Spatial steel structures with passive seismic protection.

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SUMMARY:
Intended contribution deals with multi-storey steel structures equipped with elastomeric base isolators. The main objective of the contribution is to asses the effectiveness of base isolation seismic protection. Employed methodology consists in numerical studies conducted on a set of multi-storey reference (seismically unprotected) steel 3D frames and a set of seismically protected via base isolators identical frames. The study commences with a short review of specificities brought about by spatiality to the structure, the base isolation and the seismic type loads. The numerical studies of time history type are conducted on a set of 3D steel frames of six, nine and twelve stories (including inferred relevant conclusions), while presented results refer to the twelve storey structure. Seismic loading consists of recorded Vrancea (Romania) 1977 accelerogram and a set of two recorded accelerograms in the same region in accordance with provisions of most of today seismic design codes. The results are presented in both numerical and graphical forms.

Keywords: 3D steel structures, base isolation, seismic protection

1. INTRODUCTION

Structural spatiality means more than just another orthogonal direction or an increased number of degrees of freedom versus the well paved approach of planarity. Indeed, several aspects involved in structural computation and, most of all, in seismic analyses and design can only be approached by employing spatial analyses. First of all, it has to be emphasized that spatiality brings about more than the well known torsion effect. There are other aspects that can only be viewed by involving 3D structures:: distribution of seismic loading, structural modelling including possible specificities of post-elastic behaviour, spatial behaviour of elastomeric base isolators and the interpretation of numerical results. These are the responsible factors that directed the authors to studies on, mainly, seismic protection of 3D steel multi-storey structures.

Present contribution together with its numerical results and inferred conclusions is an excerpt of a larger study of assessing effectiveness of seismic mitigation via base isolation. To reach this final objective, several previous problems had to be solved. Among the first steps that authors had to start with, is structural modelling including a clear and final decision regarding a structural – elastic or post-elastic - behaviour. Since base isolation layer is intended to redirect plasticization from structural sections to this extra-structural equipment, elastic behaviour has been decided for. Also, one objective of seismic mitigation is to increase seismic performances and, implicitly, to bring the structure into such a mechanical state that no structural damages are allowed to develop. Such and objective can be equated to elastic behaviour of studied structures.

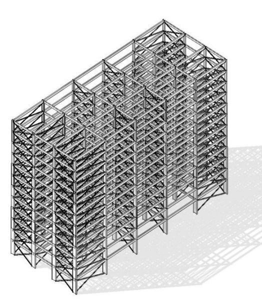
Regarding the seismic loading, a time-history type analyses has been adopted. A recorded accelerogram of March 1977 Vrancea earthquake (a reference earthquake for Romania) and two other recorded accelerograms in the same Vrancea region in accordance to provisions of Romanian Seismic Code have been considered in the analyses. The most important – by its consequences - step is the decomposition of such a seismic loading into the two orthogonal directions of the structure. Most of existing seismic design provisions do not take into account this aspect. A natural, somehow, criterion has been adopted in present study: recorded earthquakes (accelerograms) are associated to fundamental natural vibration mode (lateral transversal sway) while, along the other orthogonal direction a weighted seismic intensity of 0.6 to 0.8 is applied. This ratio has been adopted as a consequence of several previous studies and in accordance with several recommendations of the literature [P100-1/2006], [Eurocode 8]. Regarding the spatial behaviour of elastomeric base isolators, their three-dimensionality is not just the resultant of their seismic behaviour along the two orthogonal directions. The making up itself of base isolators, their general and sectional geometry together with pregnant spatial behaviour under seismic loading are responsible for their real 3D behaviour and, in fact, impose such a 3D behaviour. Presented results are based on detailed numerical time-history studies [Prodan, 2011b] on spatial behaviour of FIP Industriale [FIP Industriale] elastomeric isolators. A small set of results extracted from a larger study of the authors [Prodan, 2011b] regarding seismic behaviour of base isolators is included in present contribution.

A set of three spatial multi-storey steel structures of six stories, nine stories and twelve stories have been included in the study. To allow for correct interpretation of numerical results and relevant conclusions, the studies have been conducted in parallel: on the reference structures not equipped with seismic protection and on the same structures equipped with elastomeric base isolators. The isolators have been selected based on design type computation from an available set provided by the producer. The isolators are placed under each column on the upper surface of foundation mat.

As if the objective of a 3D seismic analysis would not be sufficient, the authors included in present contribution a generalization to 3D structures, of an analytical tool of assessing the effectiveness of seismic mitigation via base isolators. The tool consists of envelope curves – SPEC's (Seismic Protection Envelope Curves) previously proposed by the authors [Prodan, 2010], [Prodan, 2011a], [Prodan, 2012]. SPEC's are envelope curves that collect the peak values of seismic responses expressed in lateral displacements, lateral accelerations and base shear. Collected peak values of these seismic responses are, then, expressed either in time or in the periods of fundamental natural vibration mode. Variation of these envelope curves expresses – by their slope – the amount and rapidity of seismic mitigation. Indeed, the mitigation effect can be both, immediately viewed and easily assessed by the form of proposed SPEC's. As in the case of planar frames, the associated SPEC's to 3D multi-storey structures proved, again, to be a simple and versatile tool of assessing seismic mitigation.

