ENERGY DISTRIBUTION IN HIGH-RISE BUILDINGS SUBJECTED TO VRANCEA LONG PERIOD GROUND MOTIONS

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ABSTRACT :

Bucharest is the most exposed city to damage on tall buildings in Romania, due to the long predominant period ground motions, repeatedly generated from Vrancea source. The energy balance-based analysis approach has the advantage to (i) assess more efficiently the earthquake ground motion destructive potential and (ii) provide synthetic information on using the appropriate energy dissipation device type and the insertion location.

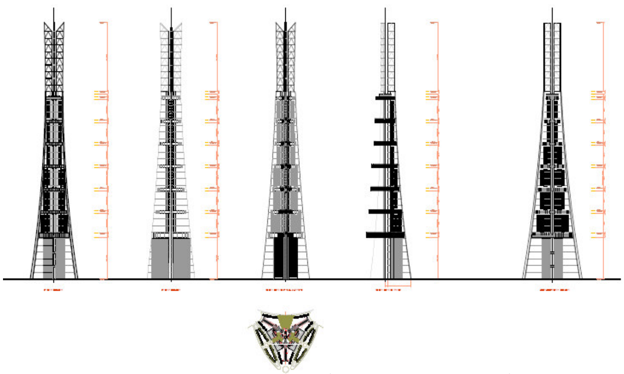
KEYWORDS: tall building, predominant period, energy balance, damage exposure

1. TALL BUILDINGS: AN ARCHITECTURAL AND ENGINEERING OVERVIEW

Tall buildings are symbols of cities, the certainty of economic growth, the force and image of a civilization. In the last centuries, more than in any other historical period, important structures were built due to modern technology developments.

What is happening nowadays in the world is unique and has no precedent. Dozens of modern cities are erected like over the night in China and India. In Dubai, Qatar or Kuwait an ocean of cranes are erecting tall structures, as higher as sophisticated. New airports, museums, stadiums, public spaces, complex transportation and telecommunication networks are continuously developing. After years of standing-by in its own self-satisfactory historical conditions, Europe is cosmetizing its appearance with the most interesting concepts and urban developments known up to now.

A tremendous variety of architectural shapes and complex structural layouts are now designed. New materials and new structural solutions are incorporated in highly eccentric tall buildings (Ali et *al*., 2007). Consequently, the structural designers have to think intelligent solutions in order to fulfill the complex architectural needs and provide appropriate structural seismic performance. Proposals of innovative architectural shapes are given in the fig.1 (Gavrilescu, 2007).



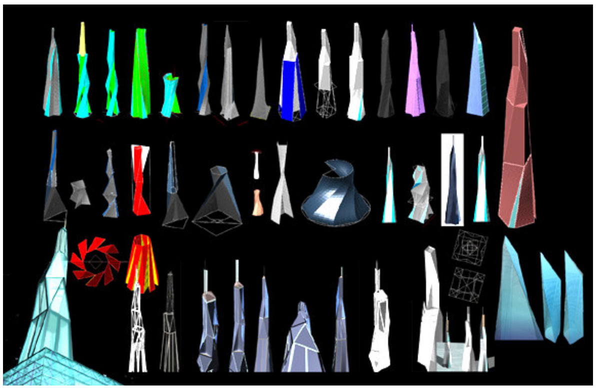


Figure 1 Innovative proposals of highly irregular shapes

In Romania, the increasing interest of business community and population, to considerably improve the actual urban environment, would lead to the completion of tall buildings, having high performance, safer and cost effective.

The history of tall buildings in Romania begins in 1800, when the *Coltea Tower* (H=50 m) has been built and was destroyed by the strong earthquake of October 26, 1802 (M_w =8.1). In the modern era, the tallest reinforced concrete *Carlton Building* (14 stories) collapsed during the November 10, 1940 earthquake (M_w=7.6) and about 32 medium-rise buildings were destroyed at the March 4th , 1977 earthquake (M_w=7.4). Currently, the tallest building in Romania is the *Free Press Building* (1975) in Bucharest, having a total height of 104 meters.

