefield, while avoiding deployment of dense arrays.

The need of considering of rotational components is also imprinted to the regulations. The Eurocode 8, part 6, [19], examining slender and tall structures such as towers, chimneys and masts takes into ac-count special variability of the seismic ground motion including ro-tational components of the ground accelerations. The EC8, part 6, propose an extended response spectrum analysis which requires response spectra of rotational accelerations to be implemented. Such rotational spectra are defined and calculated on the basis of translational response spectra as well.

A lot of works investigated the effect of rotational component of ground motion on structural response. In base isolated structures Wolf et al. [20], discussed the effect of rocking excitation on a base-isolated nuclear power plant . Politopoulos, [21], identified the exci-tation of the rocking mode in a base-isolated building due to rocking excitations. Bozev et al. [22], performed analysis accounting the ro-tational component of seismic action on towers, masts and chimneys according to EC8, Part 6. Zembaty, [23], work on rotational seismic code definition in Eurocode 8, Part 6, for slender tower-shaped structures while Zembaty and Boffi [24], identified the contribution of rocking motion to bending moments along the height of a tall to-wer using horizontal and rocking spectra computed- based on Euro-code 8. In a recently work, [25], rotational ground motion records from induced seismic events are examined. A simplified relation for the application of rotational components to seismic design codes and calculation of response of multiple-support structures subjec-ted to horizontal and rocking components are presented in the work [26], [27]. Basu et al., [28], suggests an equivalent accidental eccentricity to account for the effects of torsional ground motion on structures. Torsion in building due to base rotational excitation was investigated by De-La-Llera and Chopra, [29]. Yin et al performed e-arthquake engineering analysis of measured rotational ground mo-tions at structure, [30].

In this paper the influence of rotational component of earthquake excitation to the response of steel structure is examined. The re-sponse is calculated solving directly the equations of motions ac-counting for the rotational component applied at the base of struc-ture. Directly time history geometrical non-linear analysis is performing in order to calculate the response of structure.

2 Theoretical background

2.1 Dynamic Analysis

Rotational components of earthquake consist of one torsional com-ponent which is the rotation about vertical axis and the other two rocking components which is the rotation about the two horizontal axes. The secondary horizontal wave, SH wave, and the surface wave, Love wave, contribute to the torsional motion. Rocking mo-tion is due to the primary waves, P waves, secondary vertical wave, SV waves, and Rayleigh waves. Even though that rotational compo-nents of earthquake ground motion have been studied in literature in seismic analysis and design of structures is not taken into account.

May this come from the fact that such data are not recorded by the accelerographs. In Eurocode 8, EC8, Part 6, rotational components of the ground accelerations taking into account is seismic analysis. Response spectrum analysis or direct time history analysis can be used in order to evaluate the response of structure subjected to ro-tational component . The response spectrum analysis requires response spectra of rotational accelerations to be implemented. In EC8, Part 6 rotational spectra are defined in order to use for the ana-lysis. Time history analysis requires time history rotational motion records in order to apply in the base of structures. Structures that are influence of rotational component are slender and tall struc-tures such as towers, chimneys and masts. Those structures are spe-cial mentioned in EC8, Part 6, however, other structures such as long in plan structures, bridges, dams, high-rise buildings or specially buildings such as nuclear power stations, are also expected to be in-fluenced by rotational components of seismic action.

In the earthquake engineering community saying ground accelera-tion and velocity directly means translational component of accele-ration and velocity. Term like translational acceleration and transla-tional velocity is used to clearly distinguish from rotational acceleration and rotational velocity respectively. The term rotatio-nal rate is also often used in the rotational seismology literature. Thus, Peak Ground Translational Acceleration, PGTA, is used instead of PGA and Peak Ground Rotational Acceleration, PGRA, is defined as the maximum in the time domain of the absolute value of the rotational acceleration along the three components.

A total movement due to rotational and translational component of earthquake excitation of a single degree of freedom system, SDOF, is shown in Figure 1.

