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Analysis of a steel structure considering the rotational and translational components of the earthquake excitation.

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ΠΕΡΙΛΗΨΗ

Σε αυτή την εργασία διερευνάται η επιρροή της περιστροφικής συνιστώσας της διέγερσης του σεισμού στην απόκριση των χαλύβδινων κατασκευών. Στις περισσότερες αναλύσεις η σεισμική διέγερση προσομοιώνεται και επιβάλλεται στη βάση της κατασκευής μόνο με τις τρεις μεταφορικές της συνιστώσες, δυο οριζόντιες και μια κατακόρυφη, ενώ οι τρεις περιστροφικές αγνοούνται. Αυτό οφειλόταν εν μέρη στην έλλειψη καταγράφων της περιστροφικής συνιστώσας λόγω αδυναμίας οργάνων μέτρησης και από το γεγονός ότι αυτή η περιστροφική συνιστώσα είναι πολύ μικρή και αμελητέα ειδικά για χαμηλές κατασκευές. Παρόλα αυτά μετρήσεις έδειξαν ότι κοντά στο ρήγμα η περιστροφική συνιστώσα είναι σημαντική. Επιπρόσθετα για ψηλές κατασκευές η περιστροφική συνιστώσα έχει σημαντική επιρροή ακόμα και αν έχει μικρή σε μέγεθος τιμή. Σήμερα, η τεχνολογία παρέχει όργανα τα οποία μπορούν να καταγράψουν την περιστροφική συνιστώσα της επιτάχυνσης του εδάφους. Στον κανονισμό έχουν εισαχθεί ελαστικά φάσματα σχεδιασμού για περιστροφικές συνιστώσες της διέγερσης και χρήση τους στην ανάλυση των κατασκευών με τη μέθοδο των ιδιομορφών. Στην παρούσα εργασία διεξάγονται δυναμικές αναλύσεις και διερευνάται η επιρροή της περιστροφικής συνιστώσας της εδαφικής επιτάχυνσης στην απόκριση και στα εντατικά μεγέθη μεταλλικών κατασκευών. Από τα αριθμητικά αποτελέσματα προκύπτει ότι η επίδραση της περιστροφικής συνιστώσας στην απόκριση και στα εντατικά μεγέθη των κατασκευών είναι σημαντική και δεν θα πρέπει να αγνοηθεί για το σχεδιασμό των κατασκευών.

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ABSTRACT

In order to perform a seismic analysis of structure a full description of ground motion is needed. This means that all the six degree of freedom component, three translational and three rotational must take into account. In this research, the influence of rotational component of earthquake excitation to the response of steel structure is examined. In most of studies seismic input is being represented by translational only component of ground accelerations while the rotational one is ignored. This was due to the luck of records which measure the rotational component. Nowadays, technology provides such an instruments and relative records can be found. Elastic design response spectra for rotational components are introduced in codes. Furthermore, the rotational component was not taken into account since its influence in low structures is not significant. The results in response and in internal forces due to rotational component to steel structure are presented. Time history analysis of a symmetrical and non-symmetrical steel structures with and without rotational excitation component is performed. From the numerical results it is shown that the impact of rotational component in response and the internal forces is significant and should not be ignored in design procedure.

1 INTRODUCTION

Time history analysis of structure involves exclusively fully description 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 directly measure rotations during an earthquake. The rotational components data history can be measured directly in a free field with special accelerometers or can be extracted from measured translational 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 motions observed during an earthquake in April 1998 ιν Japan was measured with agyro-sensor, and an inertial angular displacement sensor, by Takeo [2]. Advances in rotational seismology about instrumentation, theory and observations are presented in the work of Igel et al. [3]. The application of compact and cheaper sensors based on electrochemical magnetohydrodynamic technology, used from Liu et al. [4] and Wassermann et al. [5].There are a lot of procedures that calculate rotational time series from translational recordings. 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 extension to the SSP method is the use of data from a number of closely spaced, spatially distributed stations, this procedure is called Multiple 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 content 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], 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 revised the seismic intensity parameters in order to account for the combined action of horizontal and rocking seismic motion on structures. Links between rotational ground motion and site soil conditions are proposed in the work of Sbaa et al. [17] and Perron et al. [18]. They show that the coupling of translational and rotational measurements appears to be useful, not only for direct applications of engineering 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 account special variability of the seismic ground motion including rotational 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 excitation of the rocking mode in a base-isolated building due to rocking excitations. Bozev et al. [22], performed analysis accounting the rotational 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 tower using horizontal and rocking spectra computed based on Eurocode 8. In a recently work, [25], rotational ground-motion records from induced seismic events are examined. A simplified relations for the application of rotational components to seismic design codes and calculation of response of multiple-support structures subjected 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 earthquake engineering analysis of measured rotational ground motions at structure, [30].