2. ANALYSED STRUCTURES

Design of structures with seismic protection may be an objective on its own from the point of view of structural design and design of protection equipment. Nevertheless, the literature exhibits a cvasi-unanimous accord regarding the dependence of protection effectiveness on structural height [Kasai, 2009]. To cover a certain spectrum of structures, the performed numerical studies involve a set of three structures of six, nine and twelve stories (Fig. 1).



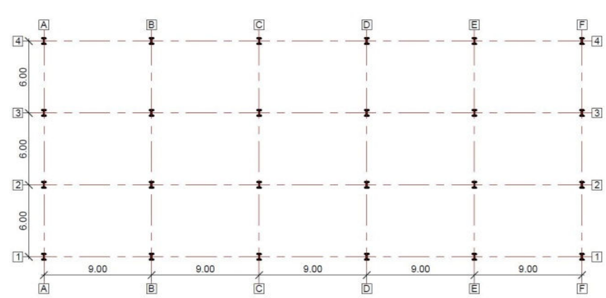
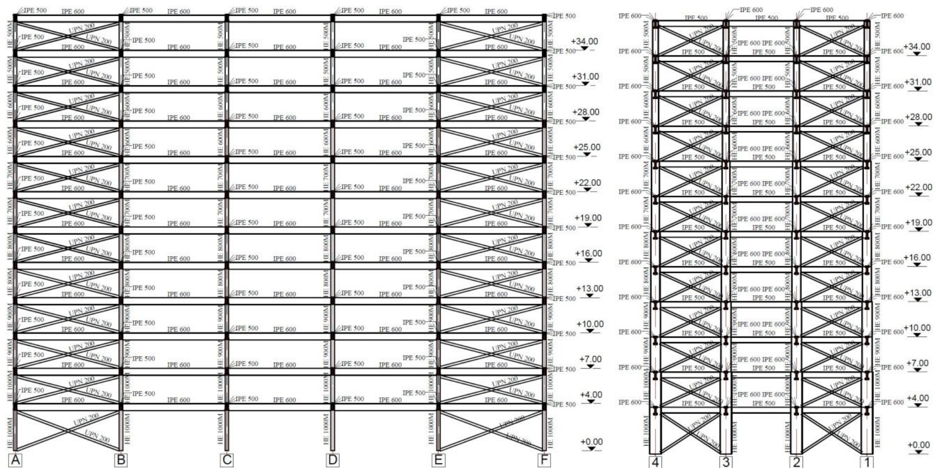


Figure 1. Reference structure Structure layout

The three spatial frames are similar in their structural make up: five transversal spans of 9.00 m and three longitudinal spans of 6.00 m each (Fig. 1). This plane geometry has been imposed by the requirement of a flexible serviceability. Transversal sections of beams and columns (Fig. 2) are the result of a seismic design according to Romanian seismic design provisions for buildings located in areas of $a_g = 0.24g$. The general level of stressing in bending of structural elements is around 80%.



Longitudinal direction Transversal direction

Figure 2. Reference structure

3. ELASTOMERIC BASE ISOLATORS

A passive protection via elastomeric base isolator is proposed. Base isolators have been design according to current practice [Naeim, 2001]. Mechanical and geometrical parameters associated to proposed base isolator are presented in Fig. 3 and Fig. 4. Structural spatiality required a 3D time history analyses of these base isolators for a better prediction of their 3D behaviour under the three recorded earthquakes.

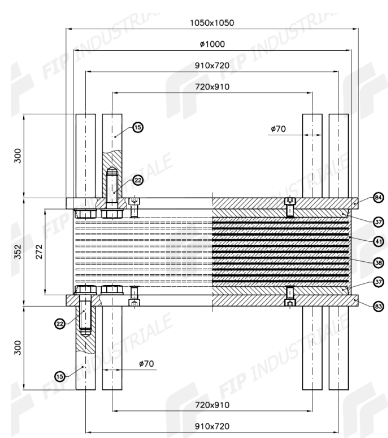


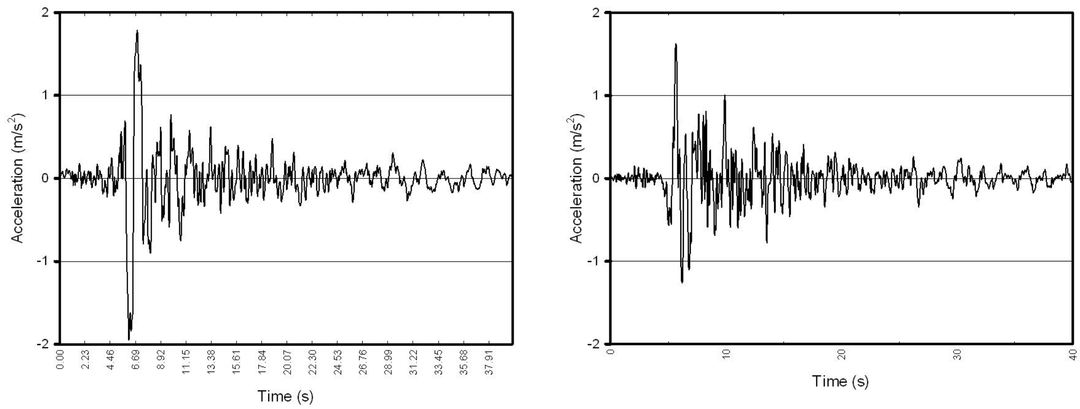
Figure 3. Elastomeric isolator – SI-S 1100/210