The seismic hazard generated from Vrancea source is the major concern for the practitioners, especially due to medium-soft soil conditions. There is an evidence of long predominant periods of ground motions (1.0~1.6 sec.). Tall buildings might have the highest exposure to significant damage as well as economical and human losses.

The standard design procedure, based on the response spectrum method approach for tall buildings, may lead to inappropriate performance, resulting in highly exposed to seismic risk structures. Ideally, a structural system must have equal performance to earthquake ground motions from all possible directions, resulting uniformly exposed to risk structure. For irregular structures however, having non-coincident mass and stiffness centers, the principal directions of motion are not obvious; an incremental directivity of input ground motion is to be considered in analyses (Iancovici et *al*., 2006).

The structural performance is mainly controlled by the mechanism of how the structure supplies the energy received from the ground motion. The energy balance-based analysis has some advantages over the current analysis procedures: (1) assess more efficiently the earthquake ground motion destructive potential, through the input energy induced into a structural system, (2) fully accounts for the total duration of the earthquake ground motion, (3) has the potential to synthetically and more efficiently describe the degrading process and (4) can provide synthetic information on the appropriate energy dissipation device type and the insertion location.

In our paper, the effect of elastic dissymmetry on the seismic energy distribution in highly flexible, structures subjected to bi-directional long period ground motions is studied. A large number of energy balance-based analyses are conducted on 60 story elastic generic structures, in order to grasp the dynamic behavior expressed in terms of time-instant and peaks of generalized and story energy distributions.

2. ENERGY-BASED CHARACTERIZATION OF THE INPUT GROUND MOTION RECORDS

The energy content of an earthquake ground motion accelerogram can be expressed in both, *time* and *frequency* domain through energy-associated parameters: the cumulative energy function and the power spectral density function (*PSD*), respectively. While one describes the intensity distribution of the accelerogram over the *time* domain, the other one describes the *frequency* decomposition of the signal's energy. Thus, the total power can be consequently obtained by integrating the *PSD* function over the frequency domain, its value yielding the mean square value of the accelerogram.

In the current Romanian analysis and design practice, the long predominant vibration period ground motion of the Vrancea 1977, March 4 earthquake (VN77) recorded at INCERC Bucharest station, is widely used. The frequency content descriptor considered in the signal's analyses is the dimensionless factor ε (Cartwright&Longuet-Higgins)

$$\varepsilon = \sqrt{1 - \frac{\lambda_2^2}{\lambda_0 \lambda_4}} \in [0,1] \tag{1}$$

where, λ_i is the i^{th} spectral moment about the mean (Kramer, 1996). The orthogonal components are characterized by small frequency bandwidths and low statistical correlation (fig.2).

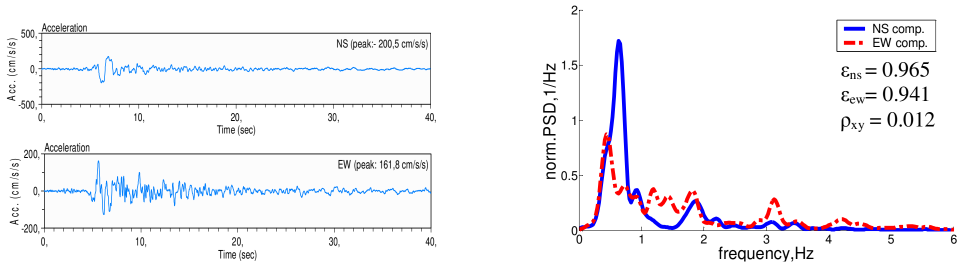


Figure 2 VN77 orthogonal ground motion accelerograms and normalized *PSD* functions

There is a very limited number of significant records that can serve to the study purpose. Alternatively, artificial ground motion accelerograms are to be generated, with the aim of realistically reproduce similar amplitude, frequency content ad effective duration, corresponding to soft soil conditions.
Artificial input ground motions were obtained using the procedure developed by Gasparini *et al.*,1976; their response spectra match the 1% damped elastic acceleration response spectrum, given in the *Romanian Seismic Design Code P100-1/2006*. A set of 10 synthetic bi-directional accelerograms having peak ground accelerations of 0.24g, associated to a 100 years mean return interval (*MRI)*, low predominant frequencies and small frequency bandwidth were thus obtained. Typical sets of artificial accelerograms and the control corresponding power spectral density functions (*PSD*), are presented in the fig.3.