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

2 THEORETICAL BACKGROUND

Rotational components of earthquake consist of one torsional component which is the rotation about vertical axis and the other two rocking components which is the rotation about the two horizontal axis. The secondary horizontal wave, SH wave, and the surface wave, Love wave, contribute to the torsional motion. Rocking motion is due to the primary waves, P waves, secondary vertical wave, SV waves, and Rayleigh waves. Even though that rotational components 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 rotational 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 analysis. Time history analysis requires time history rotational motion records in order to applied in the base of structures. Structure that are influence of rotational component are slender and tall structures such as towers, chimneys and masts. Those structures are special 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 influenced by rotational components of seismic action.

In the earthquake engineering community saying ground acceleration and velocity directly means translational component of acceleration and velocity. Term like translational acceleration and translational velocity is used to clearly distinguish from rotational acceleration and rotational velocity respectively. The term rotational 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 model of structure with concentrated mass and stiffness at each floor subjected to ground motion with translational and rotational components is shown in Figure 1.

If [**M**], is the inertia 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:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -(\{m\}\,\ddot{x} + \{m\,h\}\,\ddot{\theta}) \quad (1)$$

$\{\ddot{u}\}$: is the vector comprising the accelerations of the degrees of freedom of the structure relative to the base,

$\{\dot{u}\}$: 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,

$\ddot{x}_g(t)$: is the translational ground acceleration,

$\ddot{\theta}_g(t)$: is the rotational acceleration of the base.

The above equation can be extended to three dimensions. In that case the excitation motion consists of the three translational acceleration, two rotational accelerations, (rotation about the two horizontal axis, 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 1. 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 petition at each time step).

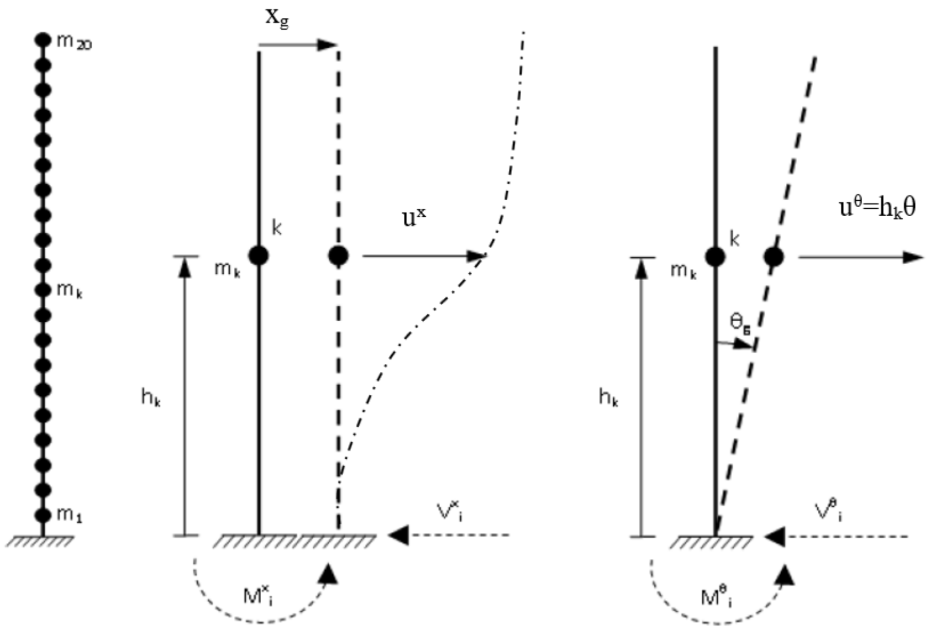

Figure 1: Response of a concentrated mass and stiffness model subjected to ground motion with translational and rotational components.