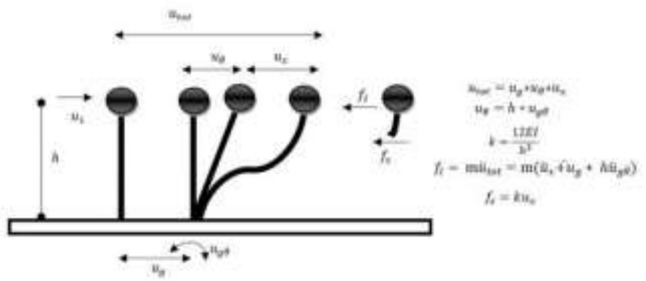

Figure 1 A total movement due to rotational and translational component of earth-quake excitation of a single degree of freedom system, SDOF

Applying a dynamic equilibrium to SDOF the equation of motion is obtained as follows:

(1)

$\ddot{} + \dot{} \; k \qquad = -(\; \ddot{} + h \; \ddot{} \;)$

A model of structure with concentrated mass and stiffness at each floor with only horizontal degrees of freedom, ignoring the rotation of plate, subjected to ground motion with translational and rota-tional components is shown in Figure 2.

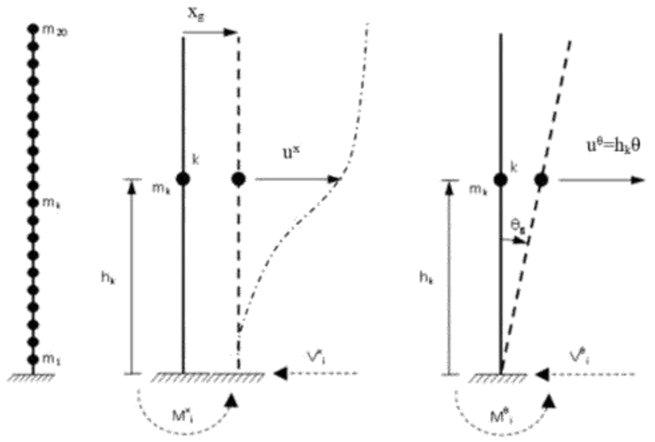

Figure 2 A total movement due to rotational and translational component of earth-quake excitation of a single degree of freedom system, SDOF

If [**M**], is the mass matrix, [**K**], the stiffness matrix and [**C**], the damping matrix the equation of motion for structure considering a translational ground acceleration along horizontal direction x together with a rotation acceleration in the vertical plane x-z are given by:

+ + = - + (2)

[ ]{ ¨} [ ]{ ˙} []{} ({ } ¨ {h})

Where:

{ U }:is the vector comprising the accelerations of the degrees of freedom of the structure relative to the base,

{ U }: is the vector comprising the velocities of the degrees of freedom of the structure,

{u}: is the vector comprising the displacements of the degrees of freedom relative to the base,

{m}: is the vector comprising the translational masses in the horizontal direction of the translational excitation. This vector coincides with the main diagonal of the mass matrix [**M**], if the vector {u} includes only the translational displacements in the horizontal direction of the excitation,

$X_g(t)$: isthe translational ground acceleration,

is the rotational acceleration of the base.

The above equation can be extended to three dimensions. In that case the excitation motion consists of three translational accelera-tion, two rotational accelerations (rotation about the two horizontal axes, i.e., rocking) and one torsional acceleration (rotation about the vertical axis).

Time history analysis can be used in order to calculate the response of structure subjected to translational and rotational component of ground motion. With this analysis the response is calculated solving directly with a numerical procedure the above Equation 2. Time history analysis can be linear or non-linear. Non linearity refers to material (change of stiffness matrix in every time step) or to geometry (solving the equation in deformable position at each time step).