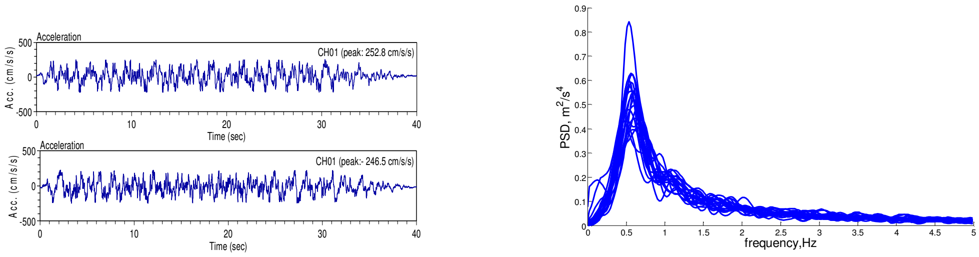


Figure 3 Typical bi-directional artificial input ground motion accelerograms
and the corresponding *PSD* functions (10 sets)

Synthetic accelerograms corresponding to various seismic hazard levels can be generated and used for analyses.

3. SEISMIC ENERGY DISTRIBUTION IN SDOF SYSTEMS

The input energy induced by an earthquake ground motion into a structural system represents a powerful indicator for the ground motion destructive potential (Akiyama, 1985). It represents the convolution of ground motion and structural properties.
Seismic energy spectra provide primary information about energy distribution in SDOF models and can be primarily used for estimating the energy content.
The energy spectra corresponding to the orthogonal VN77 acceleration records are given in the fig.4, for 1% damping ratio.

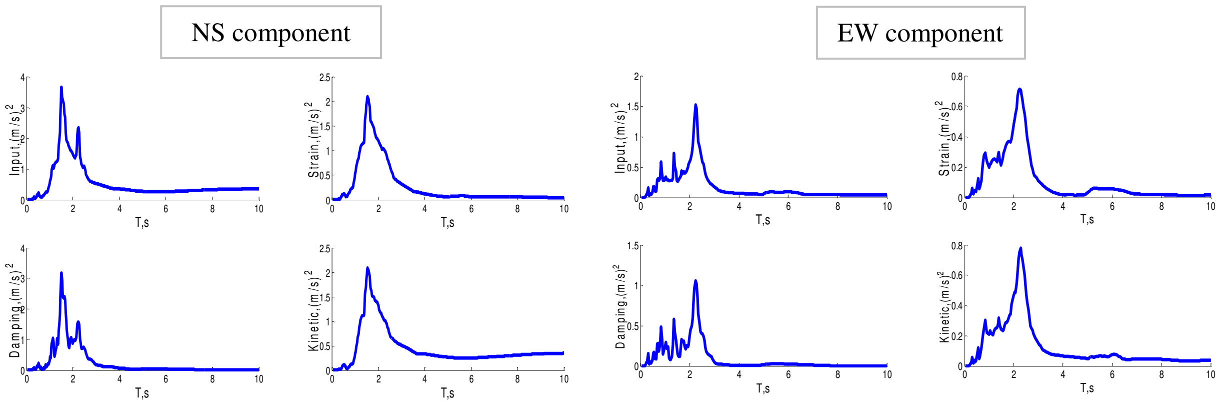


Figure 4 Energy spectra VN 77 accelerogram components (INCERC station)

While most of the energy is concentrated in the vicinity of the predominant period of the ground vibration, an energy increase tendency of the input and kinetic energy can be observed, at higher natural vibration periods.