SI-S	V kN	F_{zd} kN	K_e kN/mm	K_v kN/mm	D_g mm	t_e mm	h mm	H mm	Z mm	W kg
SI-S 1100/210	7860	27460	1.81	2441	1100	210	326	406	1150	1919

Figure 4. Elastomeric isolator – SI-S 1100/210 – technical sheet

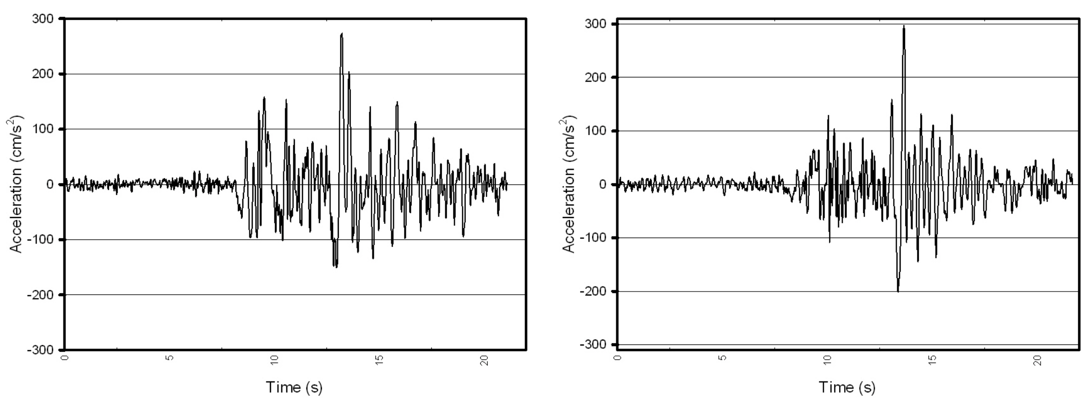
4. SEISMIC LOADING

Performed time history analyses have been carried out for three relevant recorded accelerograms in Vrancea (Romania) seismic zone (Fig. 5, Fig. 6, Fig. 7) in the presence of gravitational loads.



