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Rocking seismic excitations effect on inelastic response of reinforced concrete building with soft-story

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ABSTRACT

Well-known problem with seismic design codes is that it does not take into account the rotational earthquake components. Only Eurocode 8, in Part 6, offers response spectra of rotational accelerations for the seismic design of slender and tall structures such as towers, masts, and chimneys. However other structures such as high-rise buildings or buildings with soft-story could be influenced by the rocking seismic components. Recording rotational ground motions can only be considered in its infancy. One approach to solve this problem involves the use of computed rotational accelerograms. The effect of rotational components on the structural response is still insufficiently explored. This paper investigate the influence of the rocking seismic components on the structural response of reinforced concrete structures with soft-story. Two types of rotational ground motions are used: recorded and computed accelerograms. Under combined translational and rotational accelerograms, the results are collected in terms of themaximum of inter-story drifts, story displacements, and internal forces. Nonlinear time history analysis shows clearly that the contribution of the rocking seismic components can be significant in structural response such as displacement (up to 60%), inter-story drift (up to 32%), and axial force (up to 8%). The existence of soft-story in the structure can amplify this contribution up to 25% compared to a structure without soft-story. Therefore, the effects of horizontal rotational components should not be ignored by the seismic codes and require further investigations.

1 Introduction

In seismology, any point on the ground surface can be subjected to three translations and three rotations along and around the x, y, and z axes, respectively (Fig. 1). The last three components include two "Rocking" rotations about the two horizontal axes and one rotation about the vertical axis "torsion". Due to the lack of direct measurement instruments to record these

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rotational seismic components, only the translation components are taken into account by the seismic codes for the design of the structures. Eurocode 8 is the only seismic code that offers response spectra of rotational accelerations extracted from those of translational ones, especially for slender and tall structures [1].

However, recently, there has been a growing interest in all aspects of rotational movements and their implications in related fields such as earthquake engineering, geodesy, tectonics, etc. The efforts of researchers are focused on acquiring rotational seismic components that require recording instruments that are highly sensitive to high-frequency vibrations. Recording of rotational ground motions, directly in a free field, is still in its infancy and simultaneous measurements of six-component earthquakes are slowly accumulating. The first records of the three rotational components, obtained from a very strong explosion (1000 tons of explosives), date from 1994 [2]. Other direct measurements have been recorded in Japan from real earthquakes in 1998 [3]. Over the past two decades, with advancements in rotation sensor technology, such as fiber optics and laser gyroscopes, the direct measurement of seismic rotational motions has improved noticeably [4]. Several recordings (direct measurements of the amplitude of rotational components of ground motions) have been carried out successfully in several countries. In Greece, more than 1700 rotational motions were recorded, during the two earthquakes of 2014, by the rotational sensors installed in Cephalonia [5]. In Poland, rotational ground motion records also exist. These were recorded from induced seismic events from a coal mining basin [6]. In 2004, in the United States of America, a six degrees of freedom (6DOF) ground motion observation system was installed in highly seismic areas of southern California (Garner Valley Downhole Array). Currently, there are hundreds of direct measurements [7].

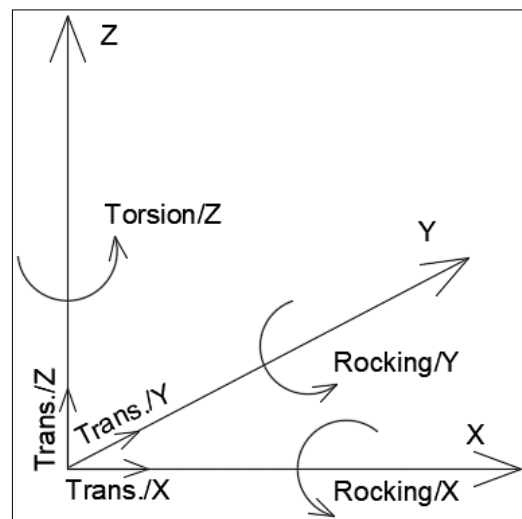


Fig. 1–Translational and rotational seismic components

However, from the engineering point of view, it is necessary to have rotation records, for major earthquakes, sufficient and relevant for structural design. This would require the installation of numerous rotational motion sensors and expect major earthquakes with epicenters near these sensors. In the meantime, researchers have at their disposal theoretical methods based on the plane wave propagation theory to extract the rotational accelerograms from those of translation. It was Newmark who proposed the first linear relations between translational and rotational seismic components [8]. Its approach has been applied and developed by many researchers [9-15].

In addition to the previously cited studies that focus on the interaction between translational and rotational ground movements, there is a growing interest in the investigation in their earthquake engineering applications which could be resumed by the three following points:

- Analysis of the combined translational and rotational ground movements effects on structural response. Recent studies by Vicencio et al. [16], Bonkowski et al. [17, 18], and Zembaty and Bonkowski [19] concluded that the contribution of rotational seismic components could increase significantly the structural response.
- Estimation of empirical relationships for rotational response spectra. Some authors like Yin et al. [16], Falamarz-Sheikhabadi [15], and Falamarz-Sheikhabadi and Ghafory-Ashtiany [14] have developed rotational response spectra.