By using a large number of synthetic accelerograms, a more accurate prediction on energy amplification phenomena can be done (fig.5).

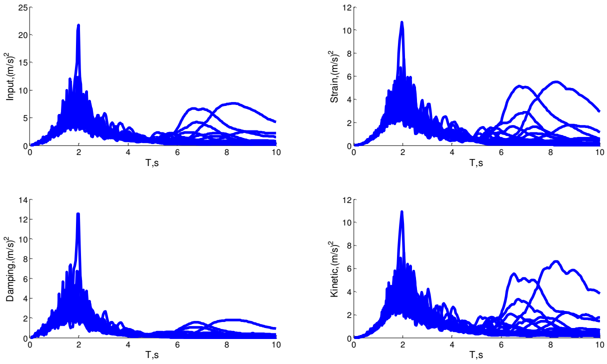


Figure 5 Energy spectra, 20 artificial ground motion accelerograms

Beside significant larger peaks of energy at quasi-resonant natural periods, most important energy amplification at higher natural vibration periods range occurs, in the case of input, kinetic and strain energy. Damping energy variation is less sensitive for highly flexible structures.

4. ENERGY DISTRIBUTION IN TRI-DIMENSIONAL FLEXIBLE MODELS

4.1. Structural analysis model

Spectral representation is less accurate at higher vibration periods. In our studies, a more refined model of 60 stories generic structure is considered. The building has a typical story plan shown in the fig. 6 (*CM* – center of mass, *CS* – center of stiffness). The plan dimensions are $L_x=30m$, $L_y=18m$ and the total height of *180m*. The model is assumed to be linear-elastic, having 3 DOF/floor. A Rayleigh proportional damping model is used; the damping ratio for the first two translational vibration modes was assumed as 1%. The distribution of stiffness in elevation is linear.

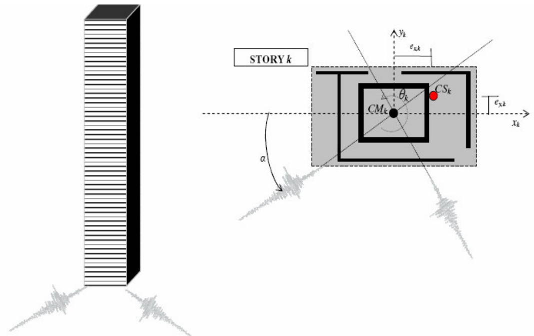


Figure 6 Tall building and typical story plan

The input ground motion consists of two orthogonal ground accelerations components, acting under the α directivity angle from the main geometrical axes of the model (fig. 6). For the purpose of investigating the energy distribution in symmetric vs. irregular flexible structures, two cases of equal eccentricity ratios ($e_x=e_y$) were considered: *0%* (symmetric system, referred as *standard system*) and 0.25 *r-highly irregular system* (25%), where *r* is the radius of gyration.

4.2. Seismic energy distribution, modal damage exposure indicators and eccentricity effect

The time-history energy equation of an elastic space model is

$$\int_0^t \ddot{u}^T(\tau) M \dot{u}(\tau) d\tau + \int_0^t \dot{u}^T(\tau) C \dot{u}(\tau) d\tau + \int_0^t u^T(\tau) K \dot{u}(\tau) d\tau = -\int_0^t M \cdot i \cdot a_g(\tau) \cdot \dot{u}(\tau) d\tau \quad (2)$$

