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A system of multiple controllers for attenuating the dynamic response of multimode floor structures to human walking

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Abstract. Composite floor structures formed by continuous slab panels may be susceptible to excessive vibrations, even when properly designed in terms of ultimate limit state criteria. This is due to the inherent vibration characteristics of continuous floor slabs composed by precast orthotropic reinforced concrete panels supported by steel beams. These floor structures display close spaced multimode vibration frequencies and this dynamic characteristic results in a non-trivial vibration problem. Structural stiffening and/or insertion of struts between floors are the usual tentative solution applied to existing vibrating floor structures. Such structural alterations are in general expensive and unsuitable. In this paper, this vibration problem is analyzed on the basis of results obtained from experimental measurements in typical composite floors and their theoretical counterpart obtained with computational modeling simulations. A passive control system composed by multiple synchronized dynamic attenuators (MSDA) was designed and installed in these floor structures and its efficiency was evaluated both experimentally and through numerical simulations. The results obtained from experimental tests of the continuous slab panels under human walking dynamic action proved the effectiveness of this control system in reducing vibrations amplitudes.

Keywords: vibration control; human induced vibrations; floors; field measurements; passive devices

1. Introduction

A great amount of ambient excitation sources may expose people on building floors to excessive vibrations. Some of the most common sources of vibrations are: the traffic of vehicles in neighboring roads, the heavy equipments employed in neighboring constructions sites, the machines installed on the building and also human activities on building floors; the latter the least severe but the most usual and recurrent source of excitation. Depending on their frequency range and intensity, such ambient vibrations may lead to human discomfort, efficiency loss on work and even fear and health damage.

In order to reduce human induced vibrations in floors, engineers have largely defended structural stiffening as an efficient solution, although in many cases structural damping could be a better solution to the needed level of attenuation requiring none or slight structural and/or architectural alterations. In the focused problem, people are at the same time vibration sources and unpleased users, and sometimes may act as dissipation devices (Varela and Battista 2011, Pedersen 2016). Being impossible to isolate the human excitation source as it is done with machines, one feasible solution is to increase damping properties of the structure. For this, some creative solutions have been proposed, as for example slabs made of a concrete with special damping components (Zheng *et al.* 2008) or yet a sandwich solution with a thin layer of viscoelastic material between two layers of concrete or layers of steel and concrete (Patel and Built 2013).

Whenever the layout of occupation of a building floor permits, a cheap solution may be achieved by using slender struts or light wall panels fixed on the floor slabs and with rubber pads on their tops compressed against the upper floor slabs, combining the needed increase in structural stiffening and damping (Varela *et al.* 2015).

An efficient solution for the vibration problem of composite floor structures formed by continuous slab panels is achieved by a system of multiple synchronized dynamic attenuators (MSDA), which are simple and cheap devices that to be installed do not need to interrupt operational activities in the building. A MSDA control system can be designed and fabricated in many different shapes and sizes as needed and tailored to fit the architectural layout. Each SDA is a mechanical device that acts in opposition phase to the structure's movement in distinct vibration modes producing inertial forces opposite to structure's inertial forces induced by external action. Passive control devices called vibration absorbers – VA were first conceived by Frahm (1911) for controlling the roll motion of ships. Vibration absorbers were later mathematically formulated by Ormondroyd and Den Hartog (1928). In civil engineering applications, an VA device has been named vibration controller – VC, dynamic attenuator – DA, tuned

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vibration absorber – TVA (Battista and Magluta 1994) and tuned mass damper – TMD (Battista and Pfeil 2000); the latter being an ambiguous name as it is in fact a dynamic attenuator and not an ordinary damper.

Despite of being largely known by engineers around the world and used in very special cases, such as high rise buildings (Aly 2014, Lu *et al.* 2016), bridges and towers (Battista *et al.* 2002, 2008, 2010, 2018) and footbridges (Bortoluzzi *et al.* 2015) for instance, passive control devices are not yet applied as a conventional solution for reduction of vibrations induced by human activities on floor slabs, such as for example walking, running and jumping.

The first studies on floor vibration problems were conducted by Lenzen (1966) who pointed out the possible application of a passive control device. Nguyen *et al.* (2014) compared a case of structural stiffening to the application of a SDA for attenuation of the vibrations of a building floor. The authors concluded that for comparable effectiveness in reducing the floor response the amount of steel material required for the SDA was less than 20% of that required for the stiffening technique.

SDAs can reduce significantly vibrations amplitudes on one isolated floor slab with well-spaced modes of vibration. It has been demonstrated that a dynamic attenuator (or vibration absorber) efficiency depends on natural frequencies and modal damping ratios (Den Hartog 1947). Theoretical models and practical technical applications of vibration absorbers (or dynamic attenuators) are presented in special technical works (Korenev and Reznikov 1993) and suggested applications as remedial measures to damp out vibrations in structures subjected to various types of dynamic loads may be found in the technical literature (Bachmann *et al.* 1995). Varela and Battista (2011) conducted an extensive program of laboratory tests to measure the efficiency of SDAs to reduce human walking induced vibrations in a 1:1 prototype scale of a steel-concrete composed floor structure. Over 80% reduction in vibration amplitudes was achieved in one of the tests when it was observed the resonance of the fourth harmonic of the human walking frequency (1.87 Hz) with the first natural frequency of the structure (7.51 Hz). Other examples of SDAs and similar passive control devices applied to attenuate human walking induced vibrations in actual floor slabs were reported by Setareh and Hanson (1992), Webster and Vaicaitis (1992), Carmona *et al.* (2014), Nguyen *et al.* (2014), An *et al*. (2015). Brzeski *et al.* (2015) studied SDAs with variable stiffness to reduce vibrations in different frequencies and Hudson and Reynolds (2012) described an active SDA like control device that can be adapted to a larger range of frequencies and respond faster and more efficiently than the ordinary SDAs, although much more expensive and dependent of electrical energy. Some other researchers used numerical tools to study the performance of other SDA like control systems to attenuate floor vibrations induced by people walking. Kim *et al.* (2014), for instance, proposed a passive control device with two asymmetric linear springs allowing translational and rotational motion and obtained a reduction of 28% in vibration amplitudes when compared to conventional SDAs.

