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EARTHQUAKE PROTECTION FOR BUILDINGS AND OTHER STRUCTURES

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ABSTRACT

Passive seismic control strategies are based on the reduction of energy, which affects a structure in case of earthquake events. Some well known approaches make use of frictional, plastic, or other energy dissipating behaviour of special devices. The following presentation reflects some basic ideas for the increase of elasticity and viscous damping for different types of structures. Spring elements may provide local elasticity and attract a great extend of the seismic energy. In many cases they represent the most flexible part of the structure. In comparison to common structural members they are designed for high operational and seismic demands. Viscodampers, installed beside the spring elements, have the task to absorb the kinetic energy. They can be used to control the displacements of the structure and the devices. The safety against collapse and defined states of serviceability of the structures can easily be assessed as the behaviour of the devices can be described as linear.

1. INTRODUCTION

The first basic idea of passive seismic control systems is to reduce the predominant frequency of the regarded system. Very flexible structures are usually not in danger of collapse during an earthquake. Low natural frequencies are indicators for a low level of induced seismic energy. Structures with higher natural frequencies take more energy from the given base excitation as the systems response may be in resonance with the excitation. In the final part of a usual frequency spectrum the induced acceleration becomes less and approaches the PGA for high frequency or rigid structures.

Regarding the above mentioned descriptions it becomes obvious that frequency reduction strategies can be applied successfully when the following conditions are given:

- The subsoil properties should be at least in a range of ‘medium’ quality. Otherwise there might be resonance effects even in the passively controlled structure, or the required target frequency would be too low to ensure the proper serviceability of the structure without any other precautions.
- The structural frequency without passive control mechanism should not be too low. Otherwise the additional ‘softening’ by the devices causes combined effects and the seismic protection efficiency will not be very high.

The second measure in utilizing passive seismic control systems is based on the increase of damping. This means may be combined with the frequency reduction strategies. On the other hand damping devices can be installed solely. Then, they have the task to damp the relative motion between two structures, two parts of the same structure, or the structure and the ‘rigid’ vicinity.

The reduction of the induced structural responses by the increase of viscous damping can be taken from different national and international standards. Some well known curves are compared and Fig. 1 provides an idea of the achieved control effect.

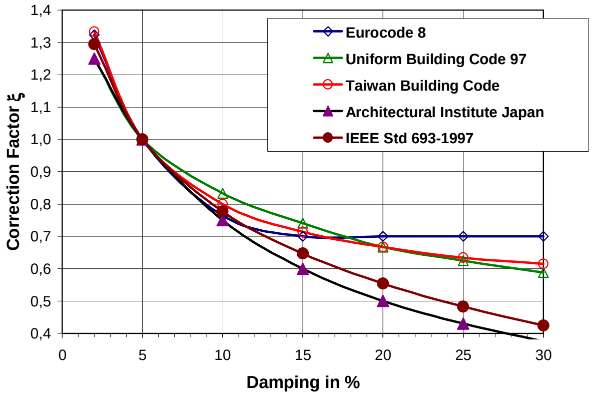

Figure 1 Effects of structural damping according to different regulations

The efficiency of the presented strategies is outlined in the next chapters giving examples for machinery, equipment and buildings in seismically active regions. Important results of numerical analyses are presented for systems with helical springs and viscous dampers arranged as supports of the structures.

A typical situation for structures on a Base-control system (BCS) is shown in Fig. 2. Here a 5-storey steel frame structure on helical steel springs and Viscodampers was tested at the Institute of Earthquake Engineering and Engineering Seismology, Skopje. Details of the supporting system are given in the left hand side of the Figure and the right part shows the maximum peak responses for each storey under a typical Turkish earthquake with and without BCS.