2.2 Response Spectrum Analysis

Response spectrum analysis, EC8 part 6, [19], Bonev et al. [22], can also be perform to calculate the response of structure subjected to translational and rotational component of ground motion. The procedure of response spectrum analysis considering the rotational component is as follows:

Knowing the mass and initial stiffness of the structure the eigenmodes $Φ_i$, eigenperiods, T_i, or eigenfrequencies, f_i, and the correspon-ding damping ratios $ξ_i$ of the structure are obtained from the solution of the following eigenvalue problem ω ,...ω

2Ž 2 i=0,...,n-1 2 Φ1, Φ, 2 ,...,Φ (3)

2Ž 1 2

$C = ΦCΦ$, $M = ΦMΦ$, $= 2C M$ (4)

The participation factor ψi, and seismic forces $F_{q,i}$ for the i th eigen-mode for translational and rotational component are given as:

, = ΦΦ ΣΤ ΜΕ Μ Φi ,i=1,...,n, , = ΦΦ ΣΤ ΜΕ Μ Φi ,i=1,...,n (5)

$F_{q,i,T} = MΦ_i$, d,i(,), i=1,² ,n, (6)

$F_{q,i,θ} = M(T$ i) , d,i ( ) i=1,...,n (7)

where E and E is the direction matrix for the earthquake for translational and rotational component:

E ={1 1 ...1}, E = {0 0 ... 0 1} (8)

is a mode vector were every element of in each degree of

Φi ∗ h, Φi

, h

Φi ∗ h = (9)

,1 h1

2

is the rotation response spectra around y axes, in rad/sec . (,)

In EC8 part 6 when the rotational components of the ground motion during the earthquake are taken into account, the seismic action may be represented by three elastic response spectra for the trans-lational components and three elastic response spectra for the rota-tional components. The rotation response spectrum is defined in an analogous way to the response spectrum of the translational com-ponents, i.e. by considering the peak response to the rotational mo-tion of a rotational single-degree-of- freedom oscillator, with natural period, T, and critical damping ratio, $ξ$. $R^θ$, denotes the ratio between the maximum moment in the oscillator spring and the rotational moment of inertia about its axis of rotation. The diagram of, $R^θ$, versus the natural period, T, for given values of, $ξ$, is the rotation response spectrum. When results of a specific investigation or of well-documented field measurements are not available, the rotatio-nal response spectra may be determined as:

( ) = 1.7 ( ) , i=1,² ,n, (8)

( ) = 1.7 ( ) , i=1,² ,n, (9)

( ) = 2.0 ( ) i=1,² ,n, (10)

The maximum seismic forces F_q for each degree of freedom are obtained combining the two-part seismic forces of each eigenmode with Square Root of Sum Squares method (SRSS), thus:

F = Σ

θ

q,i, T q,i, 2 (11)

The same calculations are done in order to calculate every other response quantity like displacement, internal forces etc.

3 Numerical example and discussion

The influence of the rotational component of earthquake has been numerically approached. A three story, steel structure, with consen-trated mass ansd stiffness subjected to an earthquake excitation with translational and rotational component. The story mass is 10 ton and the story stiffness is 10000 kN/m. The layout of the structu-ral system is shown in Figure 3.

The model was subjected to a 6.4 moment magnitude, Mw, earth-quake excitation, which took place on 17/11/2015 in Kefalonia is-land, Greece. The epicentre latitude and longitude were 38.16° and 20.50° respectively. The focus of the earthquake was at 10.7km be-low surface level. The record history of translational and rotational components were recorded in the framework of the Argonet pro-ject, a 3D accelerometric array implemented on the island of Kefalo-nia in Greece [17], [18], and is shown in figure 4.