They concluded that estimate rotational response spectra for design will require more investigation for more significant earthquakes.

- Evaluation of accidental eccentricity recommended by the seismic codes. This eccentricity is used to take into account the uncertainties (due to the geometric and material properties), the spatial variability of the masses and live loading, and the torsional ground motion. Several studies indicate that the accidental eccentricity of 5% underestimates the effects on the structural response compared to the real effects. Ouazir et al. [20], Basu et al. [21], and Hadjadj et al. [22] suggest that the approach of the seismic codes provisions for the accidental eccentricity should be re-evaluated.

Most studies previously mentioned have relied on linear analyses. They show that the rotational seismic components cannot be neglected in the structural seismic design. Also, they highlight the complexity to identify all the parameters on which the effects of rotational seismic components depend and, consequently, to draw practical and exploitable conclusions. In addition, it was concluded that these effects are governed by various parameters: the frequency content of earthquakes and their epicentral distance, the site conditions, and seismic wavelengths.

For RC buildings with soft-story, to our knowledge, no study has been performed to investigate the influence of the rocking seismic components on the inelastic structural response. Accordingly, in this study, several nonlinear time history analyses are performed to understand the effects of the combined translational and rotational seismic components on the structural response. The contribution of the rocking seismic components in structural response is evaluated in terms of the story displacement, inter-story drift, and internal forces story.

2 Horizontal and Rotational ground acceleration components used

Three translational ground motion records are selected from the strong earthquake database of the Pacific Earthquake Engineering Research Center (PEER) [23]. In addition, rotational ground motion records from the recent earthquake recording program at Kefalonia Greek Island[5] are used. Table 1 presents the main details of the selected earthquakes.

Table 1 - Details of earthquakes used

Earthquake	Station	Mw	Epic. Dist. (kms)	PGA (g)	Vs30 (m/s)	Dominant wavelengths (m)
Kefalonia Island Greek 8/11/2014	2014118-231542	5.0	9.2	0.414	250	100
Christ-church New Zealand (21/02/2011)	Lyttelton Port Company	6.3	4.0	0.86	422	170
L'Aquila Italy (6/4/2009)	V-Aterno V(AQA)	6.3	4.6	0.44	549	220
San-Fernando 09/02/1971	Pacoima, DAM, CAL, n°279	6.61	3.5	1.148	2016	800

The computed rotational accelerograms are obtained from the generalized wave model proposed by Nazarov[24]. This model does not require the angles of incidence of seismic waves. The rotational seismic components are obtained from the inverse Fourier transform of rotational spectra, extracted from the translational spectra corresponding to the given three components translational accelerograms. Equation 1 shows the relations between spectrums of accelerations of rotational and translational motions.

$$\ddot{a}_i(t) = \sum_{k=1}^{\infty} A_k^{\ddot{a}} \cos k \frac{\pi t}{T} + \sum_{k=1}^{\infty} B_k^{\ddot{a}} \sin k \frac{\pi t}{T} \quad (1)$$

Note in equations 2, 3, 4, 5 that the Fourier coefficients for the accelerations of rotational motions $A_k^{\ddot{a}_2}$ are expressed in terms of the Fourier coefficients for the translational motions $A_k^{\ddot{u}_1}$.

$$A_k^{\ddot{\alpha}_1} = \frac{1}{2} \left[\bar{A}_{31}^{(2)} A_k^{\ddot{u}_3} - \bar{A}_{21}^{(3)} A_k^{\ddot{u}_2} + \left(\bar{A}_{32}^{(2)} + \frac{1}{c_2} \bar{A}_{32}^{(t)} \right) A_k^{\ddot{v}_3} - \bar{A}_{22}^{(3)} A_k^{\ddot{v}_2} + \bar{A}_{33}^{(2)} A_k^{\ddot{w}_3} - \left(\bar{A}_{23}^{(3)} + \frac{1}{c_2} \bar{A}_{23}^{(t)} \right) A_k^{\ddot{w}_2} + \frac{\omega_k}{c_2} (B_k^{\ddot{w}_2} - B_k^{\ddot{v}_3}) \right] \quad (2)$$

$$B_k^{\ddot{\alpha}_1} = \frac{1}{2} \left[\bar{A}_{31}^{(2)} B_k^{\ddot{u}_3} - \bar{A}_{21}^{(3)} B_k^{\ddot{u}_2} + \left(\bar{A}_{32}^{(2)} + \frac{1}{c_2} \bar{A}_{32}^{(t)} \right) B_k^{\ddot{v}_3} - \bar{A}_{22}^{(3)} B_k^{\ddot{v}_2} + \bar{A}_{33}^{(2)} B_k^{\ddot{w}_3} - \left(\bar{A}_{23}^{(3)} + \frac{1}{c_2} \bar{A}_{23}^{(t)} \right) B_k^{\ddot{w}_2} - \frac{\omega_k}{c_2} (A_k^{\ddot{w}_2} - A_k^{\ddot{v}_3}) \right] \quad (3)$$