In this paper vibration problems induced by human walking are studied and evaluated based on the results obtained from experimental measurements in an actual building floors and their correlation with computational modeling simulations of the dynamic interaction problem of a composite floor structure subjected to human walking forces and also to control forces of a MSDA system.

The main novelty presented herein is the use of multiple controllers to attenuate closed spaced mode shapes frequencies of an actual composite floor structure formed by continuous precast reinforced concrete slab panels displaying excessive multimode vibration amplitudes when subjected to human walking excitation forces.

2. Short description of the composite floor structure

Fig. 1 shows one typical composite floor structure of a steel framework structure of a four stories building constructed around twenty years ago in the Campus of Catholic University in Rio de Janeiro. Originally constructed to house individual staff offices and meeting rooms, the building was recently refurbished to accommodate corporate working space free of divisory walls. Therefrom comes the vibration problems in focus which is presented and discussed in the following sections of this paper.

The typical floor shown in Fig. 1 is a composite steel-concrete structure formed by four continuous reinforced concrete slab panels simply supported by I section steel beams whose section dimensions are given in Table 1, while Table 2 presents the physical properties of the materials (steel and concrete).

Fig. 2 shows the longitudinal and the transversal cross sections of one typical reinforced concrete slab composed by two layers: one formed by conventional precast reinforced concrete strips arranged side by side having in between them blocks of Styrofoam serving as framework pieces; the other on top is a cast in place reinforced concrete layer.

3. Identification of vibration characteristics of the floor structure

The identification of the vibration characteristics of the composite floor structure was made by means of free vibration heel drop tests at the center of each slab panel. The magnitude of the impact forces applied by each person were measured in laboratory using a platform instrumented with load cells (Fig. 3). Unidirectional accelerometers (~0-1 g, 0-50Hz, Kyowa, Japan) were installed at the center of the four main slab panels in vertical direction. Because of the closed space mode shapes – that are typical of multipanel structures – the damping ratios were not obtained with the traditional decrement logarithm method due to the difficulty to isolate the vibration modes completely. Then, the damping ratios were obtained through numerical analysis of the results of the experimental tests using Ibrahim time domain identification method (Ibrahim and Mikulcik 1977).

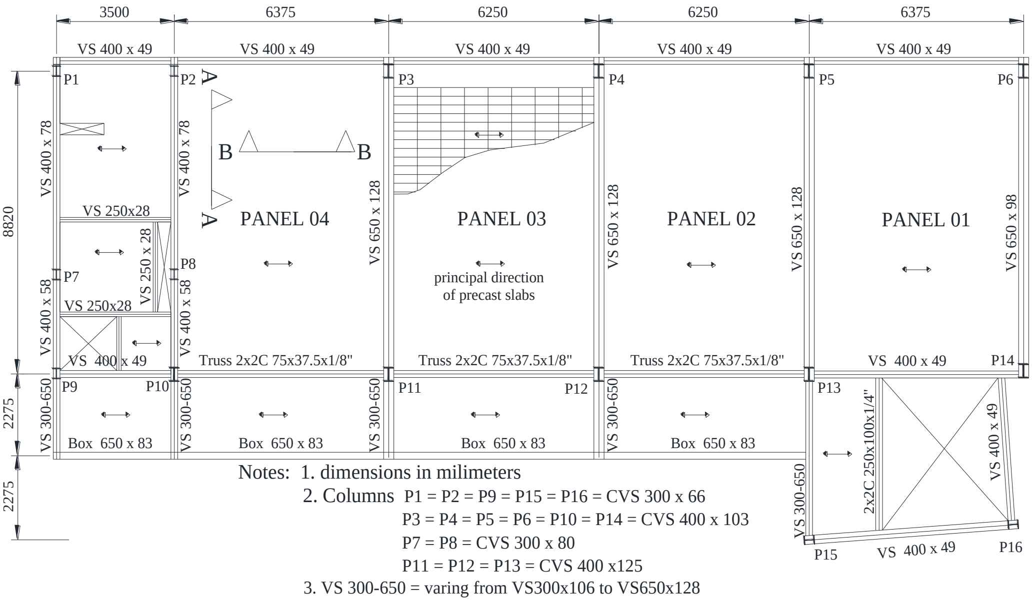
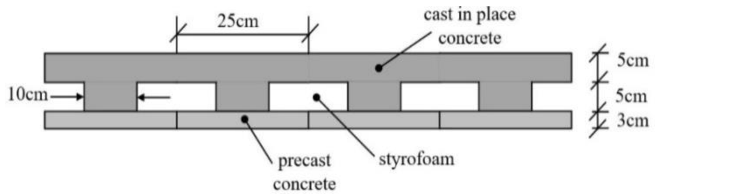
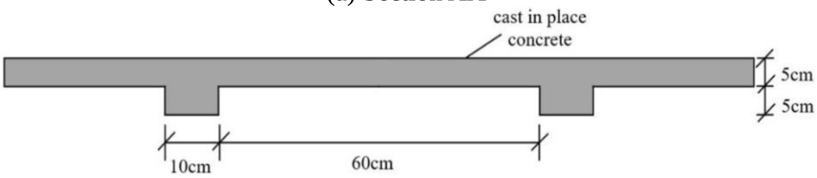