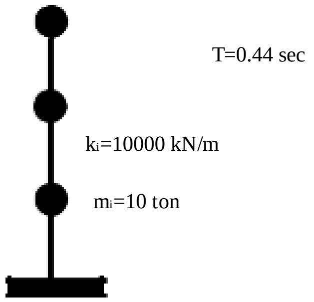

Figure 3 Properties, and layout of the 3 dof model

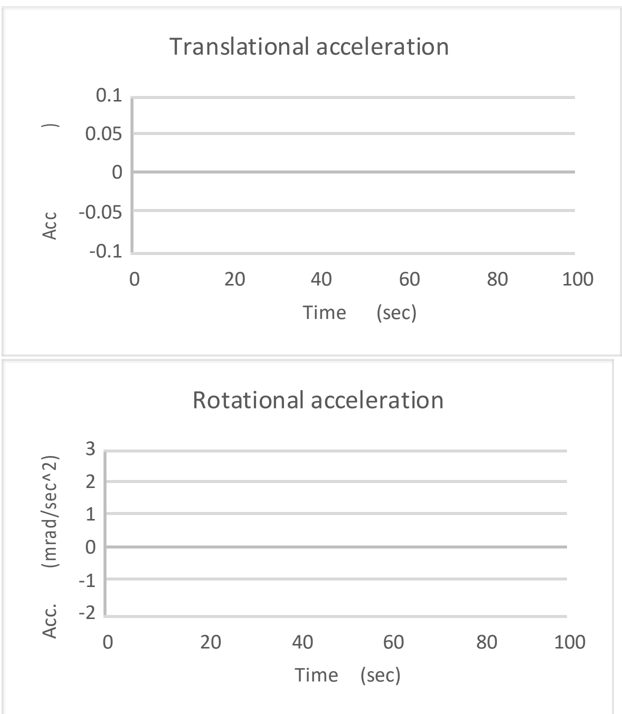

Figure 4 Translational and rotational component of earthquake excitation

A dynamic response history analysis was applied, with suitable soft-ware like SAP 2000, [31], and the response of structure was calcula-ted. Two cases of earthquake excitation were considered. One with application only of translational acceleration at the base of struc-ture and the second with simultaneously translational and rotatio-nal acceleration excitation. The results of the analysis are shown in Table 1. In this table the ratio of the response of the structure exci-ted with translational and rotational acceleration to the response of structure excited only with translational acceleration is also shown.

Then a response spectrum analysis was apllied to the structure. The parameters of accelerations spectrum were: a_g=0.24g, Soil type B, damping coefficient ξ=5%, importance factor γi=1. Based on the above parameter the rotational and translation spectrum were con-structed and response spectrum analysis was performed. The dis-placement was calculated for two cases: one using only the transla-tional spectrum and the second using translational and rotational ones. The results are shown in Table 2. In this table the ratio of the response of the structure caculated using translational and rotatio-nal spectrum to the response of frame using only translational spect-rum is also shown.

Table 1 Analysis results from response history analysis and ratio of response due to translational and rotational component to only translational component

	Top displacement (cm)		
	1^{st} floor	2^{nd} floor	3^{rd} floor
Only translational component, **T**	0.1	2.5	5.05
Translational and rotational compo-nent, **R+T**	0.15	4.0	9.6
Ratio, (R+T)/T	**1.5**	**1.6**	**1.9**

Table 2 Analysis results from response spectrum analysis and the ratio of response due to translational and rotational component to only translational component

	Top displacement (cm)		
	1^{st} floor	2^{nd} floor	3^{rd} floor
Only translational component, **T**	0.041	2.6	5.9
Translational and rotational compo-nent, **R+T**	0.049	2.9	8.26
Ratio, (R+T)/T	**1.2**	**0.9**	**1.4**

The graphical representation of the ratio of the above tables is shown in Figure 5.

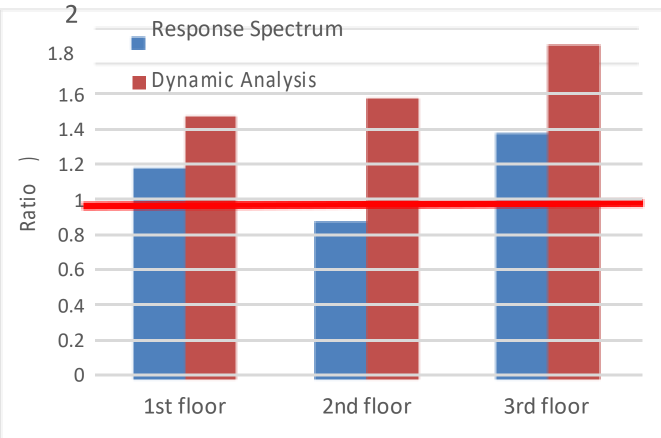

Figure 5 Translational and rotational component of earthquake excitation

From the analysis results it is shown that the displacement of struc-ture subjected to rotational and translational component of e-arthquake is larger compared to the displacement of the structure subjected only translational excitation. The ratio of the response calculated with accounting rotational and translational component to the response calculated with acounding only translational com-ponent ranges from 1.2 to 1.9 depending on the type of analysis. It is worth to note that for the response spectrum case this ratio is smaller than 1.