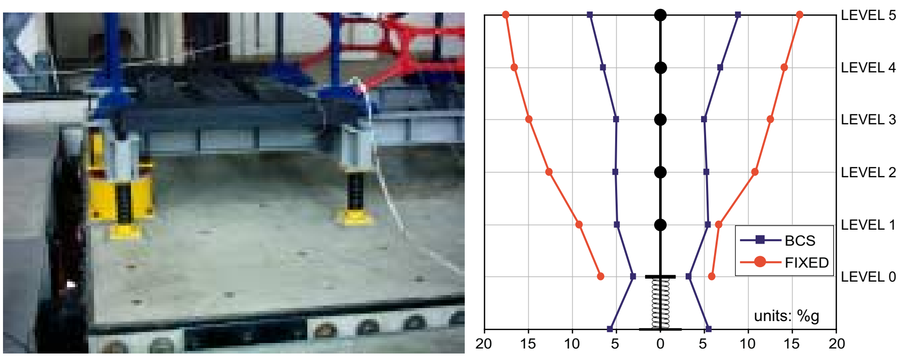

Figure 2 Five storey steel frame with BCS at IZIIS and typical acceleration behaviour

2. EARTHQUAKE PROTECTION OF MACHINERY

Earthquake control strategies of machinery is generally based on the change of support conditions. Sometimes the same devices are used for vibration control purposes simultaneously. There are many turbine decks and diesel generator sets in seismic prone areas. Induced acceleration levels are reduced and usually there is no necessity to fix the machine to the ground to protect it from turn over. An example of an elastically supported diesel engine is given in Fig. 3, left, the right side shows the support of a turbine deck..

Figure 3 Seismic protection and vibration control with helical steel springs and Viscodampers

3. EARTHQUAKE PROTECTION OF EQUIPMENT

The experience in earthquake protection of machinery can be enhanced to control structures in which originally no vibration isolation is used. Equipment, e.g. for electrical purposes or production processes, can be supported by helical steel springs and Viscodampers exclusively against seismic events. These structures frequently consist of sensitive material or require a vulnerable assembly. An air core reactor with ceramic footings in the highest seismic zone of California is discussed in the following.

The assembly consists of the reactor with a mass of about 45 tons. The COG is about 11 m above ground and as a substructure there are ceramic footings and stiffening steel cradles. Especially the footings are in danger of collapse during an earthquake. In Fig. 4 the arrangement is shown and the spring supports are indicated as boxes at the bottom

The seismic requirements are related to the IEEE 693 and the spectral acceleration figures are given in the right hand side of Fig. 4. For a common layout the footings are directly fixed to the foundation. In this configuration the frequencies would be around 3 – 4 Hz and the damping in the structure is about 2%. It can easily be seen that the seismic acceleration would exceed 3 g and the collapse of the system would be probable.

For the protection against seismic events the base-cradle is arranged on a system with helical steel springs and Viscodampers. This causes a significant change of the main system frequencies as well as of the corresponding mode shapes. The achieved system frequencies and damping ratios are as follows:

- Rocking modes: F_1 = 0,58 Hz, D_1 > 25%,
- Vertical mode: F_3 = 1,98 Hz, D_3 > 30%,
- First elastic mode: F_7 = 3,7 Hz.

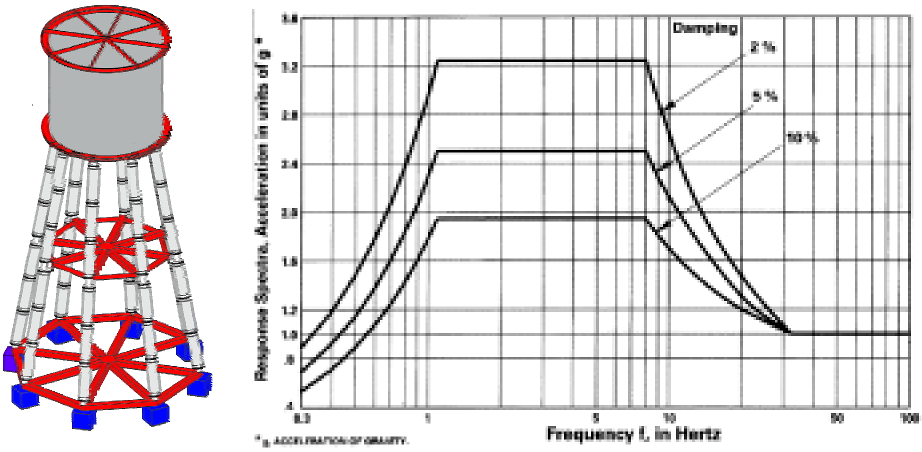

Figure 4 Layout of the air-core reactor and seismic demands according to IEEE 693

Regarding the spectral acceleration figures it becomes obvious that the induced acceleration of the reactor as well as the internal stresses in the ceramic footings under seismic action can be reduced significantly. The axial, shear and bending stresses can be found within acceptable limits. In this case the controlled rocking motion causes low frequencies and even sufficiently small horizontal displacements at the base.