where,
M, ***C*** and ***K*** are the mass, damping and stiffness matrix respectively, ***i*** is the influence matrix and $\boldsymbol{a_g}$ is the ground acceleration vector, comprising of *x, y* and θ-direction (rotational component) acceleration- neglected in this study. The components in equation (2) are the kinetic energy $\boldsymbol{E_k(t)}$, viscous damping energy $\boldsymbol{E_d(t)}$, potential energy $\boldsymbol{E_p(t)}$ and input energy $\boldsymbol{E_i(t)}$, respectively. The potential energy consists of elastic-strain energy $\boldsymbol{E_s(t)}$ and hysteretic energy $\boldsymbol{E_h(t)}$.
Prior of conducting time-expensive nonlinear analyses on complex structural models, a linear-elastic energy balance-based analysis approach gives primary and useful information on the structural behavior. Of primary importance in order to investigate the structural exposure to damage, is to focus on the amount of energy input attributable to potential damage (elastic vibration energy, E_k+E_s), by using a linear energy balance-based analysis (Iancovici, 2005).
The generalized (modal) equation of the j^{th} vibration mode has the form of

$$\int_0^t \ddot{\varsigma}_j(\tau)\dot{\varsigma}_j(\tau)d\tau + 2\xi_j\omega_{n,j}\int_0^t \dot{\varsigma}_j^2(\tau)d\tau + \omega_{n,j}^2\int_0^t \varsigma_j(\tau)\dot{\varsigma}_j(\tau)d\tau = -\Gamma_j\int_0^t a_g(\tau)\cdot\dot{\varsigma}_j(\tau)d\tau \quad (3)$$

where,
ξ_j, $\omega_{n,j}$ and Γ_j are the damping ratio, natural circular frequency and modal participation coefficient of the j^{th} vibration mode, respectively. The terms are generalized kinetic energy $E_{k,j}(t)$, generalized viscous damping energy $E_{d,j}(t)$, generalized potential energy $E_{p,j}(t)$ and generalized input energy $E_{i,j}(t)$, per generalized unit mass.
While for perfectly plan symmetric systems, the earthquake ground motion in one direction produces effects only in that direction, in the case of non-symmetric systems, the ground motion in one direction may transfer energy in the other direction (Iancovici et *al*., 2006).
The vibration modes coupling can be synthetically emphasized by the modal correlation coefficients (Der Kiureghian, 1980)

$$\rho_{jk} = \frac{8\sqrt{\xi_j\xi_k}(\beta_{jk}\xi_j + \xi_k)\beta_{jk}^{3/2}}{(1-\beta_{jk}^2)^2 + 4\xi_j\xi_k\beta_{jk}(1+\beta_{jk}^2) + 4(\xi_j^2+\xi_k^2)\beta_{jk}^2} \quad (4)$$

where, ξ_j, ξ_k are the damping ratios corresponding to the vibration modes *j* and *k*, β_{jk} is the ratio of the natural circular frequencies of the j^{th} and k^{th} vibration modes.

The structural eigendynamics for the first 12 vibration modes is summarized in the table 2.

Table 2: First 12 vibration modes correlation coefficients, ρ_{jk} (25% ecc. ratio)

Mode	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	$\boldsymbol{T_n}$**,s**
1	1.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.73
2	0.26	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.54
3	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.18
4	0.00	0.00	0.00	1.00	0.48	0.01	0.01	0.01	0.00	0.00	0.00	0.00	1.97
5	0.00	0.00	0.00	0.48	1.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	1.91
6	0.00	0.00	0.00	0.01	0.01	1.00	0.69	0.28	0.03	0.03	0.01	0.01	1.19
7	0.00	0.00	0.00	0.01	0.01	0.69	1.00	0.55	0.04	0.03	0.01	0.01	1.15
8	0.00	0.00	0.00	0.01	0.01	0.28	0.55	1.00	0.05	0.04	0.02	0.02	1.19
9	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.05	1.00	0.80	0.09	0.08	0.85
10	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.04	0.80	1.00	0.12	0.11	0.82
11	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.09	0.12	1.00	1.00	0.66
12	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.08	0.11	1.00	1.00	0.66

