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RECENT DEVELOPMENT AND TRENDS IN 3D EARTHQUAKE PROTECTION SYSTEMS

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Abstract

Passive seismic control strategies are often based on usage of devices that are effective against horizontal excitation only. Structures will always experience horizontal and vertical excitation due to seismic ground motion. Thus, the vertical seismic input should not be neglected and systems should be developed that are efficient in all three directions. This paper presents control strategies using 3-dimensional Base Control Systems (BCS) consisting of helical steel springs and viscous dampers. These passive systems yield a decrease of internal forces, accelerations as well as deformations compared to a structure without any mitigation measures. The spring elements provide a 3-dimensional flexibility and the dampers supply damping forces in all spatial directions. It is feasible to adjust the properties of the BCS including intended rocking motion in regard to the requirements of the specific project, as the elements vary especially in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between horizontal and vertical stiffness and in the damping resistance. The mentioned optimization procedure is backed up by an ongoing development of the devices themselves. Not only elements but also test methods are being further developed – an example of a new 3-D test rig is briefly introduced. Applicable optimization criteria and procedures are described. The efficiency of the system is verified by wide experience, experimental research, e.g. documented in technical literature and by measurements of two adjacent buildings, one with and one without a BCS. Some details of executed projects and results of seismic analyses underline the effectiveness of the proposed passive control strategies. Selected pictures illustrate the general applicability of the mitigation system.

Keywords: 3-D Base Control System; seismic protection; passive control; optimization

1. Introduction

Most of the earthquake protection strategies still only pay attention to the horizontal seismic effects respectively to the horizontal isolation by systems that provide horizontal low frequencies in combination with a stiff support of the structure in vertical direction. One reason could be that the corresponding devices (e.g. rubber or lead rubber bearings, friction pendulum bearings) are well-known. Another reason could be that many current design codes neglect the vertical ground motions. For some time now, the effects of the vertical seismic input receive more attention. This can be found not only in scientific research, as described in [1], but also in the latest updates of national and international standards. Some standards describe the vertical input by using a factor to just scale the horizontal spectrum, which may not be fully correct, as the vertical ground motion can be much larger than the ones in the horizontal directions. Furthermore, in general the vertical ground motions possess a higher frequency content. These effects have recently also been taken into account by some standards. In [2] different spectrum shapes are defined for horizontal and vertical earthquake input.

Regarding the three dimensionalities there are some important research information of typical base isolation systems. Shaking table tests of a full-scale building supported on Lead Rubber Bearings and on Friction Pendulum Bearings have shown very good results if horizontal (one-directional and/or two-directional) input was applied. The consideration of additional vertical input yields nearly the same results as found for a non-protected building structure, as described in [3]. Furthermore, in case of typical base isolation systems the extremely low horizontal stiffness in combination with a large vertical stiffness may lead to horizontal-vertical coupling effects that could amplify the horizontal accelerations inside the structure, for more information see [4].

Beside the well-known 2-D base isolation systems there are also other possibilities. The elastic support of buildings and machinery on elements using helical steel springs and viscous dampers to achieve vibration isolation is now “state of the art”. As the springs provide horizontal and vertical flexibility it is important to have in mind that the mode shapes of the elastically supported system will contain horizontal as well as vertical parts. Fig.1 shows a simplified system to illustrate this.

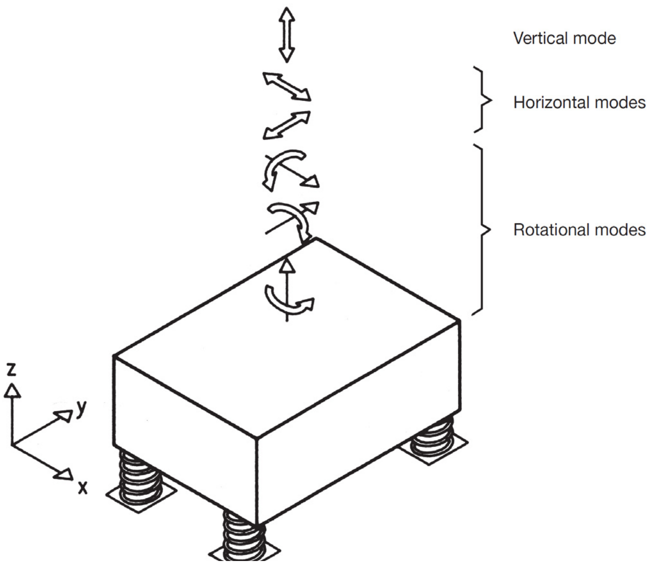

Fig. 1 – Degrees of freedom in a single mass system

The system shown in Fig.1 is defined by the mass block and the elasticity of the supporting elements. Assuming a rigid mass block, this system possesses six degrees of freedom, as it can translate in the three directions x, y and z and can rotate about the x, y and z axes.