3 CASE STUDIES - NUMERICAL RESULTS AND DISCUSSION

Five different models were subjected to an earthquake excitation with translational and rotational component. The models were: one single degree of freedom, the second and third a two and ten story, thee bay, steel plane frame. The ten story plane frame has its first eigenperiod equal to signgle degree of freedom system. The fourth and fifth models are a symmetrical and another one irregular ten-story space steel structure. The all models have 3 m story height and 4m bay opening. The loads, frame section layout and other characteristics of the models are shown in Figure 2.

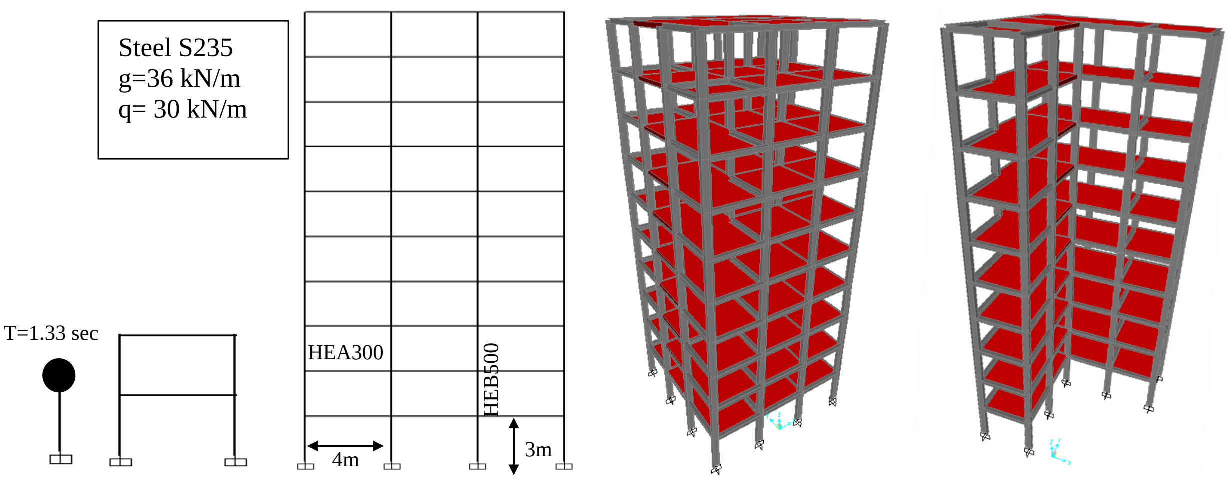

Figure 2 Layout of the steel models.

The structures were subjected in 6.4 moment magnitude, Mw, earthquake excitation which happened at 2015/11/17 in Kefalonia island, Greece. The epicenter latitude and longitude were 38.16^{o} and 20.50^{o} degrees respectively. The event depth was 10.7 km. The record history of translational and rotational component was provided by by Argonet project, a 3D accelerometric array implemented on the island of Kefalonia in Greece, [17-18] and is shown in Figure 3.

Linear dynamic time history analysis was applied, with suitable software like SAP 2000, [31], and the response of structure was calculated. Two cases of earthquake excitation were considered. One with application only of translational acceleration at the base of structure and the second with simultaneously translational and rotational acceleration excitation. In space structure except the above cases, another one where all six components of excitation (three translational and three rotational) applied at the base of the structure was also examined.

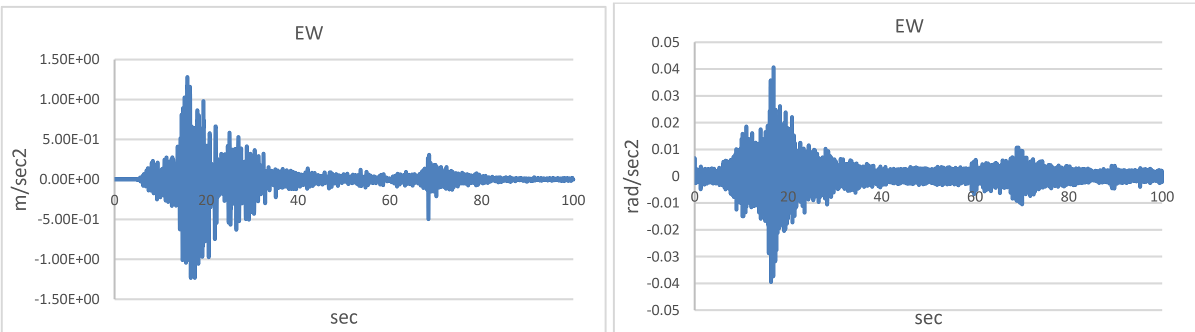

Figure 3 Translational and rotational component of earthquake excitation.