$$A_k^{\ddot{\alpha}_2} = \frac{1}{2} \left[\bar{A}_{11}^{(1)} A_k^{\ddot{u}_1} - \left(\bar{A}_{31}^{(1)} + \frac{1}{c_2} \bar{A}_{31}^{(t)} \right) A_k^{\ddot{u}_3} + \bar{A}_{12}^{(3)} A_k^{\ddot{v}_1} - \bar{A}_{32}^{(1)} A_k^{\ddot{v}_3} + \left(\bar{A}_{13}^{(3)} + \frac{1}{c_2} \bar{A}_{13}^{(t)} \right) A_k^{\ddot{w}_1} - \bar{A}_{33}^{(1)} A_k^{\ddot{w}_3} + \frac{\omega_k}{c_2} (B_k^{\ddot{u}_3} - B_k^{\ddot{w}_1}) \right] \quad (4)$$

$$B_k^{\ddot{\alpha}_2} = \frac{1}{2} \left[\bar{A}_{11}^{(1)} B_k^{\ddot{u}_1} - \left(\bar{A}_{31}^{(1)} + \frac{1}{c_2} \bar{A}_{31}^{(t)} \right) B_k^{\ddot{u}_3} + \bar{A}_{12}^{(3)} B_k^{\ddot{v}_1} - \bar{A}_{32}^{(1)} B_k^{\ddot{v}_3} + \left(\bar{A}_{13}^{(3)} + \frac{1}{c_2} \bar{A}_{13}^{(t)} \right) B_k^{\ddot{w}_1} - \bar{A}_{33}^{(1)} B_k^{\ddot{w}_3} - \frac{\omega_k}{c_2} (A_k^{\ddot{u}_3} - A_k^{\ddot{w}_1}) \right] \quad (5)$$

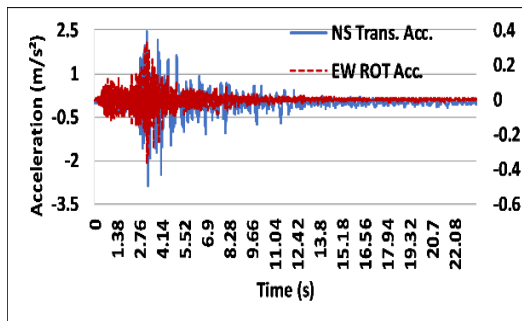
Where:

$$\bar{A}_{ij}^{(1)} = \frac{1}{A_{ij}} \frac{\partial A_{ij}}{\partial x_1}$$

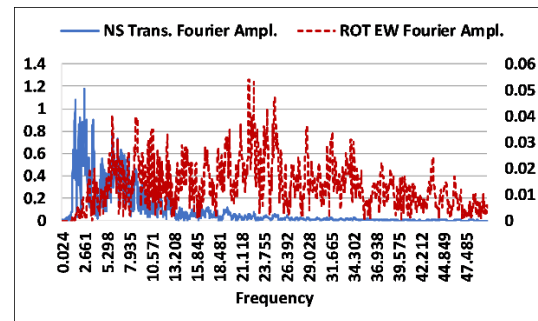
$$\bar{A}_{ij}^{(3)} = \frac{1}{A_{ij}} \frac{\partial A_{ij}}{\partial x_3}$$

$$\bar{A}_{ij}^{(t)} = \frac{1}{A_{ij}} \frac{\partial A_{ij}}{\partial t}$$

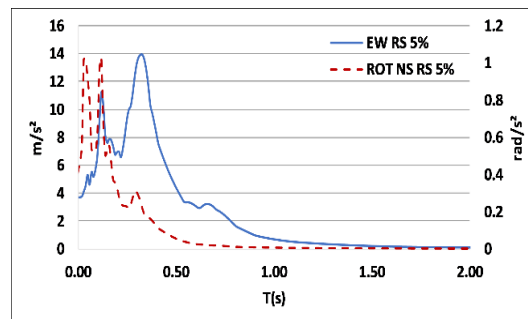
From Figs. 2-3 it's clear that rotational ground motions contain higher dominant frequencies than the translational for all earthquakes used. Also, it can be seen that the effects of rotational components are more important for stiffer structures with ashort period.