These principles are the basis for the vibration isolation of structures, using steel spring devices. It is therefore an important advantage that the same elements can also be used for seismic protection purposes through additional design criteria. Thus, it is not required to combine horizontal flexible devices with other devices for the vertical direction. The resulting support system is entitled as Base Control System (BCS) to distinguish it from the previously mentioned base isolation systems (BIS). For a base controlled structure there are several advantages. It is a 3-dimensional passive mitigation system. The reduction of the authoritative system frequencies with simultaneous increase of structural damping yields an efficient earthquake protection of the supported structure in all three directions. Compared to a non-protected structure damage can be prevented, acceleration and stress levels within the structure can be reduced significantly. The parameters of the devices do not change over time. As the elements consist of steel parts regular visible inspections are recommended. The access to the devices is easy – allowing for inspection, adjustment and exchange, if required. Table 1 shows several important features of a BCS.

Table 1 – Main characteristics of Base Control Systems

Item	**BCS**
Horizontal stiffness	Low
Vertical stiffness	Medium
Horizontal acceleration	Low
Stress / strain level	Very low
Vertical efficiency	High
Relative displacements	Medium
Vertical soil reactions	Medium
Higher modes	Nearly no effect
Exchange of devices	Easily possible
Bearing capacity	Medium – high
Vibration isolation / protection against structure borne noise	Integrated
Aging / design life	No problem
Adjustment / levelling of structure	Standard procedure
Control / levelling of vertical forces	Easily possible

The present contribution starts with a section about the principles of 3-D Base Control Systems. Their main parameters and corresponding layout procedures are discussed. The following chapters present some practical applications and an outlook for the use of these mitigation systems.

2. Basics of 3-D Base Control Systems

A protection system using devices with helical steel springs and viscous dampers is entitled as Base Control System (BCS). The spring elements are arranged below the base of the structure to support the gravity load. They are designed to yield sufficient safety margin to bear extraordinary excitation due to seismic or other loads in all spatial directions. The springs possess linear load deflection curves in vertical and horizontal directions. There is nearly no dependency between the horizontal stiffness values and the vertical displacements. Thus, the numerical description of the devices is comparatively simple and the behavior of the spring supported structure can be easily assessed. Viscous dampers that are highly efficient in all 3 directions are arranged in parallel to the springs to control resonance amplification and to increase the structural damping. Their parameters can be described by the damping resistance values for the horizontal and vertical directions. Fig.2 shows typical elements.

Fig. 2 – BCS below concrete structure: viscous damper (left), spring element (right)

The arrangement of the spring devices leads to a change of the mode shape of the supported structure and to a reduction of the dominant frequency, or in other terms to an elongation of the fundamental period of the system. Depending on the details of the seismic input, this frequency decrease could reduce the seismic demands by more than 60 %. In general, reducing frequencies yields larger relative displacements. Therefore it is required to find an optimum between the reduction of seismic accelerations and the occurring displacements. The viscous dampers serve to increase the damping and to limit displacements. The increase of structural damping from 5 % to 20 % causes a reduction of absolute accelerations, structural stresses and displacements in a range of about 35 % according to [2]. As a corresponding example a response spectrum according to [2] with chosen coefficients (S_{DS} = 0.68 and S_{D1} = 0.22) is plotted in Fig.3.

