Earthquakes and Structures, *Vol. 13, No. 1 (2017) 9-15*
DOI: https://doi.org/10.12989/eas.2017.13.1.009

Numerical study on the effects of seismic torsional component on multistory buildings

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(Received November 21, 2016, Revised May 23, 2017, Accepted May 25, 2017)

Abstract. In this paper, the influence of the rotational component, about a vertical axis, of earthquake ground motion on the response of building structures subjected to seismic action is considered. The torsional component of ground motion is generated from the records of translational components. Torsional component of ground motion is then, together with translational components, applied in numerical linear dynamic analysis of different reinforced concrete framed structure of three stories buildings. In total, more than 40 numerical models were created and analyzed. The obtained results show clearly the dependence of the effects of the torsional seismic component on structural system and soil properties. Thus, the current approach in seismic codes of accounting for the effects of accidental torsion due to the torsional ground motion, by shifting the center of mass, should be reevaluated.

Keywords: torsional rigidity; translational rigidity; accidental eccentricity; seismic torsional component; torsional coupling

1. Introduction

The propagation character of the seismic waves can be defined by three translation components of the motion as functions of time and the surface coordinates about a given point. Alternatively, seismic wave propagation may be described by three rotations and three translation components, at one point, as functions of time only. In general, these two modalities are equivalent; however, the second is more suited for the computation of structural dynamics. The issue of rotational strong ground motion has studied by several investigators. Three main approaches have been developed to incorporate rotational motions in engineering applications: first, using analytical form (Knopoff and Chen 2009, Kulesh 2009, Grekova *et al*. 2009), the second, which is based on elastic wave theory, is to extract rotational components of ground motion from recorded translational data (single and multiple station procedures). Single station procedures employ translational data recorded at a single station. Multiple station procedures employ three-component translational acceleration time series recorded in an array of closely spaced but spatially distributed accelerographs (Spudich *et al*. 1995, Niazi 1982, Oliveira and Bolt 1989, Huang 2003, Ghayamghamian and Nouri 2007), and third, direct recording of rotational components by optical dominant technology (Wassermann *et al*. 2009, Fichtner and Igel 2009). This approach remains still a field of research (Basu *et al*. 2012, 2013). In the short term, rotational components will still satisfactorily be extracted from recorded translational data using seismographic station or dense arrays procedures.

The requirement of taking into account the rotational components in the design of earthquake resistant buildings was emphasized by several studies (Ghayamghamian *et al*. 2007, Enache 2010, Gupta and Trifunac 1990, De Llera and Chopra 1994, Stathopoulos and Anagnostopoulos 2010, He and Luo 2013, Falamarz-Sheikhabadi 2014, Falamarz-Sheikhabadi 2012, Roy *et al*. 2015). Unfortunately records of this seismic component are lacking, because the conventional measuring devices are not able to record it. Therefore, Seismic codes and standards currently recommend the shifting of the center of mass (about 5% or 10% of the building dimension perpendicular to the direction of excitation) to account for the effect of accidental torsion.

It is notable that the most published studies, having analyzed the accidental torsion, are based on simplified single-story systems, by employing analytical methods with different earthquake records to evaluate the adequacy and efficiency of the design eccentricity equation. In this concern, it is shown that the behavior of a single-story building is not similar to its equivalent proportionate multistory building subjected to the combined action of three earthquake components: horizontal, rocking, and torsional components (Falamarz-Sheikhabadi 2014, Lam *et al*. 2016).

The objectives of this study are to assess numerically the contribution of torsional ground motion to the lateral response of a reinforcement concrete structure and to study how the contribution varies as the fundamental torsional to lateral ratio increases. For this purpose, several multistory structural models were exposed to five real earthquake records. The effect of torsional earthquake on the structural response is assessed by comparing the structural

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http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

displacements including the torsional seismic component to those where only the translational input is considered. This work extends the investigations of the contribution of torsional seismic component to accidental eccentricity by many researchers, using highly simplified analytic models, to dynamic analyses of detailed multistory models.

2. Characteristics of torsional seismic component

The seismic ground motion is considered to be generated by plane harmonic waves arriving at the site. The direction of propagation is assumed to lie in the vertical x-z plane. When the shear wave, SH, interacts with the free boundary surface it is reflected as SH wave with a reflection angle equal to incidence angle θ_0. Due to this, torsional component is produced.