a) Recorded translational and rotational accelerograms

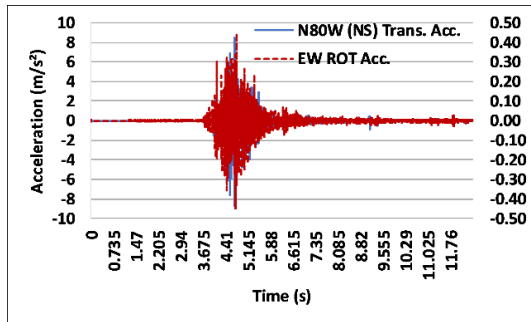


b) Translational and rotational Fourier spectra

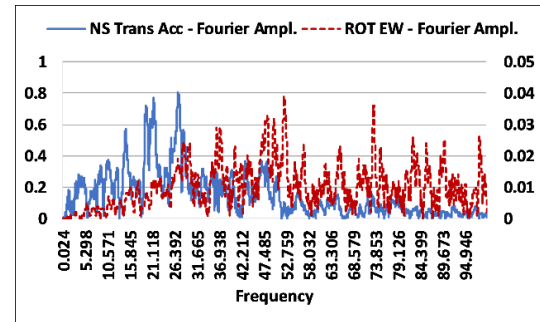


c) Translational and rotational response spectra

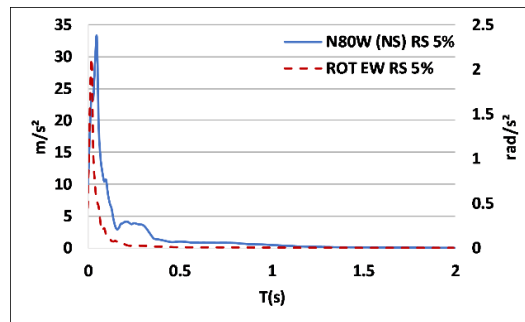
Fig. 2–Kefalonia Island Greek 8/11/2014



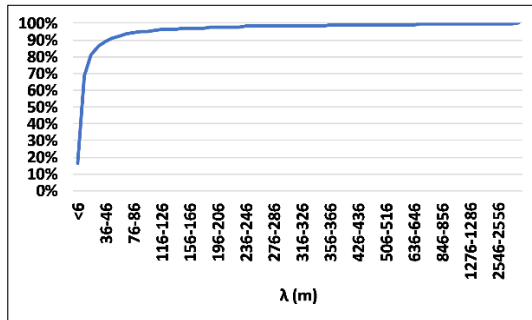
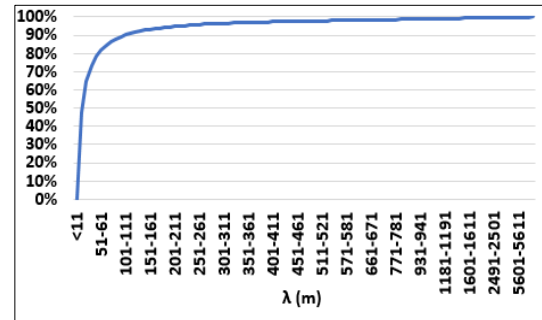
a) Recorded translational and computed rotational accelerograms



b) Translational and rotational Fourier acceleration spectra



c) Translational and rotational response spectra

Fig. 3—Christ-Church New Zealand (21/02/2011)**Fig. 4—Dominant wavelengths of recorded of Kefalonia Island Greek earthquake: $\lambda=100$ m****Fig. 5—Dominant wavelengths of Christ-church New Zealand earthquake: $\lambda=170$ m**

Also, the dominant wavelengths of the ground motions used, estimated from their Fourier spectra, are listed in table 1. In Figs. 4 and 5, only dominant wavelengths for Kefalonia Island Greek and Petrolia earthquakes are shown as an example.

3 Inelastic analysis and modelling approach

3.1 Characteristics of analysed structures

The typical floor plan for the five-story reinforced concrete building designed according to Algerian codes provisions [25, 26] is shown in Fig. 6. The columns are of size 40 cm x 40 cm and the beams are of size 30 cm x 40 cm. Fig. 7 shows the reinforcement distribution of the columns and beams. The floor-to-floor height is 3.05m. The superimposed dead loads are taken as 2.5 kN/m² and the live loads as 1.5 kN/m² for residential buildings. For

the second structure analysed, the irregularity of the soft story is induced in the reference structure with the first story height of 4.5 m. This study is limited to the first soft-story buildings because it's one of the most commonly used structural configurations in Algeria. In addition, the soft-story problem becomes more severe in the lower stories of buildings.