4 Conclusions

The influence of rotational component of earthquake excitation to the response of structures was examined. From the numerical re-sults it was obtained that the response of structure subjected to ro-tational and translational component are about double times higher than the response of structures subjected to only translational com-ponent. Parametric investigations of strucrural types as steel plane frame with different heights and bays should be done. Furthermore, analysis in 3D space steel structures with application of rotational component in two directions is under author's investigation.

References

[1] Droste Z.; Teisseyre R. (1976**)** *Rotational and displacement com-ponents of ground motion as deduced from data of the azimuth sys-tem of seismographs*. Publ Inst Geophys Pol Acad Sci**, 97**, 157– 167.

[2] Takeo M. (2009) *Rotational-motions observed during an earth-quake swarm in April 1998 off shore to, Japan. Bull Seismol Soc Am,* **99**, 1457–1467. doi:10.1785/0120080173.

[3] Igel H.; Brokesova J.; Evans J.; Zembaty Z. (2012) *Advances in rotational seismology: instrumentation, theory, observations, and engineering. J - - Seismol-***, 16**, 571–572. doi:10.1007/s10950 012 9307 6. -

[4] Liu CC.; Huang BS.; Lee WHK.; Lin C *tional and translational ground motions at the HGSD station in Tai-wan from 2007 to 2008*. Bull Seismol Soc Am, **99**, 1228–1236. doi:10.1785/0120080156.

[5] Wassemann J.; Lehndorfer S.; Igel H.; Schreiber U. (2009) *Per-formance test of a commercial rotational motions sensor*. Bull Seis-J.(2009)*Observingrota-* mol Soc Am**, 99**,1449– 1456. doi:10.1785/0120080157.

[6] Lee VW.; Trifunac MD. (1987) *Rocking strong earthquake accel-erations*. Soil Dynamics and Earthquake Engineering, **6**, 75–89.

[7] Castellani A.; Boffi G. (1989) *On the rotational components of seismic motion.* Earthquake Engineering Structural Dynamic, **18**, 785–797.

[8] Li H-N.; Sun L-Y.; Wang S-Y. (2004) *Improved approach for ob-taining rotational components of seismic motion*. Nucl Eng Des., **232**, 131–137.

[9] Basu D.; Whittaker AS.; Constantinou MC. (2012) *On estimating rotational components on ground motion using data recorded at a single station.* Journal Engineering Mechanics ASCE, **138**(9), 1141–1156.

[10] Niazi M. (1986) *Inferred displacements, velocities and rotations of a long rigidy site during the 1979 Imperial Valley, California, earth-quake.* Earthquake Engineering Structural Dynamic, **14**, 531– 542.

[11] Spudich P.; Steck LK.; Hellweg M.; Fletcher JB.; Baker L. (1995) *Transient stress at Parkfield, California, produced by the M 7.4 Landers earthquake of June 28, 1992: observations from the UPSAR dense seismograph array*. J Geophys Res **100,** 675–690.

[12] Spudich P.; Fletcher JB. (2008) *Observation and prediction of dy-namic ground strains, tilts, and torsions caused by the Mw 6.0 2004 Parkfield, California, earthquake and aftershocks, derived from UPSAR array observations*. Bull Seismol Soc Am. **98**, 1898–1914. doi:10.1785/0120070157.

[13] Basu D.; Whittaker AS.; Constantinou MC. (2013) *Extracting ro-tational components of using data recorded at multiple stations.* Earthquake Engineering Structural Dynamic, **42**(3), 451–468.

[14] Basu D.; Whittaker AS.; Constantinou MC. (2015) *Characteriz-ing rotational components of earthquake ground motion using a surface distribution method and response of sample structures*. En-gineering Structures, **99**, 685–707.

[15] Falamarz-Sheikhabadi M. R.; Zerva A.; Ghafory-Ashtiany M. (2017) *Revised Seismic Intensity Parameters for Middle-Field Hor-izontal and Rocking Strong Ground Motions.* Journal of Structural Engineering,**143,** doi: 10.1061/(ASCE)ST.1943-541X.0001646.