2.1 Numerical simulation procedure

The method of Lee and Trifunac (Lee and Trifunac 1985) to generate the artificial torsional and rocking accelerograms is widely used in structural engineering practice (Nazarov *et al*. 2015). Applying the elastic wave theory, the relation between seismic torsional component and φ_{gz} translational components of seismic motion can be obtained as

$$\varphi_{gz} = (\mathrm{i}\omega \sin\theta_0/2\beta)Ve^{-i\pi/2} = (\mathrm{i}\omega/2C_X)Ve^{-i\pi/2} \quad (1)$$

Where ω is frequency of harmonic wave, β is velocity of shear-wave, v is component of the ground motion in Y direction and $Cx=\beta/\sin\theta_0$ (Phase velocity in horizontal direction). Lee and Trifunac assumed the angle of incidence of incoming SH wave to be constant (Lee and Trifunac 1985). Thus, θ_0, angle of incidence, is equal to θ_c, critical incident angle which is $\sin^{-1}(\beta/\alpha)$.

So, the ratio of amplitudes of φ_{gz} and v can be written as

$$\varphi_{gz}/V = \omega/2C_X \quad (2)$$

At the high frequency end the phase velocities of all modes of surface waves approach $\beta_{\min}$. Thus

$$\varphi_{gz}/V = \omega/2C_X\,|\varphi_{\mathrm{gz}}(\omega_{\mathrm{n}})|/|\mathrm{V}(\omega_{\mathrm{n}})| = \omega_{\mathrm{n}}/2\beta_{\max}\,, as\ \omega_{\mathrm{n}} \to 0 \quad (3)$$

At the low frequency end, essentially only first mode is present and its phase velocity approach $\beta_{\max}$. Thus

$$\varphi_{gz}/V = \omega/2C_X\,|\varphi_{\mathrm{gz}}(\omega_{\mathrm{n}})|/|\mathrm{V}(\omega_{\mathrm{n}})| = \omega_{\mathrm{n}}/2\beta_{\max}\,, as\ \omega_{\mathrm{n}} \to 0 \quad (4)$$

The value of the ratio $|\varphi_{gz}(\omega_n)|/|V(\omega_n)|$ can be obtained at each ω_n applying the straight-line approximation. Then torsional component is obtained at each discrete frequency. The inverse Fourier transform of this spectrum provide the time history of torsional component.

2.2 Time History curves of the torsional seismic components

The structural models introduced in parametric analysis are subjected to real earthquake records. It is tried to select the earthquake records in a way that they represent different site conditions and consequently cover a broad range of frequency contents.

Furthermore, in most cases rotational effects are observed in the epicentral zone, less than 15 km from the epicenter (Hinzen *et al*. 2013). The list of selected records is presented in Table 1. The records are picked from PEER Strong Motion Database.

Fast Fourier transform was applied to time histories of translational motions with different discrete frequencies for these earthquakes; in this case, related rotational components could be obtained. The time histories of the torsional components for the five selected earthquakes are presented in Fig. 1.

As can be seen on Fig. 2, the Fourier spectra of the five torsional accelerograms are richer in a wide range of frequencies.