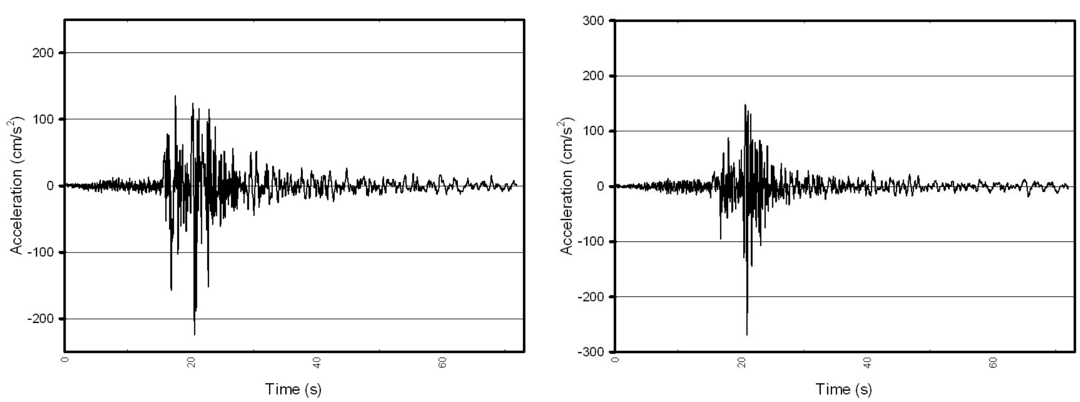
N-S direction E-W direction

Figure 5. Focşani 1986 accelerogram – Focşani 1



N-S direction E-W direction

Figure 6. Focşani 1986 accelerogram – Focşani 1

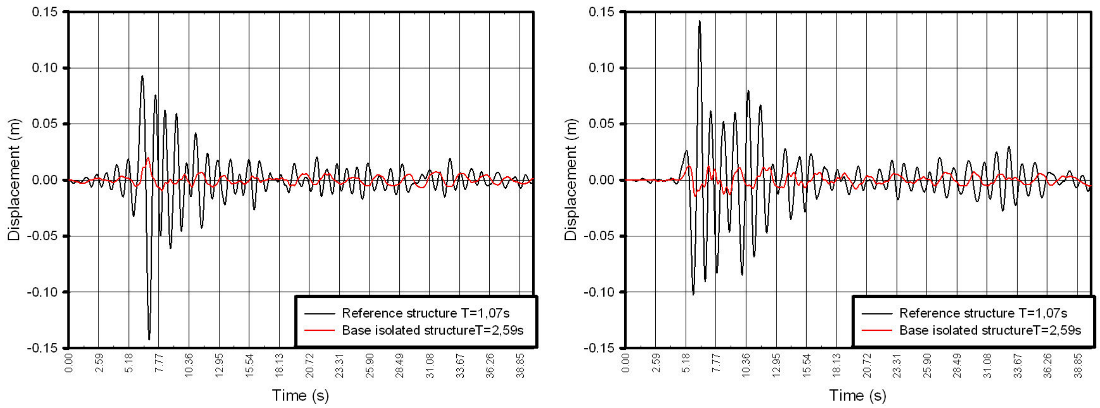


N-S direction E-W direction

Figure 7. Focşani 1986 accelerogram – Focşani 2

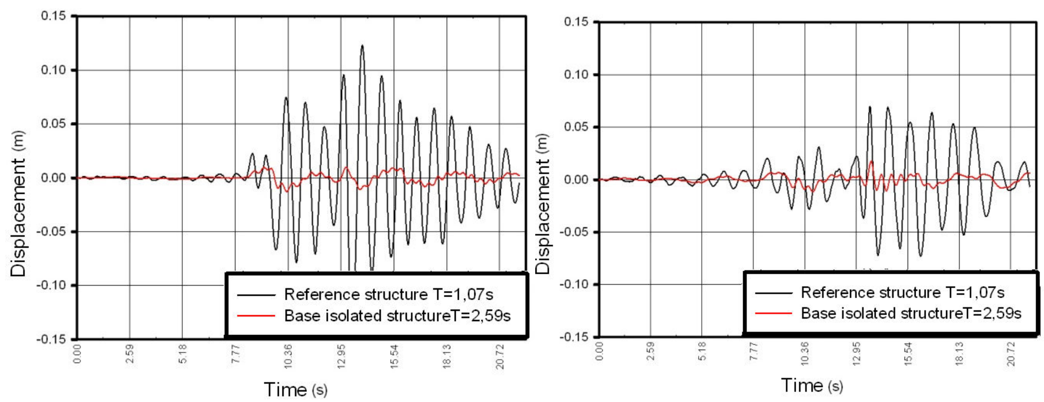
5. STRUCTURAL ANALYSES AND NUMERICAL RESULTS

Achievement of main objective of present study (assessment of effectiveness of passive protection) imposed computation of, mainly, geometrical parameters associated to a seismic behaviour of analyzed structures.



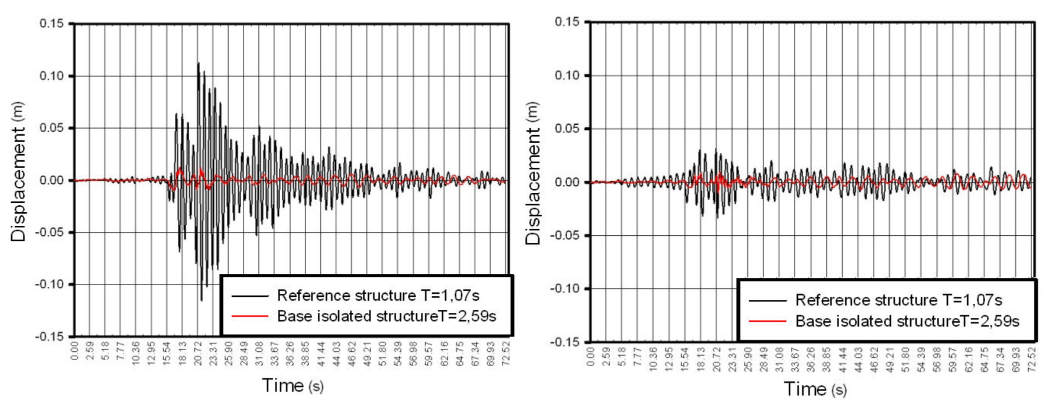
Longitudinal direction Transversal direction

Figure 8. Top lateral displacement – Vrancea 1977 accelerogram



Longitudinal direction Transversal direction

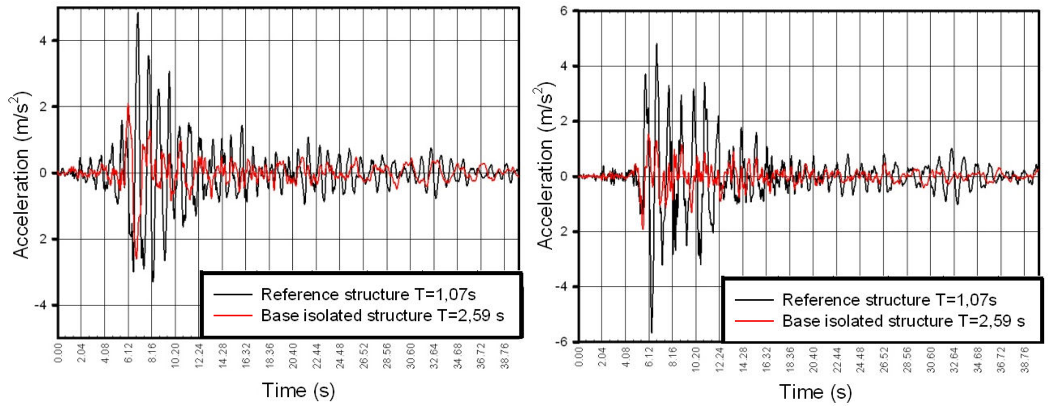
Figure 9. Top lateral displacement – Focsani 1 accelerogram