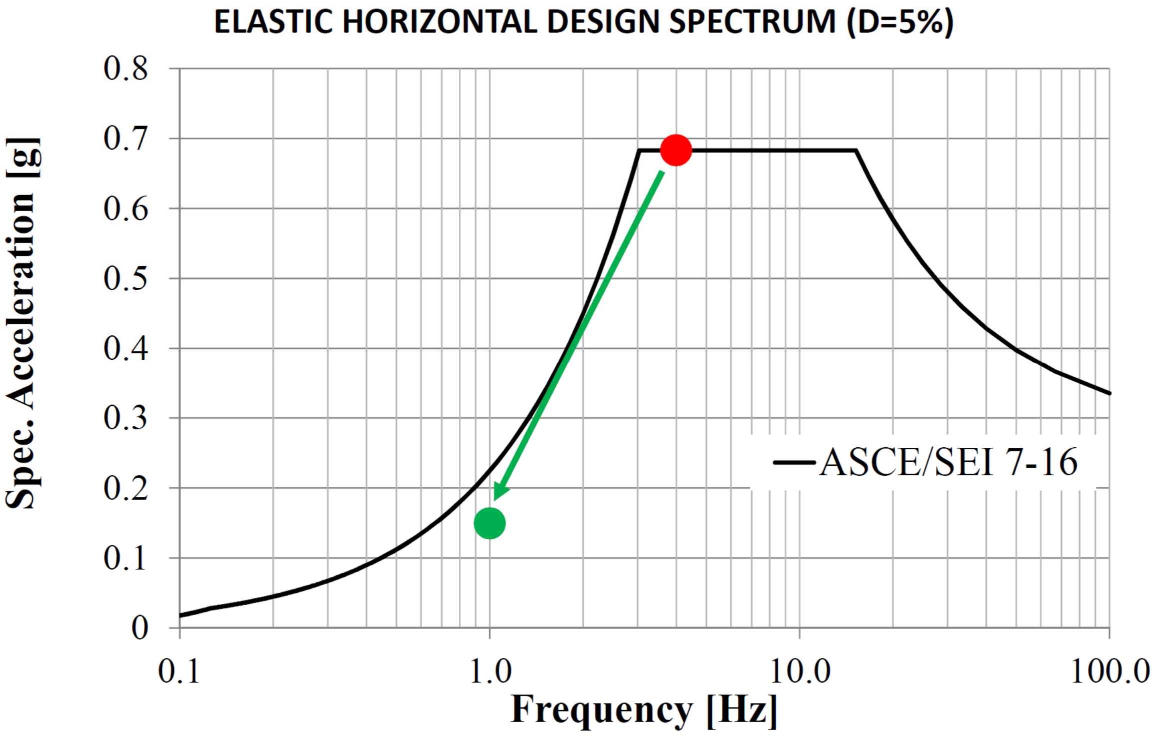

Fig. 3 – Typical effect of frequency reduction and increase of damping

The strategy of using additional damping could be combined with the frequency reduction to optimize system performance as shown in Fig.3. In summary, a Base Control System allows the tuning of the rigid body mode shapes into the low frequency range in combination with an increase of structural damping. This protection strategy results in significantly reduced seismic acceleration levels and corresponding structural advantages for the supported structure, as also presented in [5].

The BCS devices range in bearing capacity, horizontal and vertical stiffness values, ratio between vertical and horizontal stiffness and in the damping resistance values in all directions. The mentioned parameters can be used and adjusted to accommodate project specific requirements. The first property that is investigated for each project is the stiffness ratio of the spring. Using a higher stiffness ratio (vertical stiffness / horizontal stiffness) has proven advantageous for several projects. The value is used to control the seismic motion of the elastically supported structure and could lead to a substantial reduction of acceleration amplification as discussed in [6]. A low stiffness ratio could lead to a horizontal mode shape including a larger rocking component. If this rocking motion is undesirable, a higher value for the stiffness ratio is preferred. Typical values are found between 5 and 8, leading to a mode shape with less rocking.

The addition of the dampers yields larger damping ratios in the dominant mode shapes. Depending on the project specific details (i.e. spring supported mass, dimensions, material damping, general requirements, etc.) often a combination of a vertical frequency around 3 Hz and horizontal frequencies around 1 Hz, both with a corresponding damping ratio between 10 % and 30 %, present an optimum solution. Quite similar results are found by [3] using more detailed investigations of optimization criteria.

The following section presents some corresponding projects where a BCS system has been successfully implemented.