Fig. 1 Typical floor of the building



(a) Section AA



(b) Section BB

Fig. 2 Transversal sections of the concrete slab (see Fig. 1)

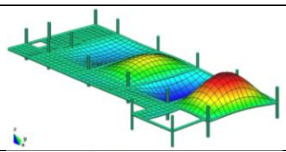
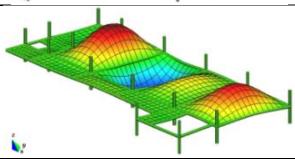
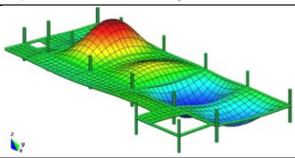
Table 1 Cross section dimensions and mass/ul of steel profiles of the floor structure

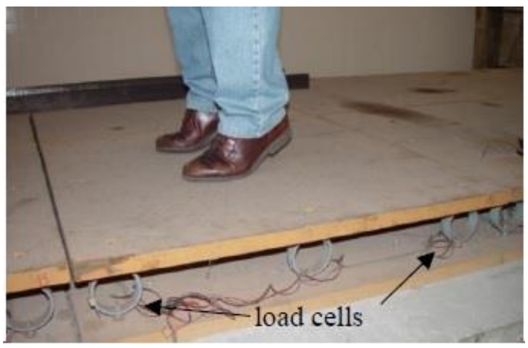
Section name	Section type	Height (mm)	Width (mm)	Flange thickness (mm)	Web thickness (mm)	Mass (kg/m)
VS 250x28	I	250	140	9.5	4.8	28
CVS 300x66	I	300	250	12.5	8.0	66
CVS 300x80	I	300	250	16.0	8.0	80
VS 300x106	I	300	300	19.0	8.0	106
VS 400x49	I	400	200	9.5	6.3	49
VS 400x58	I	400	200	12.5	6.3	58
VS 400x78	I	400	200	19.0	6.3	78
CVS 400x103	I	400	300	16.0	9.5	103
CVS 400x125	I	400	300	19.0	12.5	125
VS 650x128	I	650	300	19.0	8.0	128
C 250x100x1/4”	Channel	250	100	6.3	6.3	22
C 75x37.5x1/8”	Channel	75	37.5	3.2	3.2	4
Box 650x83	Box	650	150	8.0	6.3	83

Table 2 Physical properties of the materials

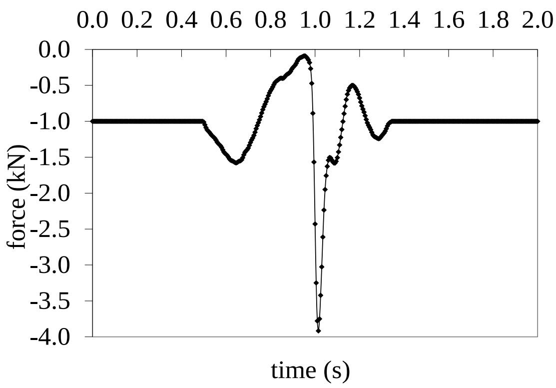
Material	Young's Modulus (kN/m²)	Poisson ratio	Density (kg/m³)
Concrete	2.885×10^7	0.21	2500
Steel	2.050×10^8	0.30	7850

Table 3 Dynamic characteristics of the floor structure

Frequency (Hz) Exp	Frequency (Hz) FEM	Damping Ratio (%)	Vibration mode
6.56	mode 1 6.51	1.00	
7.38	mode 2 7.46	1.15	
8.48	mode 3 8.71	1.32	

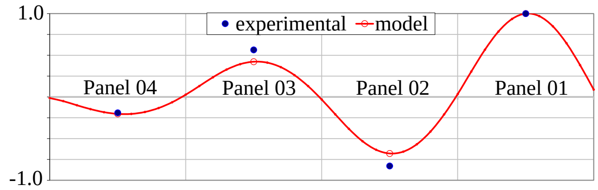


(a) Heel drop test

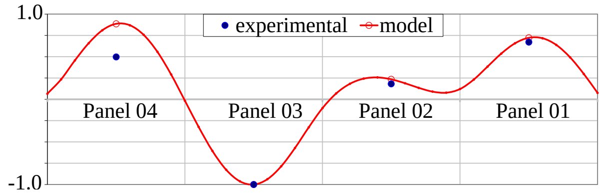


(b) Typical heel drop force x time

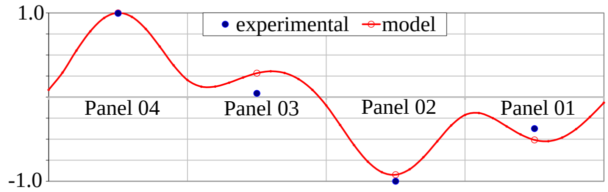
Fig. 3 Laboratory measurement of the heel drop force applied to the structure on the experimental free vibration tests (Varela 2004)



(a) First vibration mode



(b) Second vibration mode



(c) Third vibration mode

Fig. 4 Comparison between experimental and numerical vibration modes in a longitudinal sectional view

The results in terms of damping ratios (1.0% to 1.3%) are consistent with those obtained from literature to composite floors (0.4% to 2.5%, Bachmann *et al.* 1995). As can be noted in Table 3 damping factors are larger for higher vibration modes showing that damping is proportional to both modal mass and stiffness of the structure.