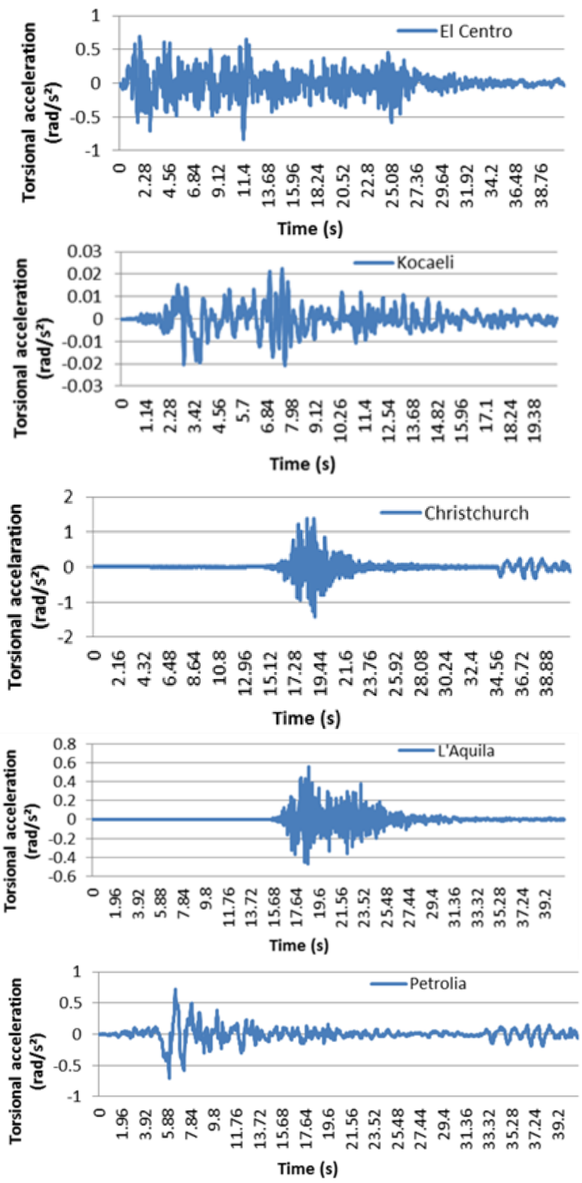


Fig. 1 Torsional time histories of the five earthquakes

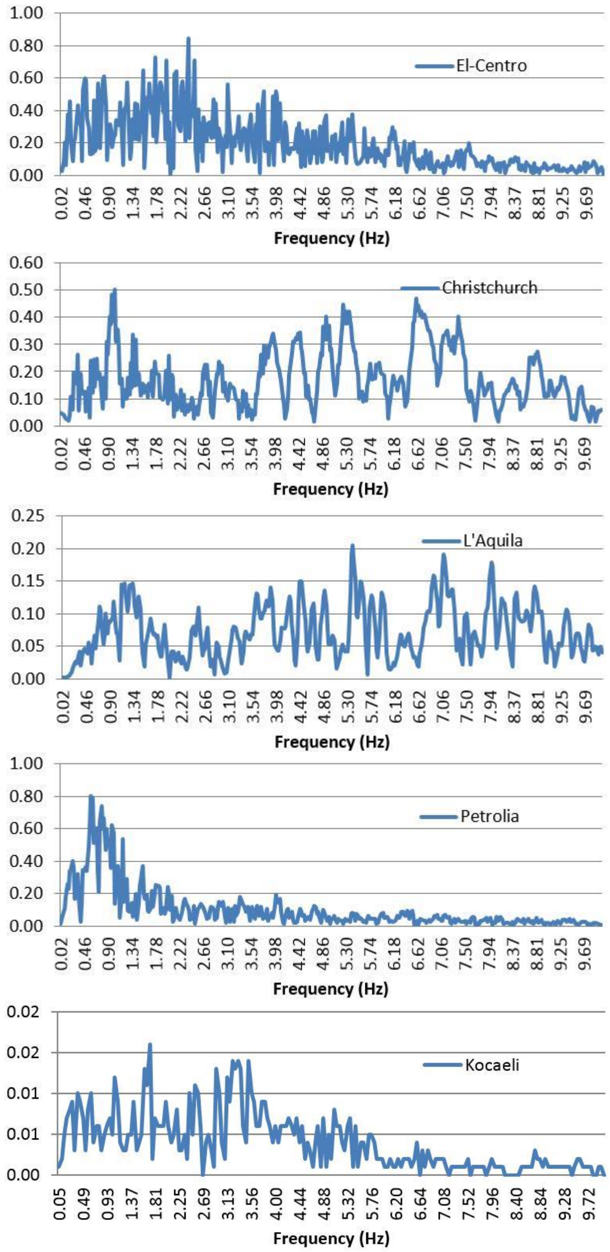


Fig. 2 Torsional acceleration Fourier spectrum

Table 1 The selected records and their characteristics

Earthquake	Station	Mw	Epicentral distance (km)	PGA (g)	Shear wave velocity (m/s)
L'Aquila Italy (06/042009)	V-Aterno V-Ateno (AQA)	6.3	4.6	0.44	549
Kocaeli Turkey (17/08/1999)	Izmit, Meteoroloji, Istasyona	7.6	09	0.22	826
Petrolia USA (25/04/1992)	CSMIP St n°89156	7.1	05	0.65	713
Christ-church New Zealand (21/02/2011)	Lyttelton Port Company	6.3	04	0.86	422
Imperial Valley (18/05/1940)	El-centro, 117	6.9	16.9	0.36	200