3. Project Examples

As a result of reduced frequencies and increase of structural damping the seismic demands of a structure in terms of absolute accelerations, internal forces, base shear etc. can be reduced by applying a 3-D Base Control System. These positive mitigation effects have been verified by theoretical and experimental research. Due to the possible incorporation of springs and dampers in finite element programs the comparison of calculated responses of a structure with and without BCS can be done easily. The experimental investigations are typically done using shaking tables. In [7] the tests of a five stories, three bay steel frame model with and without BCS at IZIIS (Institute of Earthquake Engineering and Engineering Seismology) in Skopje, Macedonia are described. Evaluating the results of ten different earthquake input records it was concluded that the BCS reduced the structural responses in terms of absolute accelerations, axial and bending strain at various locations of the structure by more than 50 % compared to the unprotected structure. At the same facility, investigations of a BCS for a massive concrete structure were performed in 2012. These prototype tests showed a high correlation between previously calculated results and measured results, as presented in [8].

Besides the tests on typical shaking tables it is nowadays also possible to test elements at a new test stand, erected in St. Petersburg, Russia. A special test rig (SIST) was developed to test real structures with seismic isolation systems in natural scale. The main idea is to shake the superstructure at its natural frequencies with full scale amplitudes instead of shaking the substructure. The configuration of the test-setup is shown in Fig.4.

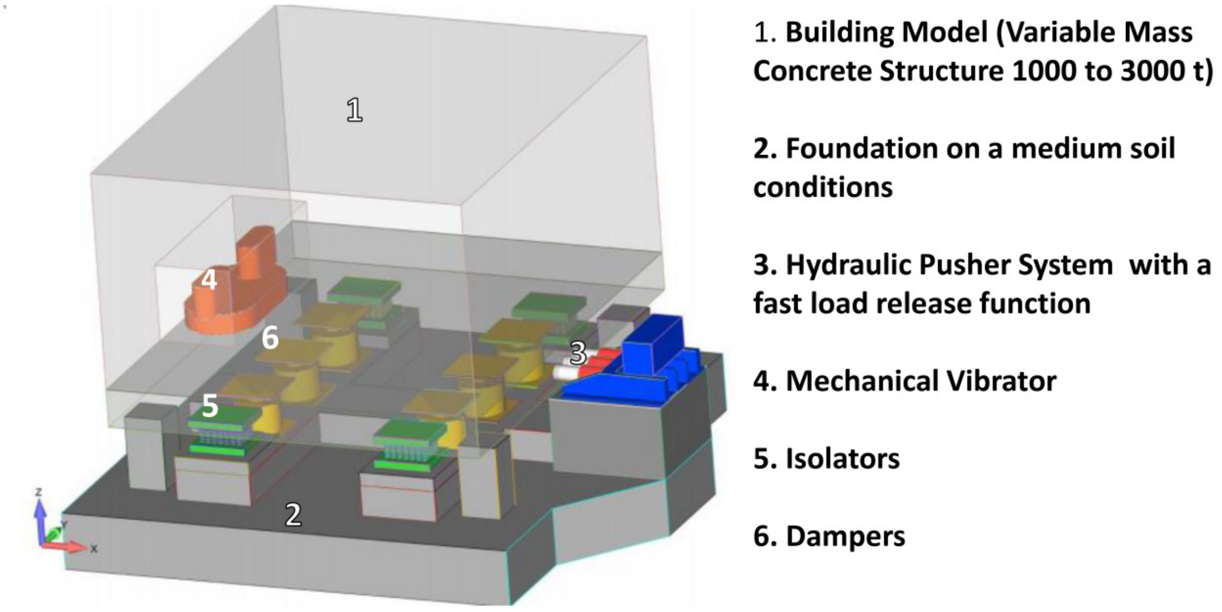

Fig. 4 – Inverse test rig SIST

The SIST consists of a superstructure with a variable mass between 1000 and 3000 metric tons, a foundation and a hydraulic pushing system. The test devices could be subjected to full dead load and seismic displacements. Initial tests of the setup verified the general functionality and operability of the test-rig. In general, it is possible to test any type of seismic isolator, snubber and damper. First a 3-D Base Control System was investigated on the new test stand. The system consisted of 4 spring devices and 4 viscous dampers. Due to the project specific requirements a vertical eigenfrequency of about 2.5 Hz and a first horizontal frequency of about 0.7 Hz were chosen as target values. Corresponding devices were designed, developed and manufactured. Using the design values the frequencies are verified by calculations. Then the elements were installed at site. Fig.5 presents the situation at the test rig.