Longitudinal direction Transversal direction

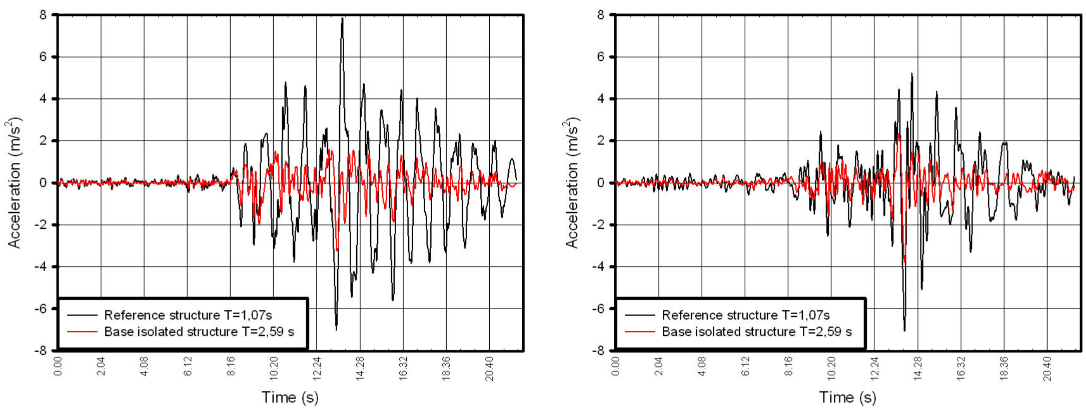
Figure 10. Top lateral displacement – Focsani 2 accelerogram

Indeed, most popular perception of a mitigated seismic behaviour is the reduction in peak values of of seismically induced parameters such as lateral displacement (Fig. 8, Fig. 9 and Fig. 10), acceleration (Fig. 11, Fig. 12 and Fig. 13), story drifts and base shear (Fig. 14, Fig. 15 and Fig. 16). Consequently, performed time history analyses focus on computation of these parameters and on their unmitigated and mitigated values.



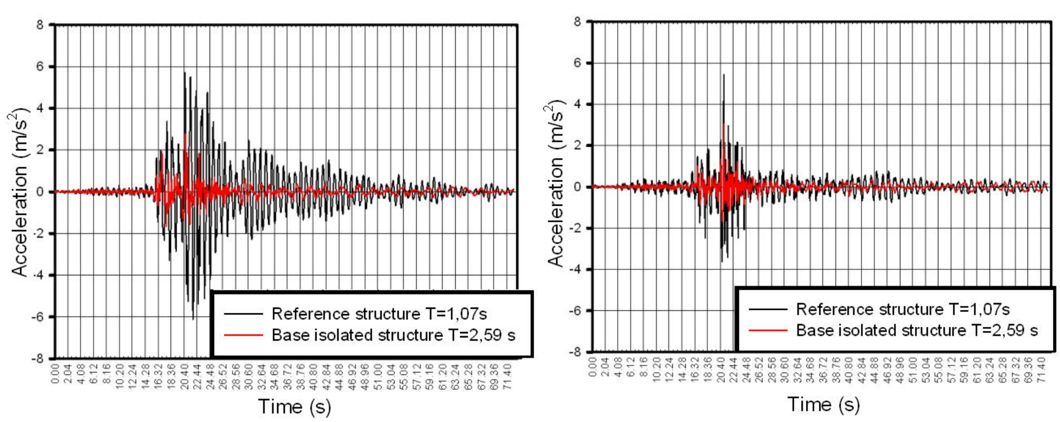
Longitudinal direction Transversal direction

Figure 11. Top lateral acceleration – Vrancea 1977 accelerogram



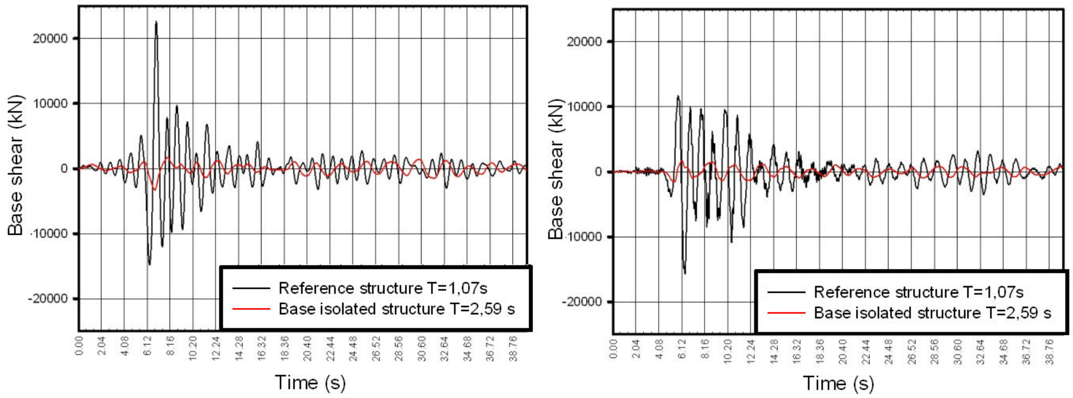
Longitudinal direction Transversal direction