Table 3 presents results of these tests and a correlation with the results from a 3D finite element model of the structure. The finite element model was built with the slab represented by 879 four-node shell elements based on Mindlin-Reissner thick plate formulation, considering membrane, shear and plate-bending behavior. The beams and columns are represented by 321 two-node frame elements with six degrees of freedom at each node. In the 3D numerical modeling it was taken into account the effect of the flexibility of the steel columns on the overall bending stiffness of the composite floor. The eccentricity between beams and slabs was also considered, resulting in a very refined finite element mesh.

The numerical x experimental correlation was also made by means of direct correlation of vibration mode shapes (Fig. 4) and frequency spectra as shown in Fig. 5 for heel drops forces at the center of panel 03 applied by the same person who performed heel drops tests in the laboratory. Based on these results in terms of the first three vibration modes one may state that the numerical model is a good approximation of the actual structure.

4. Short description of the system of multiple controllers

The MSDA passive control system designed to attenuate the human induced vibrations in the floor structure is

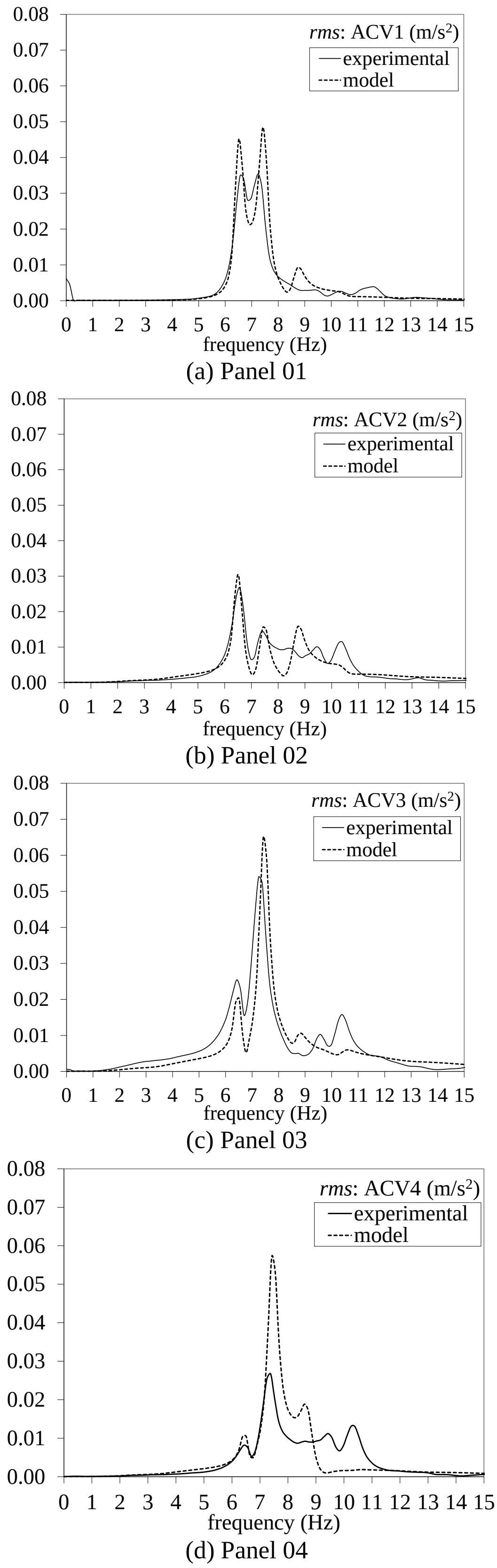


Fig. 5 Experimental *versus* numerical frequency spectra resulting from heel drops at panel 03

composed of sixteen units, each two pairs placed at the center of each one of the four slab panels (Fig. 6). The MSDA devices were designed considering the need of a fast and easy installation and fine adjustment in frequency due to the close natural frequencies of the continuous slab panels. Each SDA is composed by a cantilevered flat steel bar having lumped masses composed of bound steel plates bolted fasten together to the steel bar at certain sections. It follows the same design conception of SDAs which were successfully applied in the past to attenuate vibration in isolated reinforced concrete slab floors (Battista 2001).

The optimized design of the MSDA was carried out with the aid of a numerical approach based on linear and non-linear programing techniques (Ignizio 1976, 1982) combined with dynamic coupling (Graig and Bampton 1968) within the framework of the finite element modeling (Battista and Magluta 1994, Magluta 1993, Battista and Pfeil 2010). The input data to the subsidiary dynamic control system of multiple SDA's are given in terms of ranges of values for the ratios between SDA's masses damping factors and frequencies and the structures modal parameters counterparts. The given structures modal damping factors are those measured by vibration tests. Practical ranges for masses and frequencies are, respectively, 0.5% to 5% and 85.0% to 95.0% (considering the structure without finishing, it will became closer to 100% for the finished structure).

Fig. 7(a) shows four SDAs installed at the bottom of one slab panel and Fig. 7(b) shows a schematics of the mechanical device. Each SDA unit has a dynamic behavior of a cantilevered beam with a lumped mass located at a certain point along its length. It can be calibrated in frequency simply by sliding the lumped mass along the flat steel bar length. The damping of the SDAs has to be only slightly greater than the damping factor related to the vibration mode whose amplitudes are to be attenuated. In the present case it is mainly due to the bolted connection of the double cantilevered flat bar to the central steel hub fixed to the lower slab surface. The values of the damping ratio of each SDA unit are close to 2%. The mass of each SDA unit is 25 kg making up 100 kg for each slab panel and totalizing 400 kg. The SDA masses are of ASTM A36 steel plates (250 mm x 125 mm x 25 mm) and the flat bars are of ASTM A682 high strength steel.