3. Building models characteristics

Figs. 3 and 4 show the elevation view and the plan of a typical reinforced concrete model considered in this study to cover a wide range of torsional to lateral stiffness ratios, by varying the stiffness of the system, shown in Table 2. Dimensions of plan are 11.40 m×9.40 m and the story height is 3 m. The beams are of cross sections 30×40 cm² and the slabs are 0.15 m thick. These models are able to represent stiff and flexible torsional behavior.

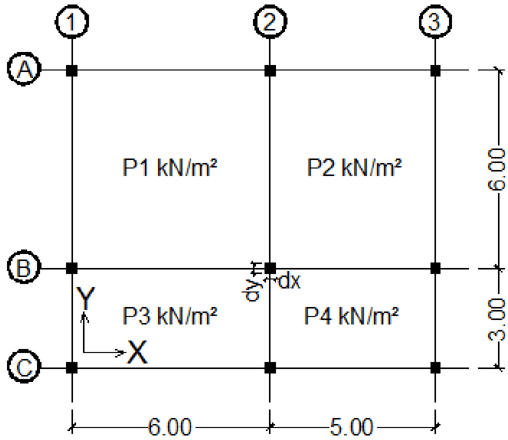


Fig. 3 Typical floor configuration

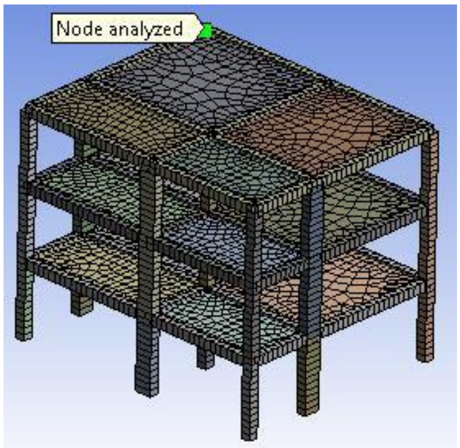


Fig. 4 Elevation view and Node selected to analyze of the dynamic behavior

Table 2 Members dimensions of a typical frame structure

Model	Columns A1, A2, A3 (cm)		Columns B1, B2, B3 (cm)		Columns C1, C2, C3 (cm)		Vertical loads (kNn/m²)			
	Dx	dy	dx	dy	dx	dy	P1	P2	P3	P4
M1	20	40	20	40	20	40	6	6	3	3
M2	20	20	20	40	20	40	6	6	3	3
M3	20	20	20	40	20	40	3	3	6	6
M4	20	20	20	40	20	40	3	9	3	3
M5	20	20	20	70	20	40	3	9	3	3
M6	20	20	20	60	20	40	3	9	3	3
M7	70	40	40	70	40	40	6	6	6	6

Table 3 Frequencies, frequency ratios and effective Masses

Model	Mode	Frequency (Hz)	Effective mass (%)		Effective mass moment (%)	Frequency Ratio
			Ux	Uy	Rz	
M1	1	0.91	0.01	90.69	0.01	Ωx=0.846 Ωy=1.75
	2	1.6	28.80	0.01	65.70	
	3	1.89	61.74	0.00	25.89	
M2	1	0.79	1.13	88.14	1.54	Ωx=0.538 Ωy= 1.06
	2	0.84	41.60	2.64	50.11	
	3	1.56	47.98	0.01	39.97	
M3	1	0.86	0.19	90.15	0.32	Ωx=0.535 Ωy=1.151
	2	0.99	33.11	0.58	50.58	
	3	1.85	57.26	0.01	40.74	
M4	1	0.83	2.23	85.10	7.94	Ωx=0.484 Ωy=1.096
	2	0.91	37.19	5.66	46.91	
	3	1.88	51.10	0.01	36.86	
M5	1	0.94	0.35	88.69	4.82	Ωx=0.423 Ωy=1.191
	2	1.12	18.14	1.89	70.04	
	3	2.65	0.02	7.45	0.42	
M6	1	0.91	0.47	88.56	4.94	Ωx=0.430 Ωy=1.176
	2	1.07	22.60	2.08	65.60	
	3	2.49	66.87	0.00	21.47	
M7	1	2.20	0.18	72.04	0.00	Ωx=1.36 Ωy=1.35
	2	2.21	77.50	0.19	0.00	
	3	2.99	0.78	0.04	0.06	