Fig. 5, left side, shows some more details of the elements consisting of combined springs and dampers. The supporting foundations are designed for a relatively low level of seismic demands as the vertical softness of the elastic system additionally causes lower transmitted forces to the foundations / subsoil. On the right part of Fig. 5 the final situation at the substation in California is shown.

Figure 5 Seismic protection devices and assembly of air-core reactors at substation in CA

4. EARTHQUAKE PROTECTION OF BUILDINGS

Buildings are usually very complex in regard to the dynamic behaviour, and they require a very high standard in safety questions. The discussed 3-storey building has the dimensions about 9 x 9 m in plan and it is located in a high seismic zone of Argentina. The lateral force resisting system consists of a R/C frame structure with infill brick walls. The entire building is resting on a concrete slab. Until the decision in favour of helical steel springs and Viscodampers several studies of the seismic behaviour under different support conditions were conducted. The analyses were performed with the following building models:

- a rigidly supported structure with a first frequency of 5,3 Hz and a damping ratio of D=4%,
- the structure supported by Helical steel springs and Viscodampers – Base-Control System (BCS) at about 1,1 Hz and D~20%, as well as
- using a Base-Isolation System (BIS) with an equivalent frequency of 0,4 Hz and D~15%.

The peak ground acceleration for this location according to the national standard of Argentina is 0,35g and for the seismic qualification all the recorded earthquakes according to Table 1 had to be taken into consideration. As a result of this study all structural responses were compared. Special attention was paid to internal stresses and subsoil demands.

Table 1 Seismic qualification with recorded earthquakes

No.	Event	Station	Date	Mag	PGA [g]
1	Cape Mendocino	Cape Mendocino	25.04.1992	7,0	1,497
2	Coalinga	Transmitter Hill	22.07.1983	5,7	1,083
3	Loma Prieta	Corralitos	17.10.1989	7,1	0,644
4	Imperial Valley	Array No. 6	15.10.1979		0,459
5	Kobe	JMA	17.01.1995	6,9	0,821
6	Chi-Chi	TCU 084	20.09.1999	7,6	0,810
7	Northridge - New Hall	La Country Fire Station	17.01.1994	6,6	0,583
8	Cape Mendocino	Petrolia	25.04.1992	7,0	0,662
9	Northridge	Sylmar	17.01.1994		0,843
10	Tabas, Iran	Tabas 9101	16.09.1978	7,4	0,852
11	Imperial Valley	El Centro	15.10.1979		0,436

Figure 6 provides an idea of the peak stresses which occur in the structures during the seismic events. It shows the peak shear forces at the bottom of a corner column. It is obvious that the high stresses in the system without any precautions do not appear for the building equipped with BCS or BIS. Although smaller horizontal acceleration figures are achieved with the BIS the stress level for the BCS and the BIS is nearly the same.

A closer look at the response-time behaviour shows that for the BIS the time instant for the highest acceleration and the highest structural stress is not the same. Higher modes are affecting the stress response for the BIS and the structure has to be stiffened to take the full advantage of the low frequency response. On the other hand these effects make the system more expensive and it might even be dangerous when they are ignored. High frequency contents can usually not be observed when pure static procedures or response spectrum methods are applied. All these effects do not occur with the BCS utilizing helical steel springs and Viscodampers. Using this strategy the seismically induced stresses are further reduced by the horizontal motion on a vertically flexible system. Here, the vertical restraint forces in the superstructure are reduced significantly.