Figure 12. Top lateral acceleration – Focsani 1 accelerogram



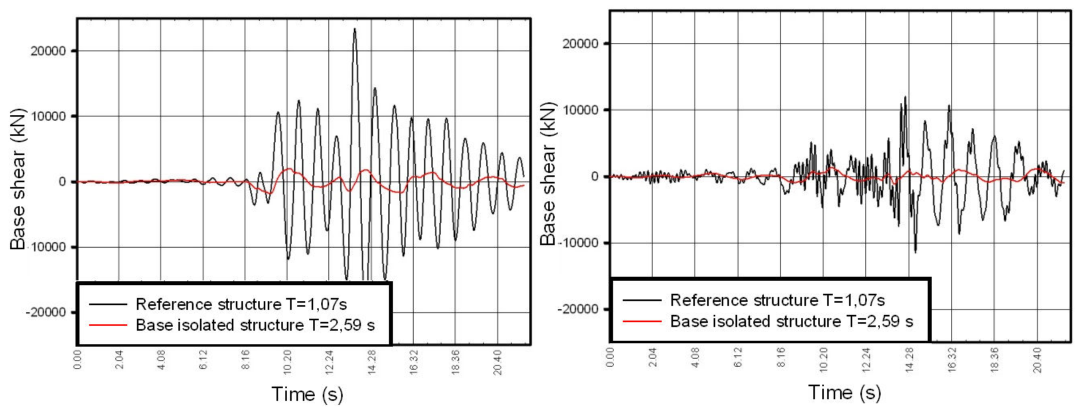
Longitudinal direction Transversal direction

Figure 13. Top lateral acceleration – Focsani 2 accelerogram



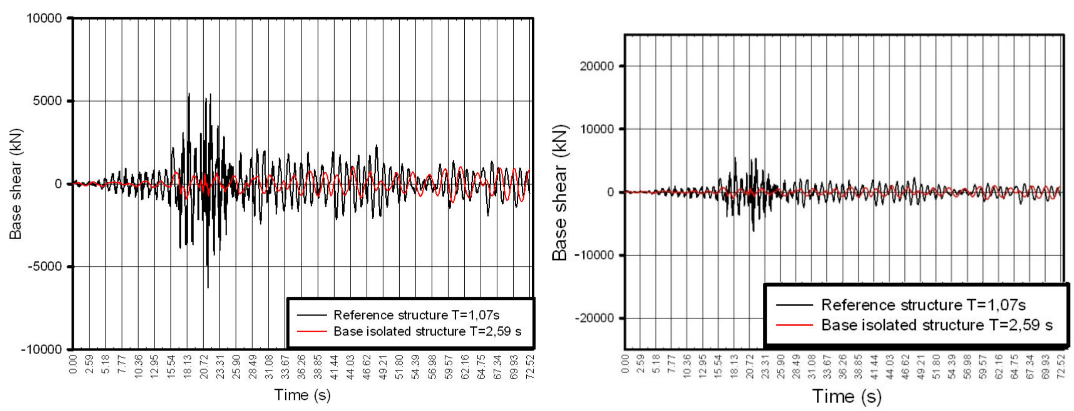
Longitudinal direction Transversal direction

Figure 14. Base shear – Vrancea 1977 accelerogram



Longitudinal direction Transversal direction

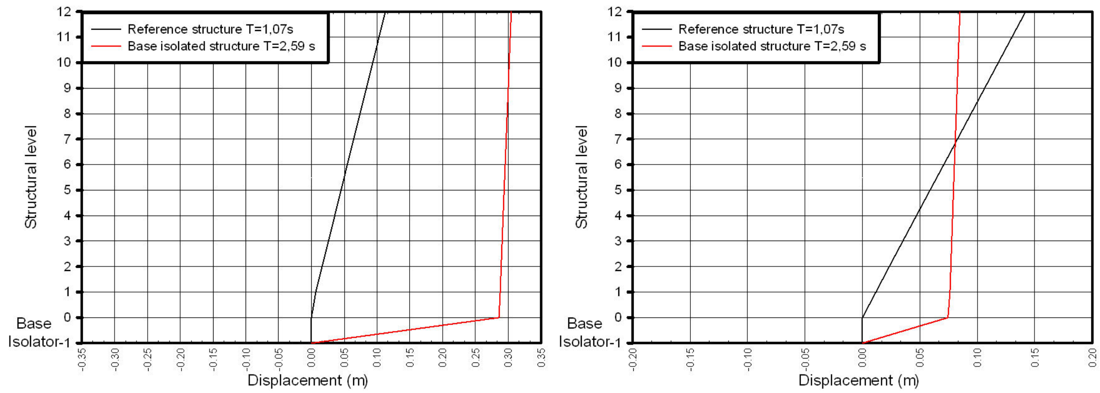
Figure 15. Base shear – Focsani 1 accelerogram



Longitudinal direction Transversal direction

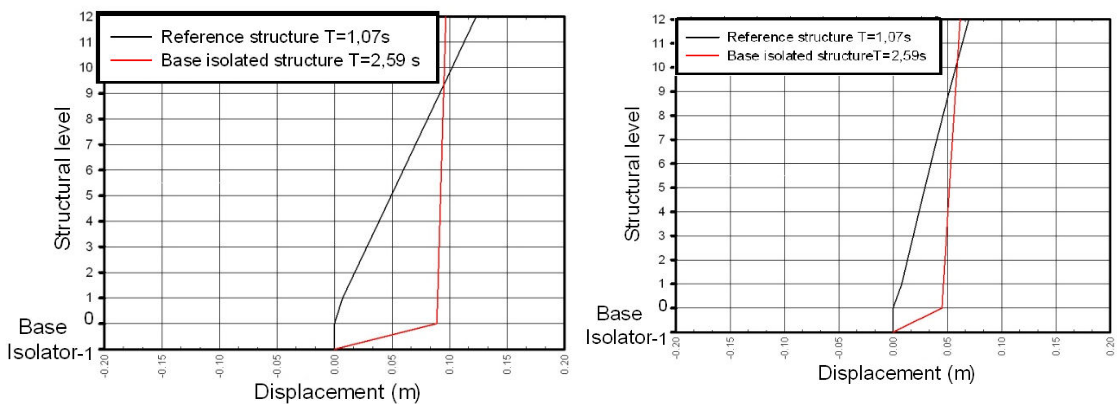
Figure 16. Base shear – Focsani 2 accelerogram