From the point of view of modal coupling, highly irregular flexible structures with closely spaced natural vibration periods, introduces larger correlation between higher modes.
By dividing equation (3) to the time-instant generalized input energy, the following relationship yields

$$d_j^{dam}(t) = \frac{E_{k,j}(t) + E_{s,j}(t)}{E_{i,j}(t)} = 1 - \frac{E_{d,j}(t)}{E_{i,j}(t)} \le 1 \tag{5}$$

where the left hand side can be viewed as time-instant modal damage exposure coefficient, noted by $d_j^{dam}(t)$.
In order to minimize the modal damage exposure, the ratio of modal damping energy to modal input energy has to be maximized. This will be primarily accomplished by adding supplemental modal damping to the existing modal damping ratio. Hence, equation (5) provides an useful tool for assessing the damage exposure of a structure, through vibration modes, by simply taking the peaks energy ratio of components (Iancovici, 2005):

$$d_j^{dam} = \frac{\left|E_{k,j}(t) + E_{s,j}(t)\right|_{\max}}{\left|E_{i,j}(t)\right|_{\max}} \tag{6}$$

The generalized input, damping and kinetic energies are little influenced by eccentricity; however the generalized strain energy increases considerably (Iancovici et *al.*, 2006). The time-histories of the first 3 generalized energies corresponding to the bi-directional VN77 components, applied under 36 incremental directions, are given in the fig. 7, for the 25% eccentricity ratio system case.

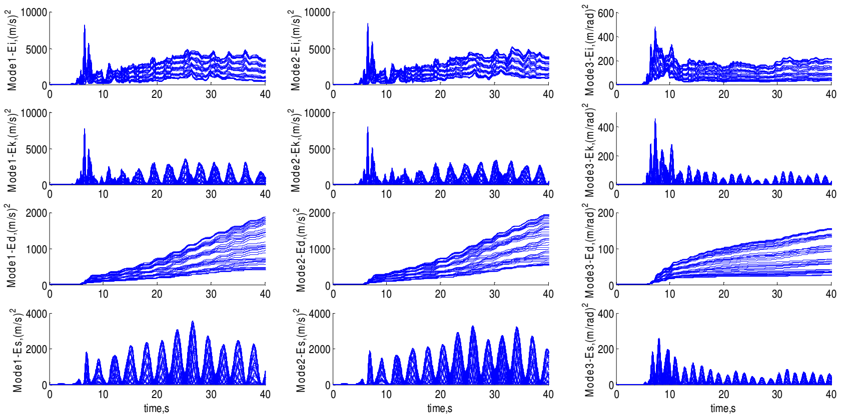


Figure 7 Time-histories of generalized energies, 36 directions, 25% ecc. ratio; VN 77 (INCERC station)

The corresponding peaks of generalized energies and damage exposure coefficients, are given in the fig.8.