The sixteen SDAs that compose the MSDA system were calibrated to attenuate the first three vibration modes of the floor structure, which were observed during the tests be the most excited by human walking forces. It is important to observe that the first three vibration modes involve all the four main slab panels which set in motion all sixteen SDA units. It is noticeable then that the MSDA system actuates in all dominant vibration modes with higher or lower efficiency depending on the ratio between the frequency of the SDA and the frequency of the dominant vibration mode to be attenuated in each slab panel. Table 4 presents the measured frequencies in each slab panel and the calibration frequencies of the SDAs. Table 5 presents the masses of the SDAs, the modal masses of the first three vibration modes of the floor structure and the ratio between them. It can be observed that the modal masses associated with the 2nd and

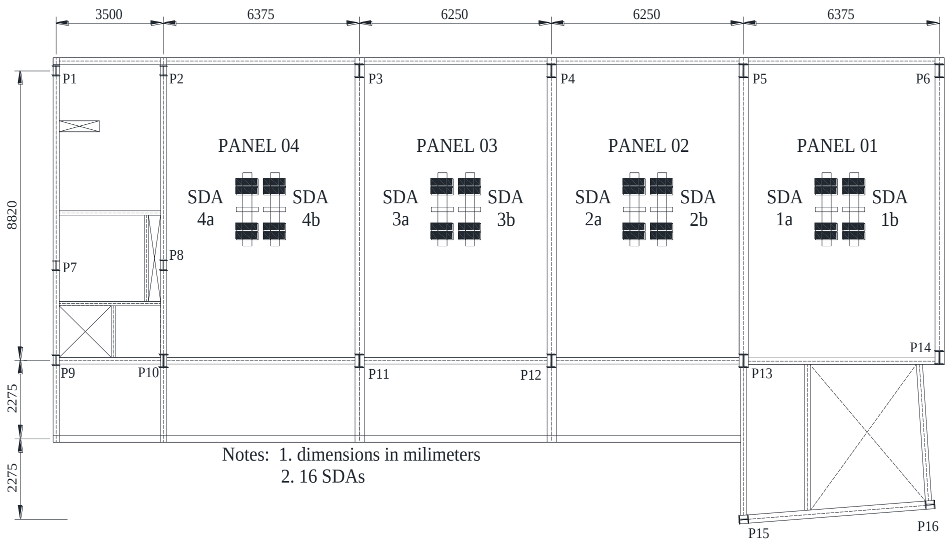
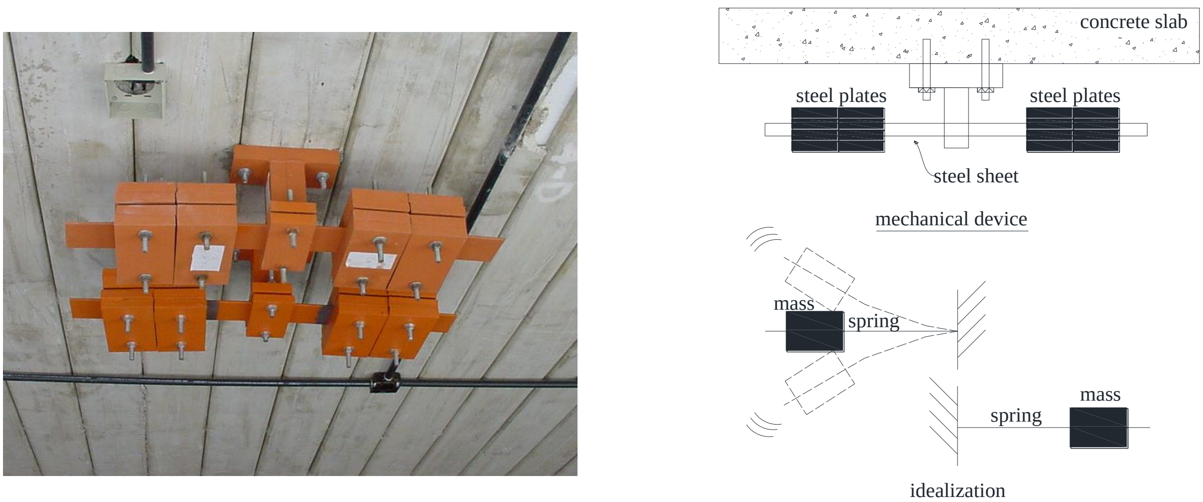


Fig. 6 Location and number identification of the SDAs



(a) Four SDAs installed at the bottom of one slab panel (b) Schematics of the mechanical system

Fig. 7 Details of one pair of SDAs unit of the control system of multiple synchronized dynamic attenuators (MSDA)

Table 4 Measured frequencies of the SDA units and of the floor panels (see Fig. 6)

Slab panel	SDAs	SDAs frequencies f_{SDA} (Hz)			Most excited floor vibration modes	Floor structure frequencies f_n (Hz)	f_{SDA}/f_n (%)
		Left	Right	Average			
1	1a	6.52	6.52	6.52	1	7.38	88.3
	1b	7.00	7.00	7.00	1	7.38	94.9
2	2a	8.48	8.28	8.38	3	8.48	98.8
	2b	5.92	5.92	5.92	1	6.56	90.2
3	3a	6.86	6.92	6.89	2	7.38	93.4
	3b	6.56	6.80	6.68	2	7.38	90.5
4	4a	7.00	7.28	7.14	3	7.38	96.7
	4b	7.52	7.52	7.52	3	8.48	88.7