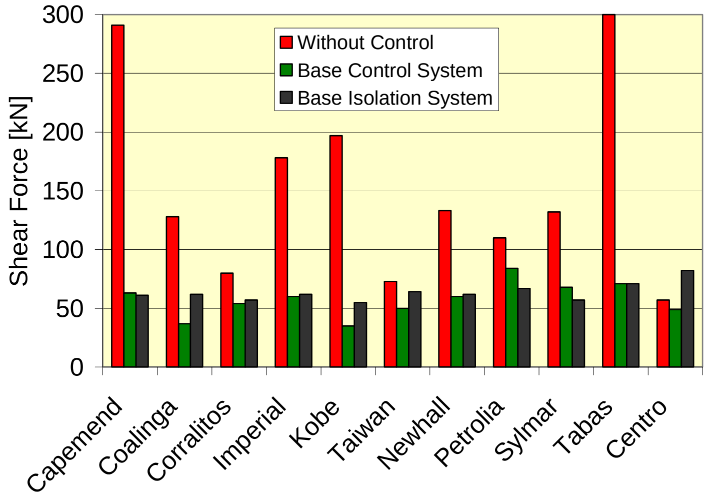

Figure 6 Stresses in the corner column – shear forces

In Table 2 the resulting subsoil reactions for each seismic event are listed. It is obvious that the average horizontal reactions become very small as per the low frequencies using BIS and BCS. On the other hand the vertical figures under BIS exceed those without any control by 26% on the average. Using BCS the peak values can be reduced by about 20%. When vertical excitation had to be considered simultaneously, this difference would even be larger.

Fig. 7 shows the differential horizontal displacement which has to be taken into consideration at the control surface. Depending on the frequency range, the duration of the event and the support systems, those figures vary very much. When helical steel springs are chosen the average value of the displacement becomes 65 mm (BCS) and the same figure for Base-Isolation Systems leads to 213 mm. For the layout of the seismic gap the maximum values have to be considered; here we have 95 mm for the BCS and 420 mm for the BIS.

Table 2 Subsoil reactions – peak responses

Event	Horizontal			Vertical		
	Without Control	Base Control System	Base Isolation System	Without Control	Base Control System	Base Isolation System
	kN	kN	kN	kN	kN	kN
Capemend	4.551	1.196	448	2.237	1.712	2.724
Coalinga	2.278	576	247	2.237	1.710	2.729
Corralitos	1.577	916	306	2.239	1.713	2.711
Imperial	3.707	912	272	2.246	1.709	2.723
Kobe	4.002	557	254	2.231	1.711	2.713
Taiwan	1.188	888	296	1.973	1.687	2.722
Newhall2	2.345	1.045	308	2.236	1.703	2.717
Petrolia	1.795	1.426	501	1.975	1.676	2.709
Sylmar	2.025	1.355	520	2.239	1.718	2.740
Tabas	5.572	1.030	551	2.244	1.720	2.713
Centro	1.083	848	572	1.972	1.681	2.779
Average	**2.738**	**977**	**389**	**2.166**	**1.704**	**2.725**
%		**36**	**14**		**79**	**126**

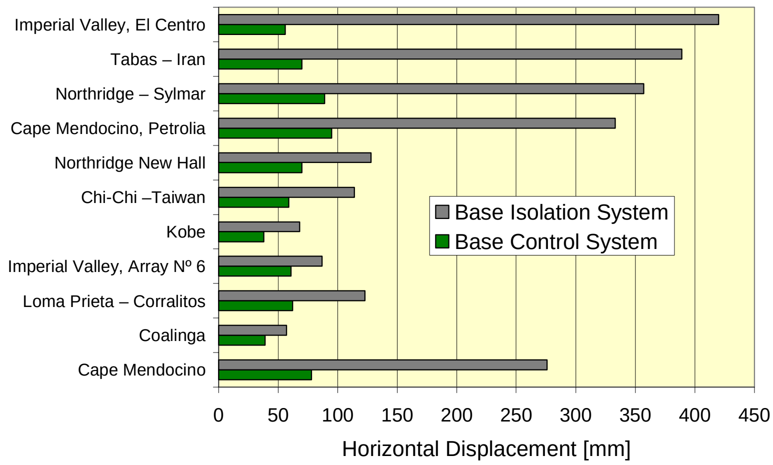

Figure 7 Horizontal peak displacement in the devices

Figure 8 gives an impression of the layout of the support system with helical steel springs. The seismic gap – horizontal clearance between floating building and vicinity - was chosen with 100 mm. Figure 9 shows a picture of the apartment building and the installed spring–/Viscodamper system.