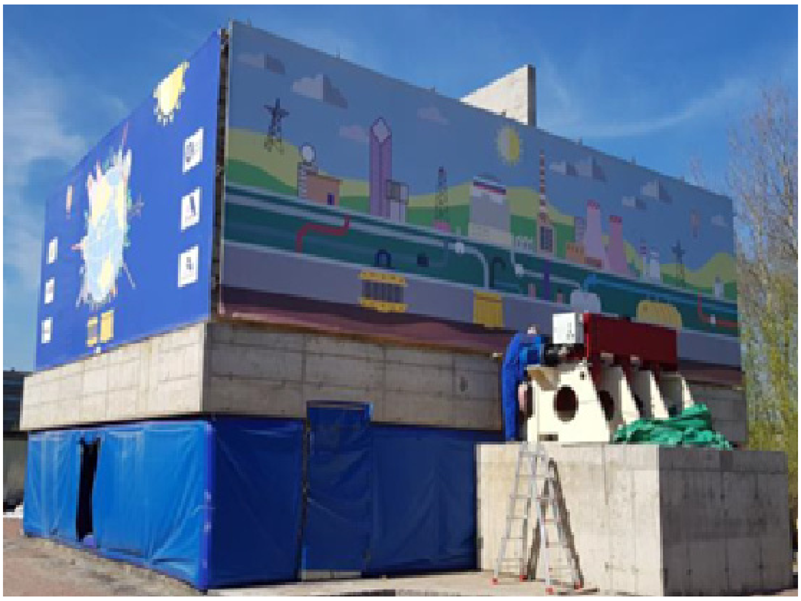

Fig. 5 – General view of the SIST

The test results of a 3-D Base Control System show that the devices provide previously defined optimal parameters to the superstructure, as described in [3]. The most important mode shapes are plotted in the following Fig. 6. Mode 1 consists mainly of a translation in horizontal x-direction with a small tilting about the y-axis. The Mode 3 represents the vertical translation.

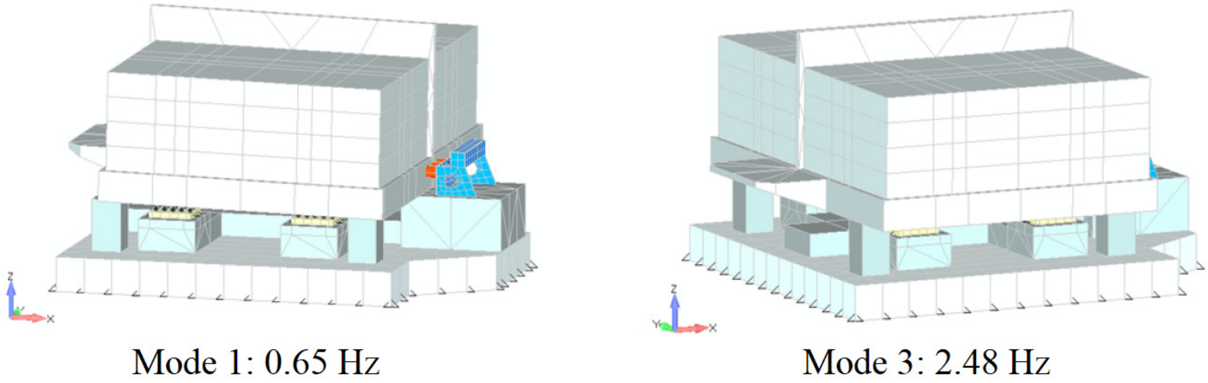

Fig. 6 – Natural frequencies and modes of SIST using a 3-D BCS

During the 16th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures this test rig was presented to the public during a "Technical Tour". Some more details can be found also in [9].

In parallel to the theoretical and experimental investigations there is experience from completed projects worldwide. In the following, two examples are presented. In the first example, seismic protection was in the main focus regarding the choice of support system. The second example represents the combination of the requirement of an efficient vibration isolation system with a location within a seismic zone.

3.1 Students Home – Mendoza University, Argentina

There is one project that is especially worthy to mention, as it is usually impossible to make a direct comparison between a real structure with an earthquake protection system and an identical structure without mitigation system. In 2004 two identical apartment buildings were built in Mendoza, a high seismic zone of Argentina. One building consists of a conventional "rigid base" and the second adjacent building is supported by a Base Control System consisting of 4 steel spring elements and 4 viscous dampers. Both structures are composed of three floors of reinforced concrete and masonry infill. The dead load of one structure amounts to about 260 metric tons. Its main dimensions are about 8.2 x 8.7 m in plan with a height of 9 m. The National Technological University of Mendoza installed seismic accelerometers in both buildings upon their completion. Nearly one year later the calculated efficiency and predicted general feasibility of the BCS supported structure was tested against a real earthquake with a peak ground acceleration of 0.12 g. Fig.7 shows a picture of both buildings and one exemplarily comparison of measured results.