Regarding the intensity of seismic loading along the two orthogonal directions of analyzed structures, the accelerograms are, actually, recoded along these directions (Fig. 5, Fig. 6, Fig. 7). As recorded values shows, the ratios of peak values intensities along the two orthogonal directions prove previous results of seismic intensity decomposition (1.0 to 0.6 ÷ 0.8) proposed by authors [Prodan, 2011b].



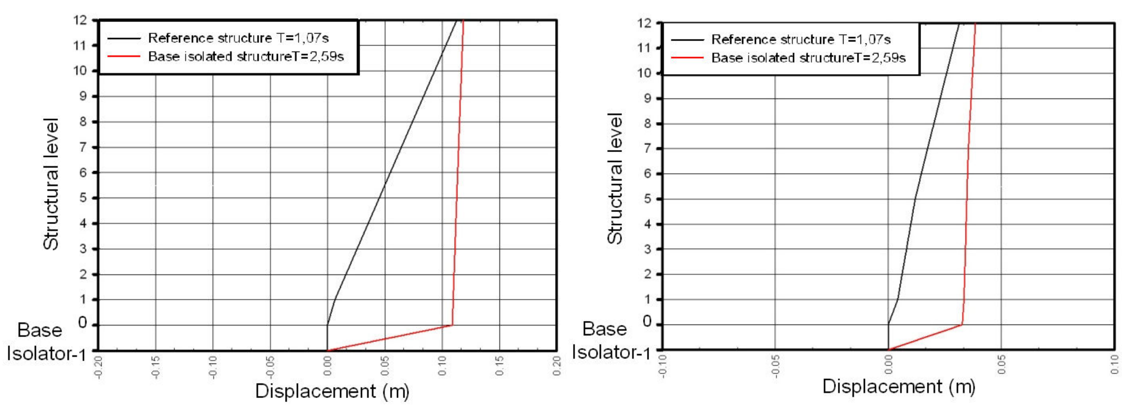
Longitudinal direction Transversal direction

Figure 17. Story drift – Vrancea 1977 accelerogram



Longitudinal direction Transversal direction

Figure 18. Story drift – Focsani 1 accelerogram

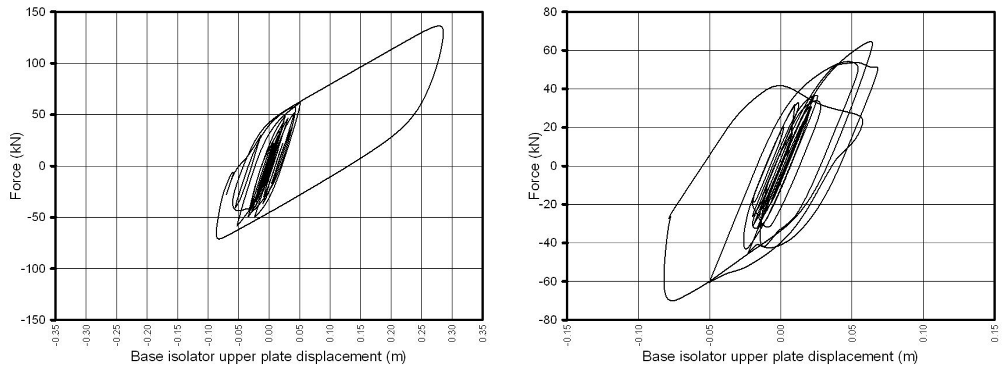


Longitudinal direction Transversal direction

Figure 19. Story drift – Focsani 2 accelerogram

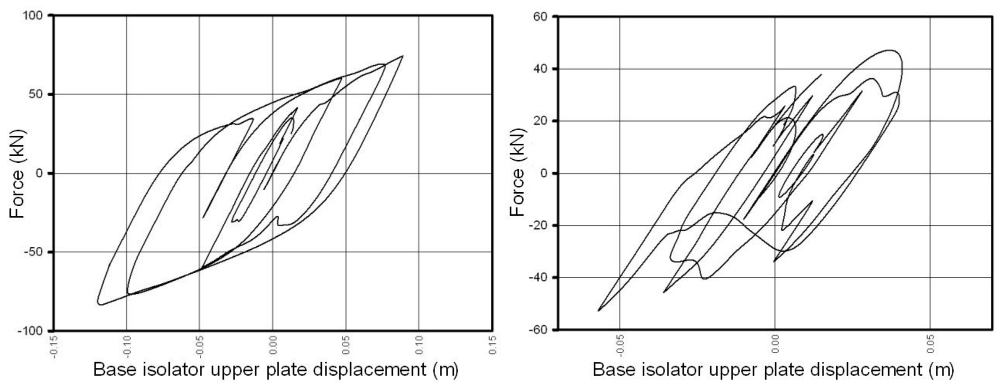
Computation and, first of all, the values of story drifts (Fig. 17, Fig. 18, Fig. 19) are dealt with due to the fact that their upper code limits can only be observed on protected structure since in the case of unprotected structure such limitations lead to large sectional geometry. This approach of observing provisions of serviceability limit state on protected structure exclusively is, in fact, the common procedure of design of multistory structures provided with passive protection via base isolators [Soong, 1997].