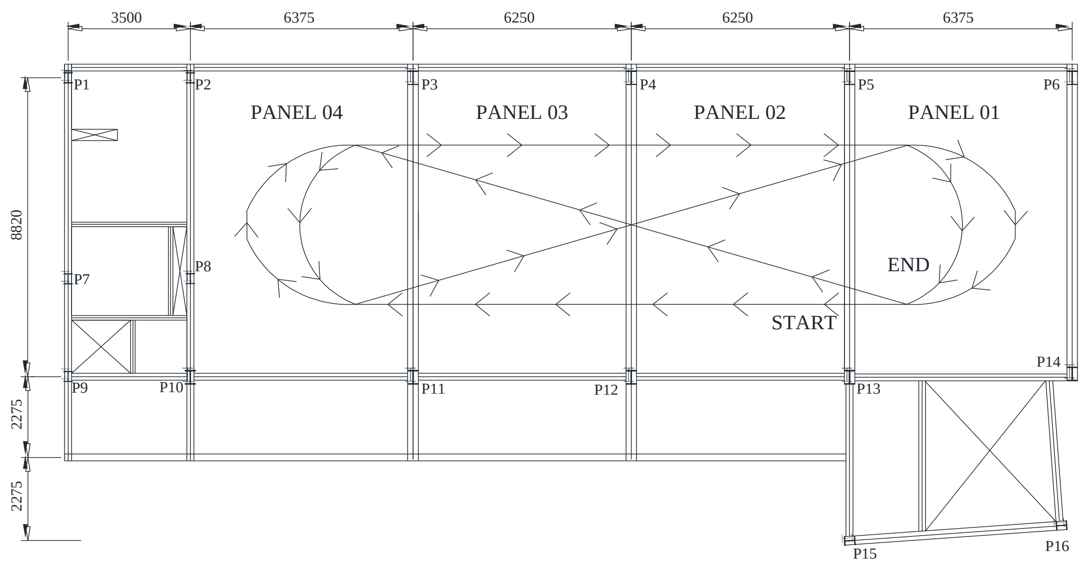


Fig. 8 Steps trajectory followed by people walking during tests

Table 5 Ratios between the SDA masses and the modal masses of the first three vibration modes of the floor structure

Mode number	Structure´s modal masses m_m (kg)	SDAs masses M_{SDA} (kg)	M_{SDA}/m_m (%)
1	6,435	400	6.2
2	8,861	400	4.5
3	7,977	400	5.0

3rd vibration modes are greater than the first mode's modal mass. This feature is commonly found in composite floor structures composed by multiple slab panels. In the structure focused herein the lateral balconies (see Fig. 6) are mobilized together with the slab panels 03 and 04 in the 2nd and 3rd vibration modes increasing their modal masses, particularly of the 2nd vibration mode.

5. Human walking tests and simulations

Vibrations induced by human walking in the composite floor structures dealt with herein were first reported by workers just after the inner divisory walls were removed during the refurbishing of the building. In order to evaluate the dynamic responses of the structure under human walking excitations, a series of walking tests were performed and correlated to computer simulations of the dynamic interaction of people walking and the floor structure.

5.1 Human walking tests

The vertical accelerations of the floor structure induced by three workers with different weights (90 kg, 70 kg and 110 kg) walking on the continuous floor slabs were measured at the center of each of the four main slab panels. In each test campaign the workers walked during three minutes one after the other following the trajectory showed in Fig. 8 passing by all the four main slab panels. Their walking steps frequencies in the tests were neither rhythmically guided nor stimulated by any device. The variable step frequencies during the tests were estimated to be in the range of 1.7 Hz to 2.1 Hz.

5.2 Human walking simulations

Computer simulations were also performed to get the dynamic responses in terms of the vertical accelerations at the center of the slab panels induced by three people with the same weights of the workers walking along a trajectory similar to that showed in Fig. 8. Some parameters were approximated to be used in simulations such as the step frequencies and the walking trajectories of the persons. The human walking force was approximated as a Fourier series (Bachmann *et al.* 1995 and many others).

$$F(t) = G + \sum_{i=1}^{nh} G\alpha_i \sin\left(2\pi i f_w t - \phi_i\right) \quad (1)$$

where $F(t)$ is the human walking force acting on the floor surface; t is the time; G is the person weight; i is the i^{th} harmonic of fundamental walking frequency; nh is the required number of harmonic terms to well simulate the walking force; α_i is the dynamic force coefficient of the i^{th} harmonic term of Fourier series; f_w is the walking step frequency; ϕ_i is the phase angle between the i^{th} and the first harmonic of the walking force.

The values of step frequencies were randomly sorted step by step in the range of 1.7 to 2.1Hz that was an attempt to simulate the human walking tests. It was used four harmonics to describe the human walking force. The values of the dynamic force coefficients of the Fourier series are to be taken from polynomial functions which approximate the curves obtained by Rainer *et al.* (1988). The phase angles are $\phi_1 = 0$, $\phi_2 = \pi/2$, $\phi_3 = \pi$ and $\phi_4 = 3\pi/2$.

5.3 Theoretical x experimental correlation

Figs. 9 present for each one of the four main slab panels the correlation between simulated numerical results and experimental results in terms of the dynamic response amplitudes in frequency domain at the center of the slab panels. Despite of the uncertainties related to the correct sequence of steps, their associated frequencies and lengths, it can be noted in the frequency spectra showed in Figs. 9 the good agreement between theoretical and experimental results. It is worthwhile observing that the second mode (7.38 Hz) – a dominant mode in the motion of the first, third and fourth panels – was the most excited mode in experimental tests as well as in numerical simulations. To get in perfect resonance with this vibration mode, people should be walking with a fundamental step frequency equal to 1.85 Hz whose fourth harmonic frequency is 7.40 Hz. It is noticeable that 1.85 Hz is very close to the average value (1.90 Hz) of the frequency range (1.70 Hz to 2.10 Hz) of the variable step frequencies estimated from the tests.