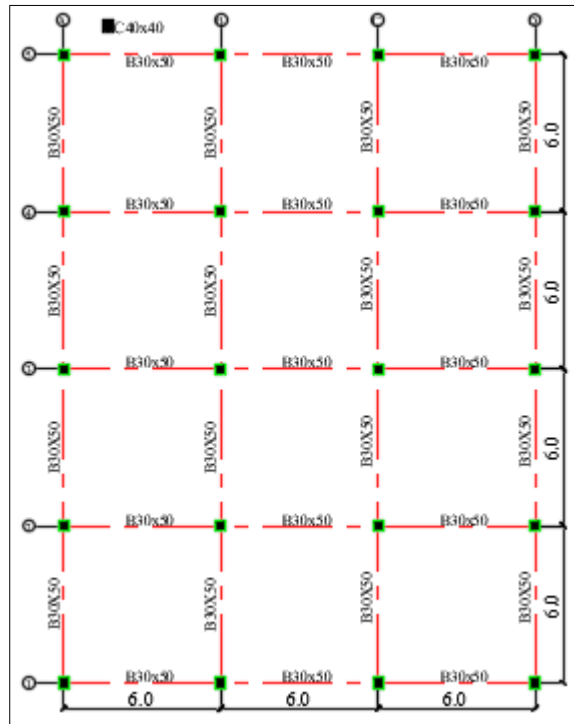


Fig. 6–Typical floor configuration of the structure

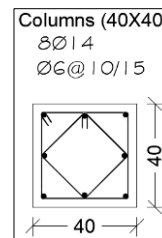
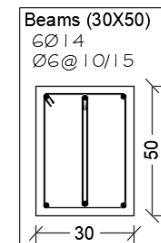


Fig. 7–Reinforcements of beams and columns

3.2 Nonlinear modelling approach

In order to understand the influence of the rocking seismic components on the behaviour of buildings with soft-story, several Fast Nonlinear Analyses (FNA) are performed through Finite Elements software Etabs[27]. Standard Rayleigh damping is used, with 5% of critical damping. A two-dimensional fiber model is adopted for reinforced concrete members (columns and beams). Nonlinear physical properties of materials are defined by their constitutive models: Mander models for concrete confined and unconfined (Fig. 8), an elastic-plastic stress-strain relation for steel (Fig. 9).

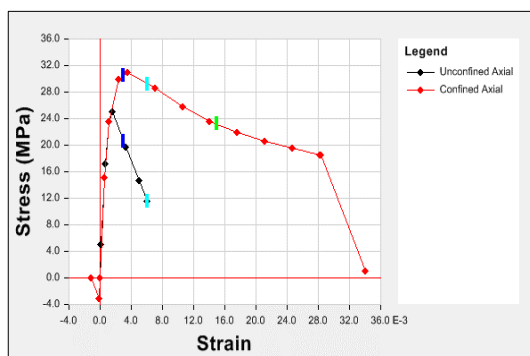


Fig. 8– Nonlinear Behavior model of unconfined and confined concrete

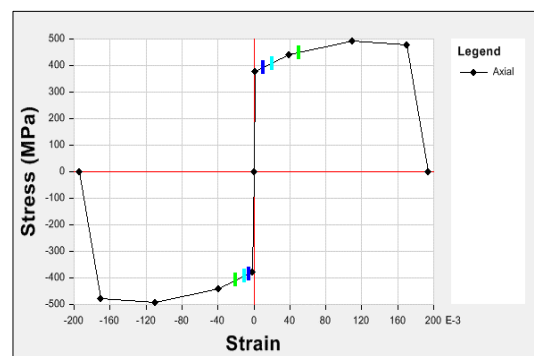


Fig. 9– Elastic-plastic behavior model of steel

4 Results and discussion

To compare the inelastic structural response for both structures with and without soft-story, the following parameters are selected: maximal story drift, maximal story displacement, maximal story shear, and maximal overturning moment. And to estimate the contribution of the seismic rocking components, the different structural responses are normalized, i.e. the normalized structural response ($R+T/T$) is the ratio of the maximum structural response under combined translational and rotational accelerograms ($R+T$) divided by the maximum structural response under translational accelerograms (T) only. First of all, from the analysis results, it should be noted that the seismic rotational components can increase or sometimes decrease the structural responses.

4.1 Inter-story drift

Figs 10-11 present the inter-story drifts for both structures with soft-story and without soft-story under translational earthquake excitations with and without rocking excitations. The results indicate that the maximum effect of the rocking excitations contributes up to 32% and 28% for structures without and with soft-story, respectively. In addition, it should be noted that in the case of structures with soft-story, the maximum increases are located on the ground floor, i.e. at the level of the soft-story. Also, for the two seismic excitations, Kefalonia Island Greek (2014) and Christ-Church NZ (2011), we notice additional significant increases of 17.7% and 21.4%, respectively, of the rocking excitations contribution in the structures with soft-story compared to those without soft-story. As expected, the effects of rotational components are significant for earthquakes that have the shorter dominant wavelengths: Kefalonia Island Greek ($\lambda=100$ m) and Christ-Church NZ ($\lambda=170$ m), (see Table 1).