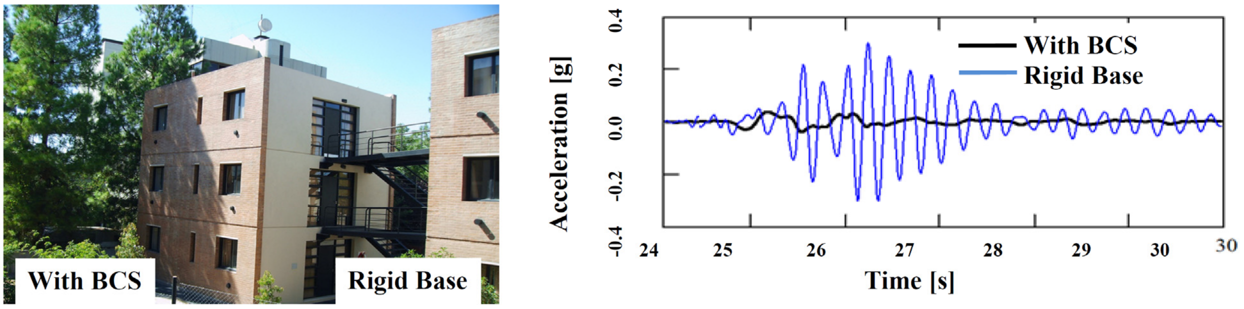

Fig. 7 – View of buildings and comparison of measured seismic responses at the roof

The comparison of the measured curves shows that the acceleration values at the roof of the base controlled building are reduced by more than 70 % in comparison to the unprotected building. For the second horizontal direction similar reduction values were obtained. Here, it should be noted that these results were achieved with relatively small displacements (several millimeters only) within the BCS devices. Thus, it is important to have in mind, that the efficiency of a BCS cannot be judged by having a look at the relative displacements only. After some minor adjustments of the characteristics of the initial analysis model due to the measured results, it was shown in [10] that corresponding reduction factors can be found also in regard to internal stress and strain values as well as to subsoil reaction loads. The axial forces in columns were reduced by more than 60 %, shear forces by more than 75 %, and critical bending moments were decreased by about 90 %. Thus, the BCS has successfully revealed its outstanding seismic protection capability for a building under real seismic conditions.

3.2 Porta Nuova Isola, “Bosco Verticale”, Milan, Italy

The Porta Nuova project in Milan, Italy includes several building complexes such as a new metro station, parks and several underground car parks. One highlight are the green twin towers called “Bosco Verticale” (Vertical Forest), planned by the Italian architect Stefano Boeri and his partners from the architectural company Boeri Studio, Gianandrea Barreca and Giovanni La Varra. The trees and plants arranged on the facade and balconies are intended to improve the microclimate in the apartments and to reduce noise, dust and heat. Both high-rise towers were constructed between 2008 and 2013 and completed in 2014. One of the two residential structures (shown in Fig.8) is located in the immediate vicinity of the southern subway tunnel that runs under the site. Due to the subway line, vibration and structure-born noise problems could have occurred within the building. These effects can be significantly minimized by an elastic support of the building. For this purpose, a vertical system frequency of approximately 3.1 Hz was chosen. Furthermore, it was important to consider wind loading as well as the seismic input that can be described by a peak ground acceleration of 0.07 g and an amplification factor of 2.65 for the plateau range between 2.6 Hz and 7.1 Hz.

Fig. 8 – Bosco Verticale

The building with a length of about 22 m and a width of about 28 m possess 19 floors with a total height of about 85 m. Due to the total design load of 250.000 kN the tower is elastically supported on 276 steel spring elements. The selection of the element type and the arrangement of the devices was initially made taking into account the static building loads and the local space conditions. As described in the previous chapter, the elements can safely absorb the static loads and offer sufficient margin for additional movements in all three spatial directions due to dynamic loads. The selected helical steel springs have a high stiffness ratio of about 7 to achieve a low horizontal natural frequency with a low rocking component of the corresponding mode shape. At the same time the elements provide the required low frequency for the vertical direction to ensure the vibration isolation efficiency.