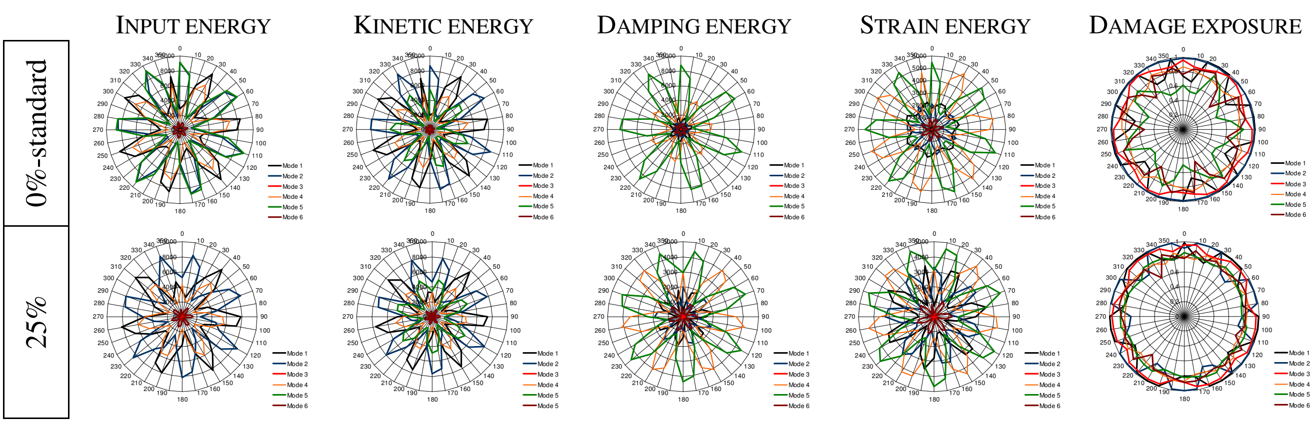


Figure 8 Peaks of generalized energies, 36 directions, 25% ecc. ratio; VN 77 (INCERC station)

The results are showing that the response of the standard system has a more uniform energy distribution in terms of modal contributions. Basically the damage exposure decreases with higher modes; the more important reduction corresponds to the standard system. For irregular system, damage exposure is more pronounced for higher modes. The peaks of story energy distributions in the *x*-, *y*- and θ-direction are represented in the fig. 9.

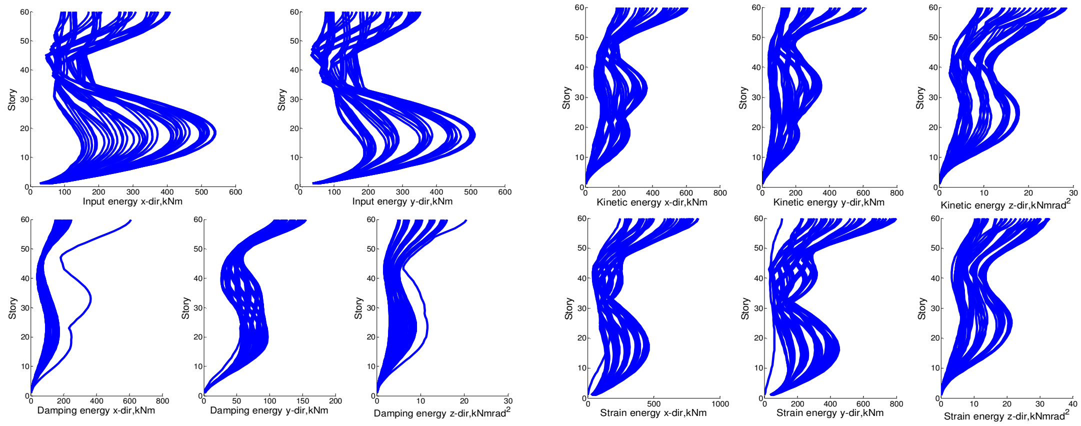


Figure 9 Maximum story energies, 25% ecc. ratio, 36 directions,VN77 records (INCERC station)

The analysis results permit to identify the critical direction of motion from the point of view of energy supply, and the supplemental system requirements for a defined seismic performance. By correlating the energy with common structural response parameters (i.e. story drift ratios, that controls the damage level), a larger scatter of correlation coefficients of peaks input and strain energy with the corresponding drift ratios are observed (fig. 10).

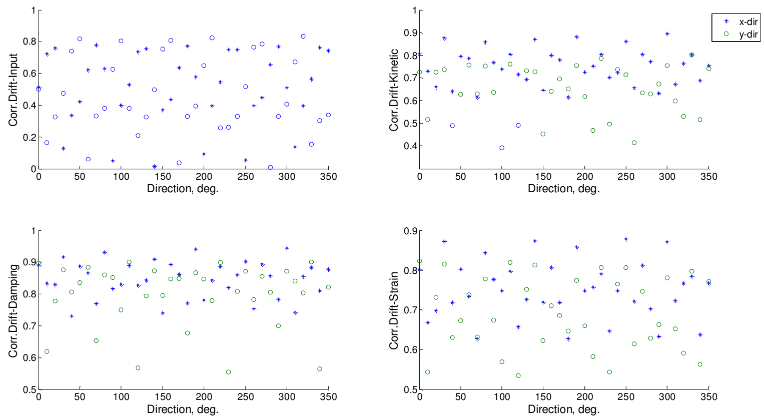


Figure 10 Correlations of maximum story energies and maximum drift ratios, 25% ecc. ratio, 36 directions, VN77 (INCERC station)

However, a high correlation is observed between peaks story kinetic and damping energies and associated drift ratios. This suggests that supplemental dissipation devices may considerably improve the energy distribution in irregular and highly irregular structures.