6. Evaluation of MSDA performance

6.1 Experimental evaluation of MSDA performance

The evaluation of the effectiveness of the MSDA control system were carried out by means of experimental human walking tests of the composite floor structure with and without the controllers (section 5.1). The comparison between the controlled and the uncontrolled structure can be made by observing the results in terms of the frequency spectra of the vertical acceleration time responses at the center of the slab panels (Figs. 10). In the referred figures it is indicated the percentage reductions of modal amplitudes of vibrations in the controlled structure with respect to the uncontrolled one. It should be pointed out that the uncontrolled and controlled tests are not exactly the same, considering that it is very difficult to anyone to walk at the same pace in two different tests. Nevertheless, the tests were as similar as possible, especially in terms of average step frequency. The reduction in amplitudes varied from 38% to 80% in the dominant modes (6.58 Hz to 8.48 Hz). The greater reductions were obtained in panels 01 and 03 associated with the second vibration mode (7.38 Hz) of the original structure. It can be also noted that at the same panels the vibration amplitudes of the third vibration mode (8.48 Hz) was increased. This may have occurred because the SDAs were tuned to 6.52 Hz and 7.00 Hz, which is closer to the first and second vibration modes than to the third one. Despite of that the overall maximum vibration amplitudes were substantially reduced. An even greater reduction could be achieved by calibrating some few SDA units closer to the frequency of the third mode in the panel most excited in this vibration mode.

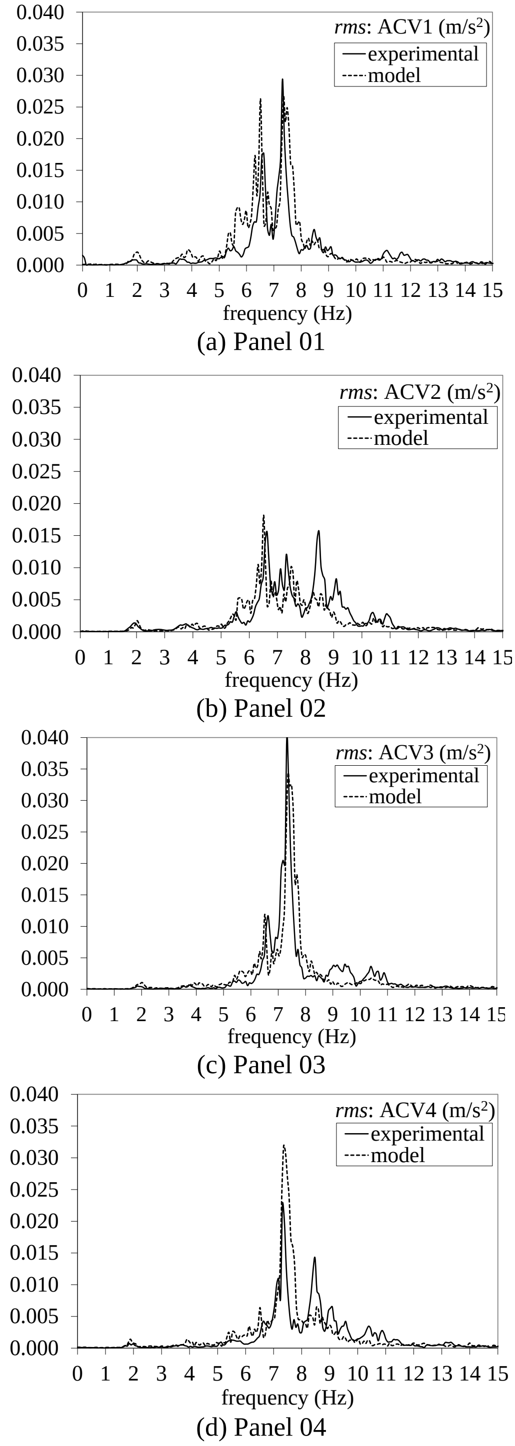
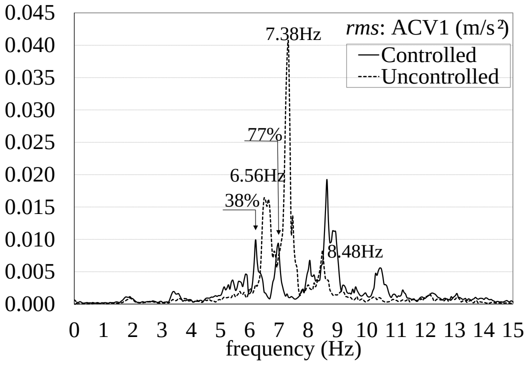
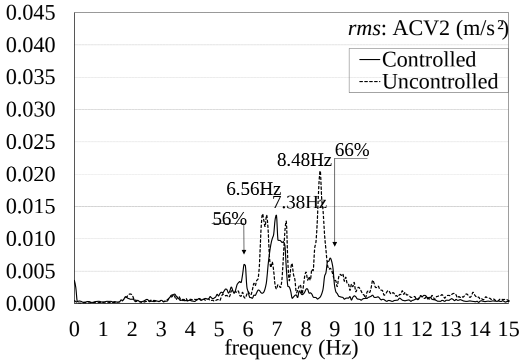


Fig. 9 Comparison between experimental and theoretical frequency spectra of acceleration responses induced by human walking