Parallel to the spring elements, 32 viscous dampers were arranged in order to increase the structural damping and at the same time to limit the relative movements of the structure. The results of an initial study show that the seismic accelerations at the roof could be reduced by approximately 50 % using the combination of springs and dampers. Fig.9 illustrates a section of the element arrangement below the structure. The elements are placed on an approximately 2 m high concrete pedestal. Thus, the space underneath the floor slab can also be used by the residents of the building.

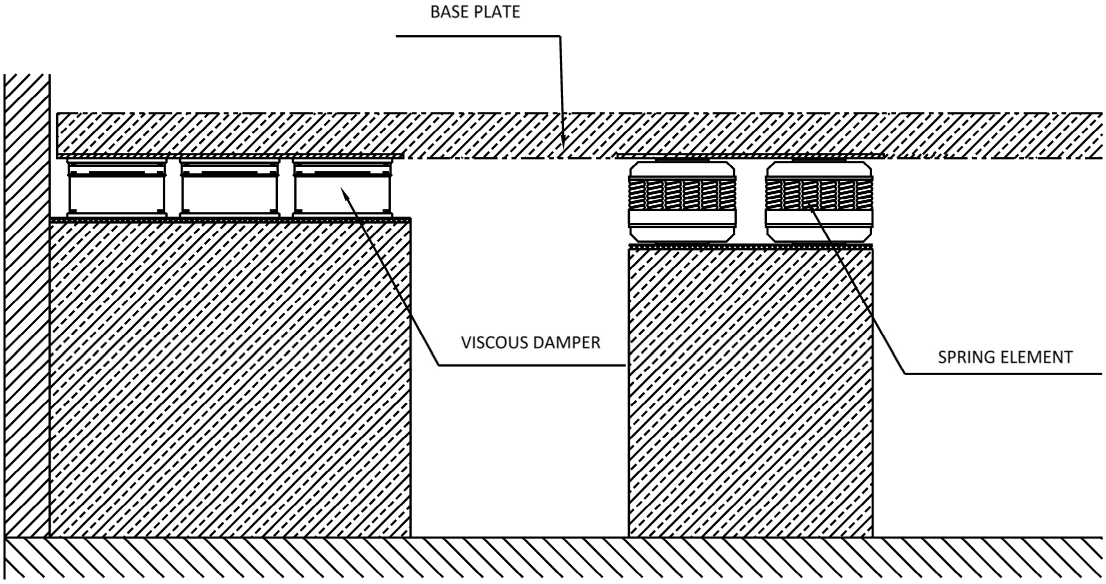

Fig. 9 – Cross-section of building

4. Outlook

It can be stated that more and more worldwide projects require horizontal and vertical earthquake protection. Furthermore, protection against vibrations also plays an important role – especially in residential construction, since, for example, due to urban densification, more and more buildings are being constructed in the immediate vicinity of vibration sources (e.g. near railway lines). Usually there is a combination of requirements for a structure – often not only in regard to the ultimate limit state but increasingly also in terms of serviceability limit state.

As explained in the previous chapters, steel springs and viscous dampers can reduce not only the effect of horizontal seismic input but also the effect of vertical excitations. In addition to this three-dimensional effectiveness, the ability to isolate vibrations is an important characteristic of a BCS. In general, these systems can be used not only for new structures but also for existing structures. This is especially an advantage if vibration problems (e.g. regarding serviceability) are detected after completion of the structure. It should be kept in mind that the elements of a BCS are constantly under development, for example in terms of dimensions of the devices and load-bearing capacity. Thus, the use of Base Control Systems should be further investigated and considered for practical application for buildings, machinery and other structures.

5. Conclusion

Following the introduction, the present contribution starts with a short presentation of the basics of 3-D Base Control Systems. The elastic support on a BCS causes, depending on the project specific details, a reduction in frequency and a simultaneous increase of structural damping. Thus, the seismic protection of a structure, such as machinery or a building, can be significantly increased. Furthermore, a BCS meets the frequent demands for a passive system, with long-term stability, simple replacement, easy control and ability to compensate short and long term settlement of the substructure. The shown project examples illustrate the effectiveness of the proposed systems and underline that by means of extended design criteria the elements used for vibration isolation of a structure can simultaneously serve to improve the seismic behavior.

6. References

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