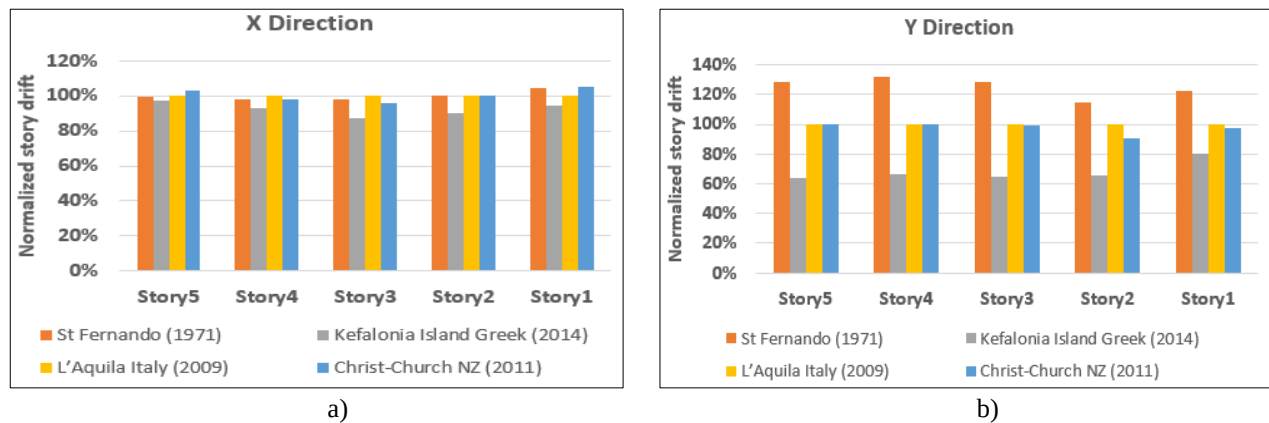


Fig. 10– Ratio of story drift under combined translational and rotational accelerograms ($R+T/T$)(structure without soft-story)

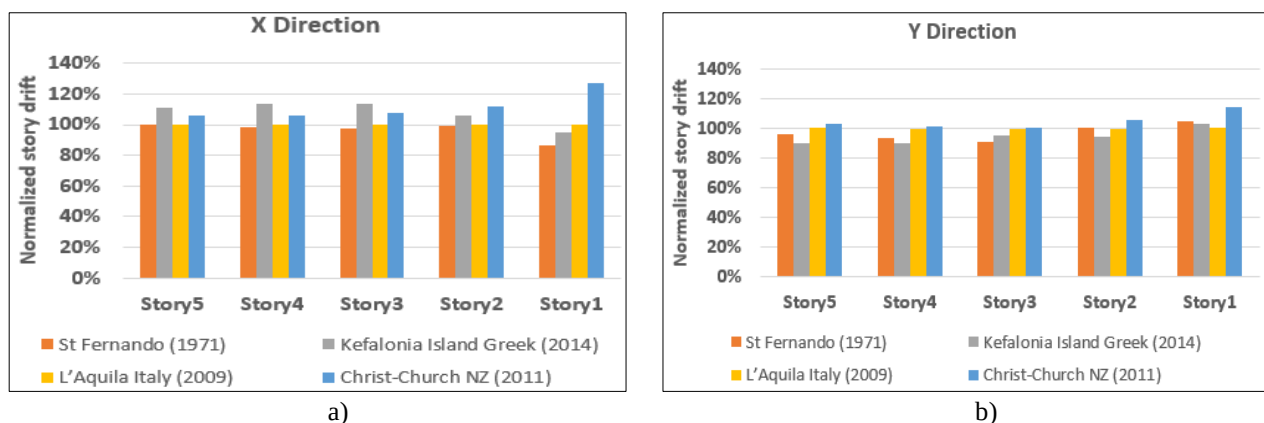


Fig. 11–Ratio of story drift under combined translational and rotational accelerograms ($R+T/T$) (structure with soft-story)

4.2 Story displacement

As for the results of the Inter-story drift, we still notice that the rocking components increase the maximum story displacements up to 42% and 60% for the structures with and without soft-story, respectively (see Fig. 12(a)-(b) and 13(a)-(b)). Also, at the level of the ground floor of structures, we observe an additional increase, of the rocking excitations contribution in the structures with soft-story compared to those without soft-story, up to 18.5%, 25.2%, and 14.6% for St Fernando (1971), Kefalonia Island Greek (2014) and Christ-Church NZ (2011) earthquakes, respectively (Figs 12-13). Thus, the presence of the soft-story in structures could significantly increase the effects of the rocking seismic excitations compared to the structures without soft-story.