5. ENERGY DISTRIBUTION USING SUPPLEMENTAL DISSIPATIVE DEVICES

Various techniques were proposed by time, to reduce the vibration effects in tall buildings. The use of Tuned Mass Damper system (Ormondroyd et *al.*, 1928; Den Hartog, 1956;) for instance, was proven to be effective especially for structures subjected to harmonic or wind excitation. However by setting up in appropriate way the parameters of TMD in conjuction to structural properties, important reduction in seismic response may be achieved (Gupta et *al.*, 1969; Wirsching et *al.*, 1973; Villaverde et *al.*, 1993).
Ideally from the point of view of energy concept, the tuning process should lead to a rather uniform energy

distribution, in elevation and plan. For the simplest method of a TMD inserted on the building's top, a more realistic achievement would consist of getting uniform energy distributions in sway motion and important reduction in torque component motion.
For illustration purposes only, for those 36 directions of VN77 input ground motion (quasi-harmonic type), we show that inserting a TMD having 1% mass ratio in terms of 1st mode and 1% damping ratio, on the building's top, say - the story strain energy supplied by the structure becomes almost equal in the *x*- and *y*- directions (fig.11).

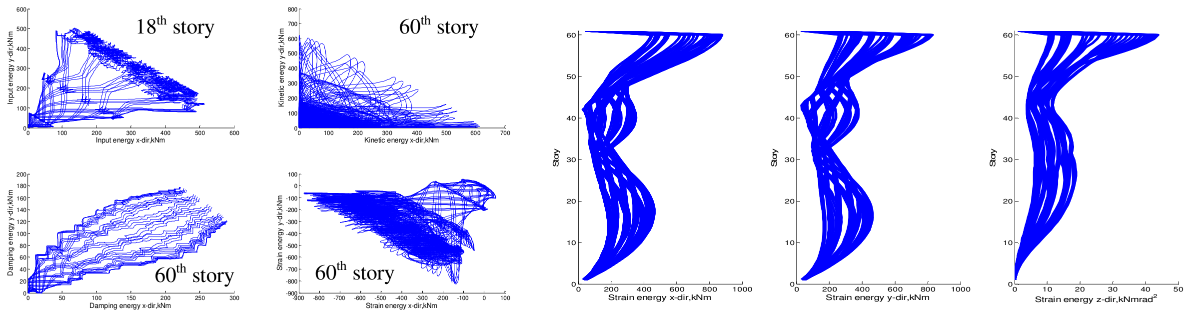


Figure 11 Time-histories and maximum story strain energies distribution (TMD inserted on the building's top)

Detailed damper design as well as higher stories conformation is an important issue. More effectiveness from the point of view of torque component may be achieved by internal insertion of these devices in specific locations.

6. CONCLUSIONS

Irregular flexible systems are more exposed to seismic damage than symmetric systems, subjected to long period ground motion. While in the case of *standard system* simple analysis procedures might be employed in order to get the main directions of motion, for eccentric systems, the critical directions of motion can be obtained by performing dynamic response analyses for several directions.
A higher level of structural analysis and design approach might be incorporated, primarily based on large computational capabilities. The integrated analysis format, consisting of dynamic response analysis and energy balance-based analysis, has the capability to evaluate more efficiently the high eccentricity effect and considerably improve the performance of irregular systems by setting-up appropriate energy dissipation devices, based on desired synthetic target energy parameters (i.e. input energy, damage exposure). More detailed studies are necessary, based on a large amount of input motions and structural configurations for setting-up transparent criteria's for dissipation devices parameters identification using energy concept.

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