[16] Falamarz-Sheikhabadi, (2014) *M. R. Simplified relations for the application of rotational components to seismic design codes.* Engi-neering Structures**, 59**, 141–152.

[17] Sarah -Sbaa; Fabrice Hollender; Vincent Perron; Afifa Imtiaz; Pierre Yves Bard; Armand Mariscal; Alain Cochard and Alain Dujardin (2017) *Analysis of rotation sensor data from the SINAPS@ Kefalonia (Greece) post-seismic experiment—link to sur-face geology and wavefield characteristics*, Earth, Planets and Space, **69**, 124.

[18] Vincent Perron; Fabrice Hollender; Armand Mariscal; Nikolaos Theodoulidis; Chrisostomos Andreou; Pierre-Yves Bard; Cécile Cornou; Régis Cottereau; Edward Marc Cushing; Alberto Frau; Sébastien Hok; Agisilaos Konidaris; Philippe Lan-glaude; Au-rore Laurendeau; Alexandros Savvaidis; and Angkeara Svay (2018) *Accelerometer, Velocimeter Dense-Array, and Rotation Sensor Datasets from the Sinaps@ Postseismic Survey (Cephalonia 2014–2015 Aftershock Sequence)*, Seismological Research Let-ters, **89**(2A) doi: 10.1785/0220170125.

[19] EN 1998-6, Eurocode 8:Design of structures for earthquake resistance – Part 6: Towers, masts and chimneys. 2005.

[20] Wolf JP.; Obernhueber P.; Weber B. (1983) *Response of a nu-clear plant on aseismic bearings to horizontally propagating waves.* Earthquake Engineering Structural Dynamic**, 11**, 483–499.

[21] Politopoulos I. (2010) *Response of seismically isolated structures to rocking-type actions.* Earthquake Engineering Structural Dy-namic, **39**, 325–342.

[22] Bonev, Z.; Blagov, D.; Vaseva, E.; Mladenov, K. (2009) *Account-ing the rotational component of Seismic action on towers, masts and chimneys according to BDS EN 1998-6.* International conference UACG-2009: Science and Practice. Fascicule VIII, Vol. XLIV 185-195.

[23] Zembaty Z. (2009) *Rotational seismic code definition in Eurocode 8, Part 6, for slender tower-shaped structures*. Bull Seismol Soc Am., **99**(2B), 1483–1485.

[24] Zembatyy Z.; Boffi G. (1994) *Effect of rotational seismic ground motion on dynamic response of slender towers*. European Earth-quake Engineering, **8**, 3-11.

[25] Zembaty Z.; Mutke G.; Nawrocki D.; Bobra P. (2017) *Rotational ground motion records from induced seismic events*. Seismol Res Lett**, 88**,13–22. doi:10.1785/0220160131.

[26] Falamarz-Sheikhabadi, M. R.; Ghafory-Ashtiany, M. (2015) *Ro-tational components in structural loading.* Soil Dynamics and Earthquake Engineering**, 75**, 220–233.

[27] Falamarz-Sheikhabadi, M. R.; Zerva, A.; Ghafory-Ashtiany, M. (2016) *Mean absolute input energy for in-plane vibrations of multi-ple-support structures subjected to horizontal and rocking compo-nents*. J. Probab. Eng. Mech., **45**, 87.

[28] Basu D.; Constantinou MC.; Whittaker AS. (2014) *An equivalent accidental eccentricity to account for the effects of torsional ground motion on structures*. Engineering Structures, **69**, 1–11.

[29] De-La-Llera JC.; Chopra AK. (1994) *Accidental torsion in build-ings due to base rotational excitation*. Earthquake Engineering Structural Dynamic, **23**,1003–1021.

[30] Yin J, Nigbor RL.; Chen Q.; Steidl J. (2016) *Engineering analysis of measured rotational ground motions at GVDA*. Soil Dyn Earthq Eng, **87**, 125–137. doi:10.1016/j.soildyn.2016.05.007.

[31] Computers and Structures, Inc. Linear and Nonlinear, Static and Dynamic Analysis and Design of Three-Dimensional Struc-tures, SAP2000 Version 14.0.0, 2009.