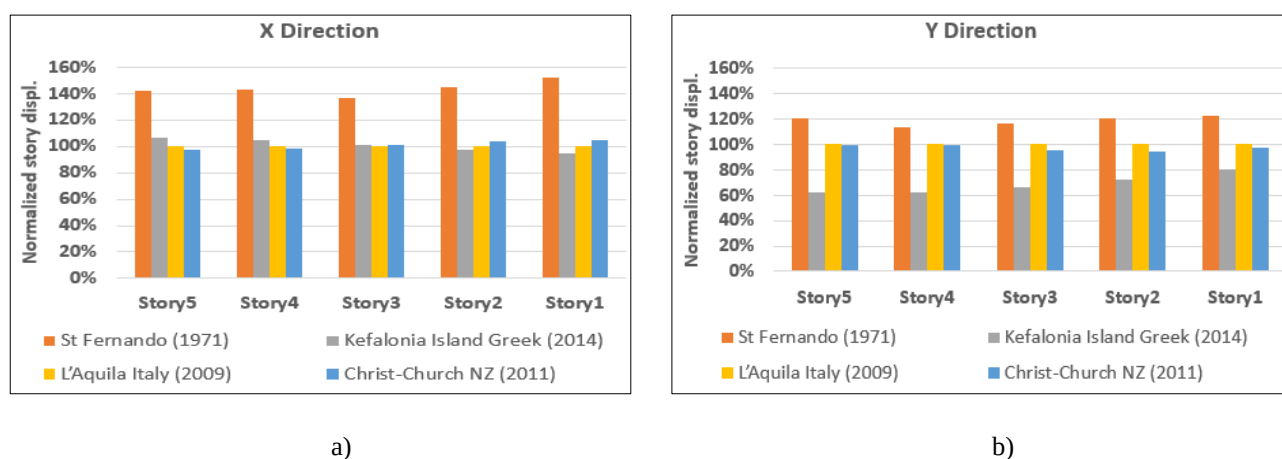


Fig. 12–Ratio of maximum story displacement under combined translational and rotational accelerograms ($R+T/T$) (structure without soft-story)