The building systems, analyze Table 2. Members dimensions of a typical frame structured in the study can be categorized as a “special class of multistory buildings” possessing the following properties:

- The centers of mass of all floors lie on vertical line.
- The resisting elements are positioned orthogonal to the x and y axis and the centers of rigidity of all stories lie on a vertical line.
- The floors diaphragms are infinitely rigid in their own plane.

The torsional seismic component has dynamic amplifications for shorter translational periods than the translational components (Stathopoulos and Anagnostopoulos 2010). Thus, asymmetric reinforcement concrete buildings, with three stories, were analyzed.

4. Parametric study by finite element method

A series of time-history analysis carried out here in order to illustrate the influence of the torsional seismic component on the torsional response. To obtain the knowledge on the torsional response of buildings, a key elastic parameter is the frequency ratio (Ω), which are defined as the predominantly torsional frequency ω_θ divided by the predominantly translational frequency ω_X or ω_Y

$$\Omega = \omega_\theta/\omega_X \quad \text{or} \quad \Omega = \omega_\theta/\omega_Y \tag{5}$$

The fundamental frequencies can be resolved by the standard procedure for solving eigenvalue problems or by the Rayleigh method (Chopra 1995, De La Llera and Chopra 1994).

If Ω is greater than 1.2 the response is mainly translational and structure behavior is defined “torsionally stiff”; conversely if Ω is lower than 0.8, the response is affected to a large degree by torsional behavior and, then, the structure is defined as “torsionally flexible” (De La Llera and Chopra 1995). If the ratio is unity, the maximum degree of translational and torsional coupling is likely to occur.

In the case of a torsionally stiff structure, a single translation mode controls the displacement in on direction. Thus, the typical dynamic behavior of such structure is qualitatively similar to the response obtained using static analysis. The seismic response of torsionally flexible structure is qualitatively different from that obtained in the case of static loading at the center of mass. The main reason is that the displacement envelope of the structure depends on both the translation and the torsional modes.

The dynamic properties of the three-dimensional reinforced concrete framed structures have been calculated by 3D computer modal analyses and are shown in Table 3. We can notice that the model M7 is torsionally stiff while the others are torsionally flexible structures in X direction.

To illustrate the effect of torsional ground motion component, the dynamic analyses of the structures are carried out using the finite element software “Ansys”. The structures analyzed were first excited simultaneously by the horizontal translational and the torsional components of the ground motion and then only by the two translational components. The torsional accelerograms, calculated with the method of Lee and Trifunac through the translation recorded accelerograms were implemented into Ansys. In this concern, Ansys makes it possible to introduce the rotational and linear accelerations of the global Cartesian reference frame for the analysis.

The contribution of the torsional component is assessed by comparing the responses in terms of displacements (Δ) under the two loading conditions: $\Delta_{Trans+Rot}$ is the maximum displacement for the model subjected to three components of ground motion and Δ_{Trans} is for the same result obtained when the model is subjected to the two translational components.

Fig. 5 shows the increase in the displacement response due to torsional component. The general trends of the curves for the coupled systems are similar to those obtained in the literature (Xuanhua *et al*. 2014, Hernandez and Lopez 2004).

It is seen that the normalized displacement Ď decreases as the Ω value increases, which means that the system becomes torsionally stiffer. In other words, the responses of the torsionally flexible buildings are sensitive to torsional excitation. We can see also from Fig. 5 that resonance between translational and torsional frequencies, i.e., when Ω≈1, is not a critical issue.

According to Fig. 5, for low-frequency ratios (Ω=0.423, 0.43 and 0.535), the normalized displacement Ď has high values in two cases: El-Centro and Christchurch earthquakes (Ď=5 and 3.15, respectively). For the others cases, L’Aquila, Petrolia and Kocaeli earthquakes, the maximum values are less (Ď=1.67, 1.26 and 1.07, respectively).