The results of the analysis in terms of displacement, acceleration and base shear of each structure are shown in Table 1. In this table the ratio of the response of the structure excited with translational and rotational acceleration, denoted as T+R, to the response of structure excited only with translational acceleration, denoted as R, is shown. The graphical representation of the table 1 is shown in figure 4.

From the analysis results it is shown that the top displacement, the acceleration and the base shear of structure subjected to rotational and translational component of earthquake are higher compared to the displacement, acceleration and base shear of the structure subjected only to translational excitation. The ratio of the response of structure subjected to rotational and translational component of earthquake to the response of structure subjected only translational excitation, (T+R)/T ranges from 1.1 to 1.6 depend on what kind of building and on what kind of response ones looking for. In figure 4 it is clear that for any kind of the response (displacement, acceleration and base shear) the ratio (T+R)/T is greater than one.

Table 1 The ratio, $\frac{\mathrm{T+R}}{\mathrm{R}}$, of response due to translational and rotational component to the response of only translational component.

Structure \ Response		Top displacement (cm)	Top acceleration (m/sec^2)	Base shear (kN)
SDOF (T=1.5sec)		**1.18**	**1.13**	**1.18**
Two story plane frame		**1.05**	**1.14**	**1.05**
Ten story plane frame (T_1=1.5sec)		**1.15**	**1.20**	**1.16**
Ten story space frame, regular	EW	**1.45**	**1.58**	**1.42**
	NS	**1.30**	**1.40**	**1.45**
	ALL (6 dof)	**1.44**	**1.59**	**1.41**
Ten story space frame, irregular	EW	**1.24**	**1.39**	**1.36**
	NS	**1.39**	**1.56**	**1.48**
	ALL (6 dof)	**1.15**	**1.28**	**1.42**

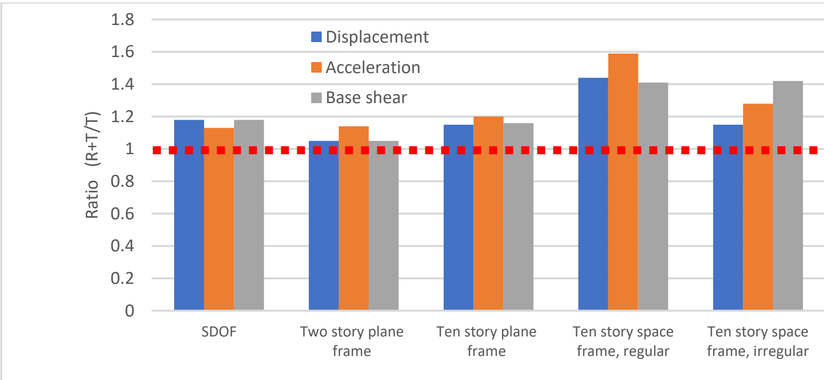

Figure 4 The ratio, $\frac{\mathrm{T+R}}{\mathrm{R}}$, of response due to translational and rotational component to the response of only translational component.

4 CONCLUSIONS

The influence of rotational component of earthquake excitation to the response of steel structures was examined. From the numerical results it was obtained that the response of structure in terms of displacement, accelerations and base shear subjected to rotational and translational component is higher than the response of structure subjected only to translational component. The ratio of the response accounting or not the rotational component of excitation is ranges from 1.1 to 1.6. Further parametric investigations of different structures with different, materials, heights and bays should be done in order to propose a more general value of ratio. This general value can be proposed by codes and in engineering practice ones will executes analysis accounting only on translational component and then will multiple the results with this general value of ratio in order to take the effects of rotational components.

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