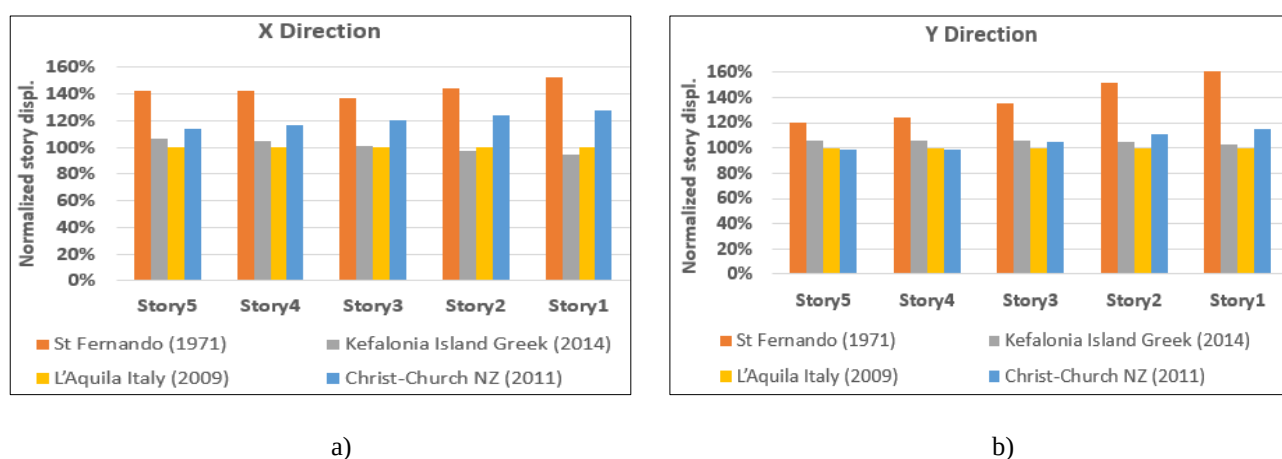


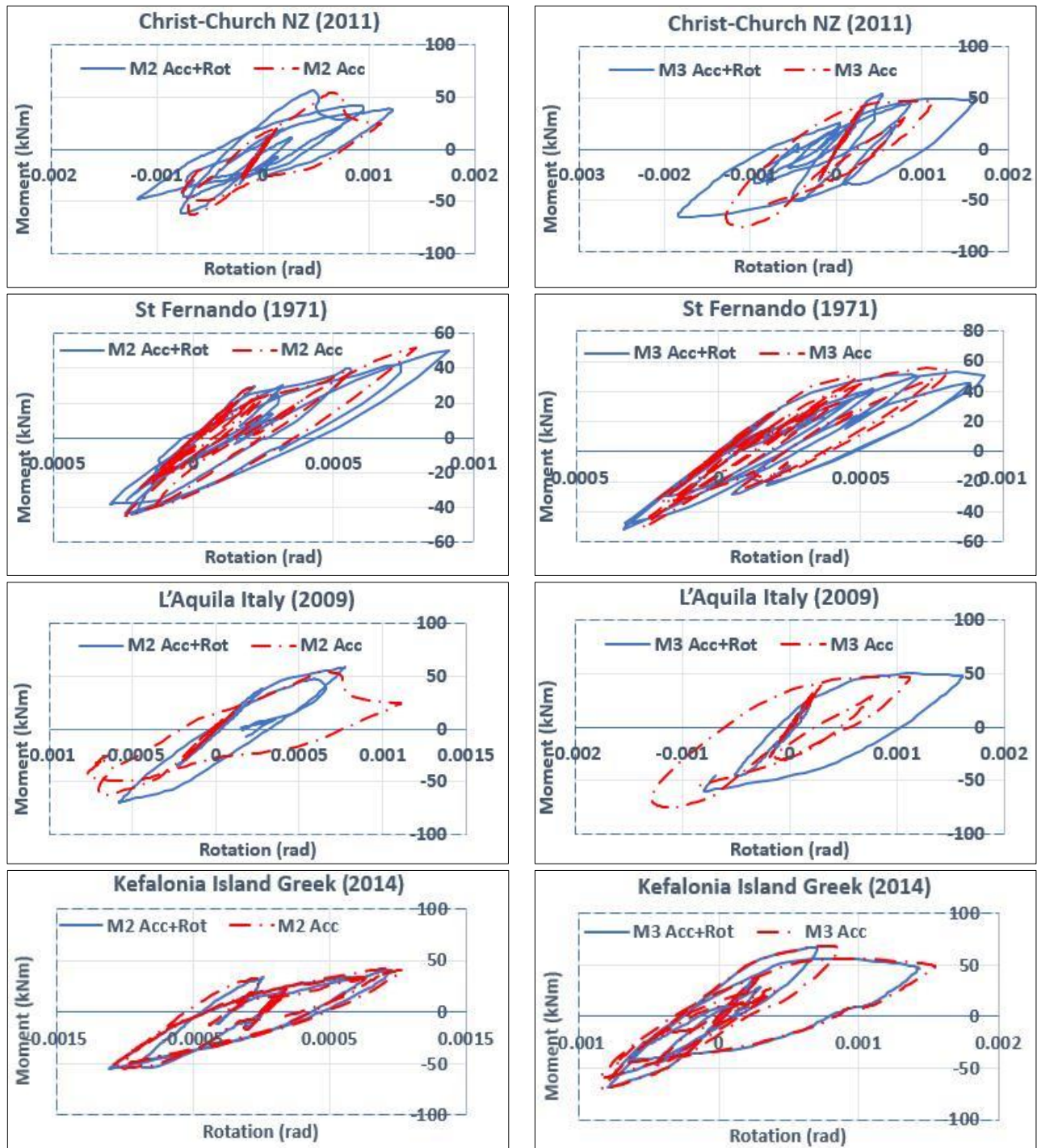
Fig. 13. Ratio of maximum story displacement under combined translational and rotational accelerograms ($R+T/T$) (structure with soft-story)

4.3 Internal forces story

From table 2, it is observed that internal forces story, moments, and shear forces, under combined translational and rotational accelerograms have a negligible variation compared to those under the translational accelerograms only. The expected difference is certainly absorbed by the yielding of the structural elements. As shown in Fig. 14, for example, for both structures with and without soft-story, subjected to four earthquakes, the maximum moments have a negligible variation for both cases translational and rocking component and translational component only. Unlike moments and shear forces, the variation for axial forces in lower columns is notable, an increase of up to 8% and a decrease of up to 37.54%.

Table 2 - Normalized structural response (R+T/T) in terms of internal forces story

Earthquake	Maximal Shear (kN)	Maximal Moments (kNm)	Maximal Axial forces (kN)
St Fernando (1971)	-0.3%	+0.4%	-37.54%
Kefalonia Island Greek (2014)	-0.9%	+0.1%	+8%
L'Aquila Italy (2009)	-0.4%	+0.4%	-5%
Christ-Church NZ (2011)	+0.0%	-0.3%	-33.81%



Xdirection

Ydirection

Fig. 14. Maximum hinge response curve in columns of first soft-story under combined translational and rotational seismic excitations

5 Conclusions

In order to investigate the behavior of multi-story reinforced concrete structures with soft-story under the combining translational and rocking excitations, inelastic time history analysis is performed. The contribution of the rocking seismic components can be significant in structural response such as displacement (up to 60%), inter-story drift (up to 32%), and axial force (up to 8%). The existence of soft-story in the structure can amplify the contribution of rocking seismic components up to 25% compared to a structure without soft-story. Also, as expected, the effects of horizontal rotational components are significant for earthquakes that have shorter dominant wavelengths (rigid structures).

Finally, it should be emphasized that the interaction between translational and horizontal rotational seismic components cannot be ignored because it strongly influences the seismic response of structures. However, to avoid hasty conclusions, and before making recommendations for seismic codes, much more recorded or computed rotational ground motions analyses are needed. Future research should further investigate the contribution of the rotational seismic components by taking into account the soil-structure interaction.

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