From Figs. 2, 5 and Table 3, we can notice that the highest values of normalized displacement (Ď=5 and 3.15) occur under the resonance between the ground motions and the structures. The frequency contents of El-Centro (0.49-2.37 Hz) and Christchurch (0.85-7 Hz) earthquakes correspond with fundamental frequencies of the building models (0.79 Hz, 0.83 Hz, 0.86 Hz, 0.91 Hz, 0.94 Hz and 2.20 Hz). But, this resonance does not occur in the case of Petrolia earthquake (Ď=1.26), for which the frequency content corresponds too (0.49-2.37 Hz). It is clear that the variation in structural response is not only dependent on the earthquake characteristics but also dependent on the soil properties.

Fig. 6 is presented to show that the normalized displacement Ď increases as the shear wave velocity increases. Thus, the soil conditions can significantly influence the increase in the displacement response due to torsional component. The amplification is more noticeable for the small values of shear wave velocity (stiff soil). However, for higher values (very dense soil and Rock), the amplification is considerably reduced.

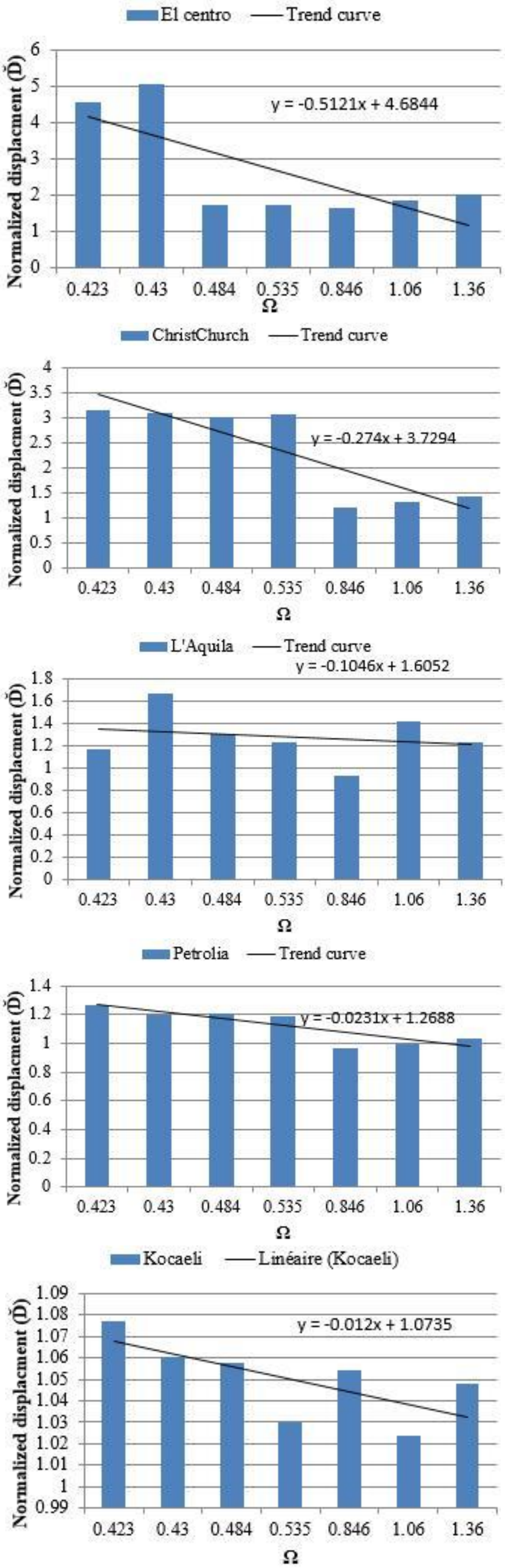


Fig. 5 Effect of frequency ratio on normalized displacement

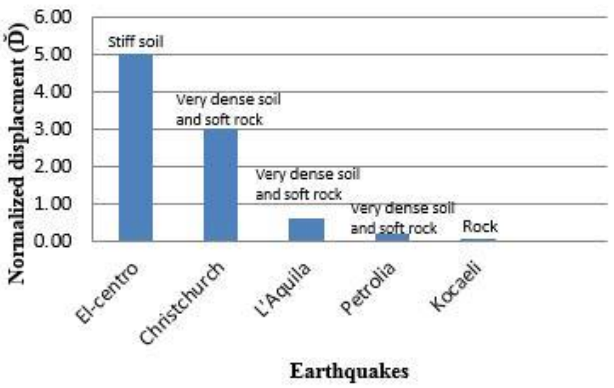
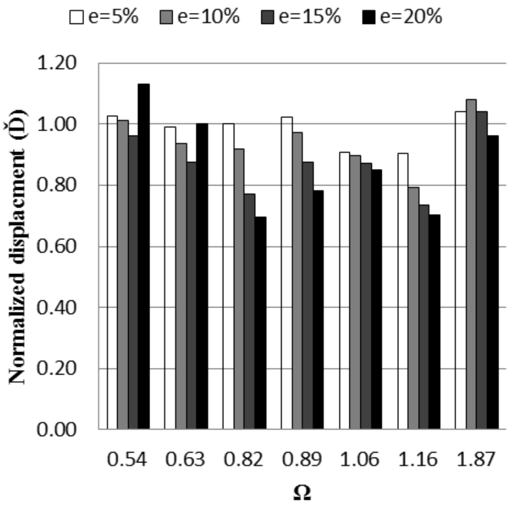
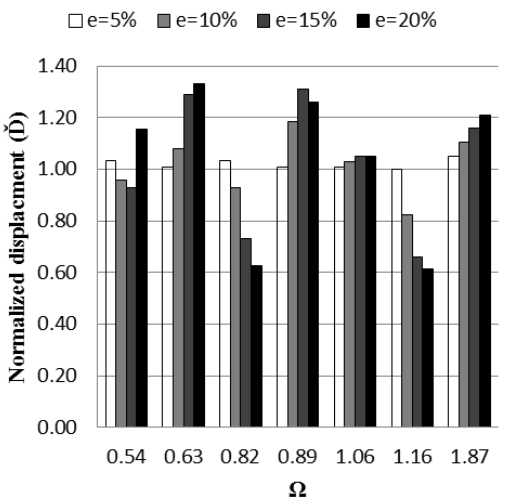


Fig. 6 Effect of different soil conditions on normalized displacement



Seismic motion in the direction x



Seismic motion in the direction y

Fig. 7 Effect of frequency ratio on normalized displacement, by applying the conventional calculation of accidental eccentricity e

The conventional approach of accidental eccentricity, recommended by seismic codes, does not depend on the frequency ratio (Ω) or soil conditions.

This method does not produce the desired result: shifting the center of mass at each floor level to consider the effects of accidental torsion alters the modal properties of a structure (Basu and Giri 2015). An increase in accidental eccentricity should lead to an increase in torsional response. However, the examples considered above do not exhibit this trend (Fig. 7). In this case, the systems analyzed previously (M1, M2, ..., M7) are reanalyzed by shifting the center of mass and subjected to the acceleration response spectra corresponding to the horizontal components of the selected El-centro accelerograms, for damping ratio equal to 5% of the critical damping value. By comparing the Figs. 5 and 7, it can be seen that the shifting of center of mass does not properly account for the effects of torsional ground motion in accidental eccentricity. We can notice that the highest value of normalized displacement Ď is less than 1.4 in Fig. 7, whereas in Fig. 5, this value is about 5.

5. Conclusions

In this paper, the effect of torsional component of earthquake on linear dynamic responses of multistory buildings was investigated by finite element method. It should be emphasized that the results of this study are valid only within the framework of presented modeling (special class of multistory buildings) and analysis assumptions.

- From the numerical linear analyses of the studied structures, we confirm that it is undeniable that the torsional seismic wave has a considerable unfavorable effect on the structural response.

- Accidental torsion, induced by the torsional component, depends mainly on frequency ratio and frequency content of excitation. The torsionally flexible structures are more sensitive to this component. But, the effect of torsional ground motion is considerable also for torsionally stiff structures (the normalized displacement Ď can reach 150% or 200% in some cases). This leads to suggestions that conventional accidental eccentricity (about 5% or 10% of the building dimension perpendicular to the direction of excitation) should probably be improved by more effective provision (Anagnostopoulos *et al*. 2015).

- The finite element method has the advantage, in comparison with the analytic method for the simplified single-story model, that it can be used to more complicated structures comprising wall and frame resisting elements or having different nonlinearities.

- The torsional seismic component and their effects are more complicated and require more studies to support the obtained results.

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