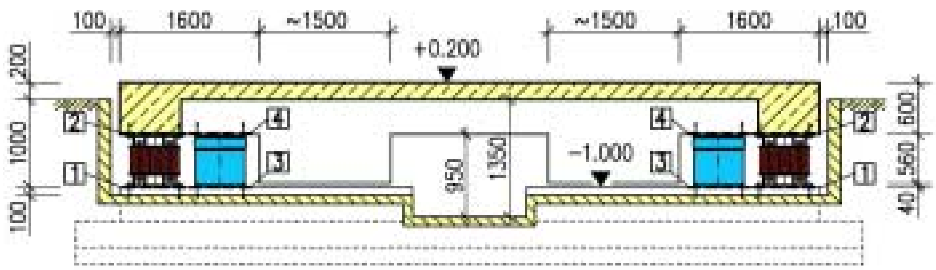

Figure 8 Cross section of the base slab with helical springs and dampers

Figure 9 Apartment building in Mendoza and installed Base-control system

5. CONCLUSIONS

After a brief outline of the fundamentals of seismic control strategies, some examples for the earthquake protection of machines, equipment and buildings are discussed in the paper. The proposed elastic support of heavy machinery as well as equipment causes low system frequencies as well as high damping values. The seismic performance is improved as induced accelerations and structural stresses are reduced significantly. It was shown that controlled rocking effects have positive effects on the structural performance during seismic events. In comparison to other strategies the horizontal differential displacements in the control surface are in the range of only a few millimeters even under severe earthquake actions.

Finally, the seismic analysis of an apartment building in Argentina under 11 recorded seismic events was presented. The comparison study took into account 3 different support systems. Internal stresses, subsoil reactions and horizontal motion in the control surface were calculated and the protection level of rubber bearings (BIS) and helical steel springs and dampers (BCS) were discussed. Depending on the frequency content of earthquake both systems BCS and BIS are suitable for the reduction of internal stresses. Vertical subsoil reactions under BIS become relatively high when compared with the system without any precautions. On the other hand the seismic gap for structures using BCS can be chosen with 100 mm only. There are maximum figures between 38 and 95mm and the same figures using rubber bearings can be found in a range between 57 and 420mm. The execution of the chosen Base-Control System was briefly described.

In the discussed examples helical steel springs and Viscodampers are used as seismic control devices. They are easy to implement in the analysis as the load-deflection curves can be assessed as linear. It is well known that springs are acting in the axial direction as they are usually also carrying the dead load of the structure. For the purpose of earthquake protection the vertical demands usually become higher and the horizontal component becomes more important in regard of the target frequency and mode shape of the seismically controlled structure.

REFERENCES

EN 1998-1, EUROCODE 8. Design of Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings.

Uniform Building Code, Structural Engineering Design Provisions, Volume 2, 1997.

Taiwan Building Code (TBC) Seismic Actions.

Architectural Institute of Japan (AIJ), Recommendations for Loads on Buildings – Chapter 7: Seismic Loads.

IEEE Std 693 (1997) Recommendations Practice for Seismic Design of Substations.

Nawrotzki P. (2002) Artificial Increase of Elasticity and Damping for Seismically Excited Structures. Proc. 12th European Conference on Earthquake Engineering, London, Paper No. 58.

Nawrotzki P., Jurukovski D. and Rakicevic Z. (2005) Shaking Table Testing of a Steel Frame Structure with and without Base Control System. Eurodyn, Paris.

Somaki T., Nakatogawa T., Miyamoto A., Sugiyama K., Oyobe Y. and Tamachi K. (2001) Development of 3-dimensional Base Isolation System for Nuclear Power Plants, SMIRT 16, Washington.

Villaverde R. (2002) Roof Isolation System Implemented with Steel Oval Elements: Exploratory Study. Proc. 3rd World Conference on Structural Control, Como, Italy.