The obtained constitutive hysteretic numerical results are presented in Fig. 20 and Fig. 21.



Longitudinal direction Transversal direction

Figure 20. Hysteretic behaviour of isolator – Vrancea 1977 accelerogram

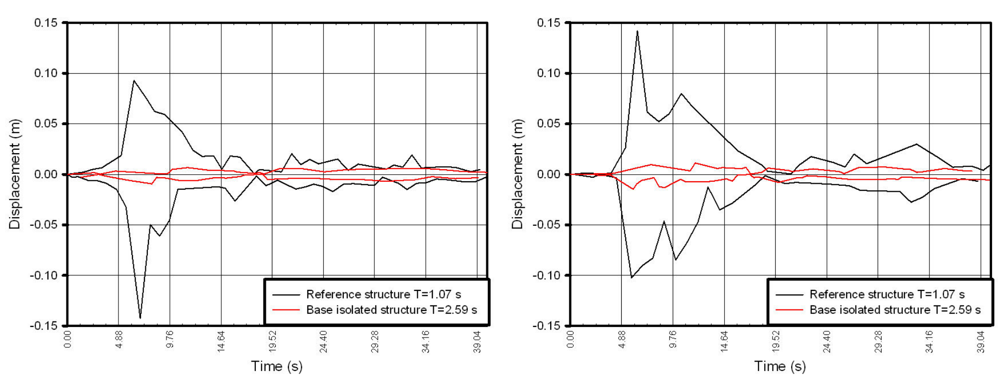


Longitudinal direction Transversal direction

Figure 21. Hysteretic behaviour of isolator – Focsani 1 accelerogram

6. SPECS'S

Regarding the proposed approach – via SPEC's – to the assessing of the effectiveness of seismic mitigation, it may be noticed in Fig. 22 the simple and direct way to this objective: the length in time of the SPEC's and their slope emphasizing the starting moment and the moment of "involvement" of passive protection equipment during the earthquake action.



Longitudinal direction Transversal direction

Figure 22. SPEC – Top lateral displacement – Focsani 2 accelerogram

7. CONCLUSIONS

Present contribution focused on several aspects of seismic mitigation of multistory steel structures: the implications of a time history type analysis performed on 3D structures, the use of several recorded accelerograms and the possibility of assessing the effectiveness of seismic mitigation via proposed SPEC's. Regarding the 3D analysis, an important aspect is the amount of seismic action (intensity) along the two orthogonal directions of the structure.

The 100% and (60 – 80)% intensities applied along the two orthogonal axes of the analyzed structures in presented analyses is the result of a set of numerical simulations of seismic actions acting along arbitrary directions. Concerning the use of three accelerograms different in both, their peak values and the periods of seismic action, it may be concluded that greater period earthquakes induce greater lateral displacements at base isolators level (Figure 20 – 21) than the smaller period earthquakes. This conclusion proves valid even when the peak values of accelerations of smaller period earthquakes (Focsani 1 and 2) are greater than those of higher period earthquakes (Vrancea 1977).

The proposed approach to assessing seismic mitigation could be referred as simple, rapid and consistent to the seismic response in both cases (protected and unprotected structures). Computed SPEC's, referring here to lateral top displacements, may be extended to several other components of performed base analyses of 3D multistory steel structures.

REFERENCES

P100/1-2006 – Romanian Seismic Design Code - P100/1 – 2006

Eurocode 8 - Design of structures for earthquake resistance - EUROCODE 8 – EN 1998

FIP Industriale - http://www.fip-group.it/fip_ind_eng/index_fip.html – FIP Industriale website

Prodan, O., Ladar, I. and Alexa, P. (2010). Seismic performances of steel structures with supplemental damping. Numerical studies.*14th European Conference on Earthquake Engineering*. **Vol I:** 474.

Prodan, O., Ladar, I. and Alexa, P. (2011a). How mitigating is base isolation. *Taller, Longer, Lighter*. *IABSE-IASS 2011*. **Vol I**: 264.

Prodan, O., Ladar, I. and Alexa, P. (2012), Spatiality effects in seismic response of passively protected steel frames. *Behaviour of steel structures in seismic areas, STESSA 2012*. **Vol I**: 797-802.

Kasai, K., et. al.,(2009). Full-Scale Tests of Passively 5-Story Steel Building Using E-Defense Shake Table: Test Concept, Method and Building Specimen. *Behaviour of Steel Structures in Seismic Areas*, STESSA 2009. **Vol I:** 11-17

Naeim, F., (2001). The Seismic Design Handbook, Springer

Prodan, O. (2011b) Mitigation of seismic response of multistory spatial structures by passive protection, PhD Thesis, Technical University of Cluj – Napoca, Romania (in Romanian)

Soong, T.T. and Dargush G.F., (1997). Passive Energy Dissipation Systems in Structural Engineering, Wiley, Chichester – England