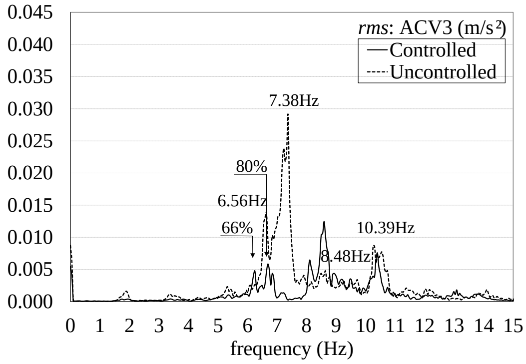
Table 6 presents the *rms* values of vertical acceleration at the center of the slab panels obtained during human walking tests performed on the uncontrolled and controlled structure. Even considering the already mentioned uncertainties involved in this tests it is noticeable the effectiveness of the MSDA control system to attenuate vibrations induced by human walking activity. The average reduction in terms of *rms* acceleration was 42.9%. This



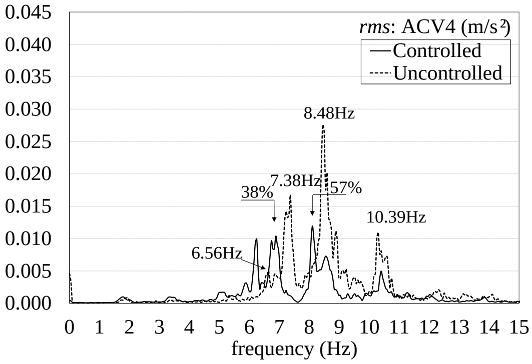
(a) Panel 01



(b) Panel 02



(c) Panel 03



(d) Panel 04

Fig. 10 Comparison of controlled and uncontrolled acceleration amplitudes at the center of the four main slab panels

attenuation would be maximized in a perfect resonance condition, simultaneously for all the closed spaced vibration modes. But, this is not feasible in a multipanel floor structure where higher and lower vibration amplitudes depend on the closeness of any of the multiple harmonic frequencies of the human steps to the natural vibration frequencies of the composite multipanel floor structure.

Fig. 11 presents a collection of points related to the experimental *rms* values of vertical acceleration at the center of the slab panels measured during human walking tests performed on the uncontrolled and controlled structure. This figure also shows the two lines referred to the acceleration limits recommended by the ISO-2631-2 (1989). It can be noted in Fig. 11 that the acceleration amplitudes at the center of all uncontrolled panels are higher than the recommended value for conference rooms (40 mm/s²), while for controlled panels this is the case only for panel 01. With regard to the acceleration limit for offices (20 mm/s²) all four slab panels displayed acceleration amplitudes higher than the recommended one.

6.2 Theoretical evaluation of MSDA performance

The motion of the floor structure provided with a MSDA control system attached to it is governed by a system of coupled differential equations. The modal superposition method was applied and the pair of equations for each mode of interest was solved by means of the Runge-Kutta method.

Table 6 Measured *rms* values of the vertical accelerations at the center of the slab panels

Slab panel	Uncontrolled structure (*rms* mm/s²)	Controlled structure (*rms* mm/s²)	Reduction (%)
1	68.5	47.8	30.2
2	53.2	32.8	38.3
3	62.0	29.6	52.3
4	61.2	30.1	50.8
Average	61.2	35.1	42.9

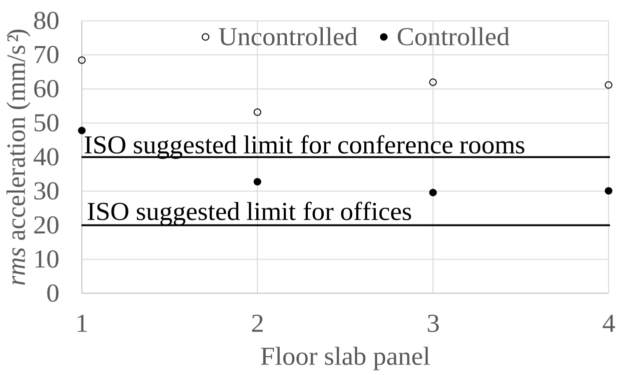


Fig. 11 Measured *rms* values of the vertical accelerations at the center of the slab panels in comparison with ISO 2631-2 (1989) recommendations

$$M\ddot{x}+Kx+k_a(x-x_a)+C\dot{x}+c_a(\dot{x}-\dot{x}_a)=F \qquad \text{(2a)}$$

$$m_a\ddot{x}_a+c_a(\dot{x}_a-\dot{x})+k_a(x_a-x)=0 \qquad \text{(2b)}$$

In Eqs. (2) $x_a, \dot{x}_a, \ddot{x}_a$ are the SDA's vertical displacement, velocity and acceleration, $x, \dot{x}, \ddot{x}$ are the structure´s modal amplitudes of vertical displacement, velocity and acceleration, *M*, *K* and *C* are the modal mass, stiffness and damping of the structure, m_a, k_a and c_a are the mass, stiffness and damping of the SDA and *F*(*t*) is the dynamic modal force.

The same human walking simulations described in sub Section 5.2 were also applied to the controlled structure. A straightforward comparison between the dynamic responses of the controlled and the uncontrolled structures can be made by observing the results in terms of the frequency spectra of the vertical accelerations at the center of the slab panels (Figs. 12). These figures indicate the percentage of reductions in response amplitudes obtained for the dominant vibration mode. The reduction in amplitudes varied from 16% to 75% in the dominant modes (6.51 Hz to 8.71 Hz). The greater reduction were obtained in panels 03 and 04 associated with the second vibration mode (7.46 Hz) of the original uncontrolled structure. Conversely, it can be noted in the numerical model that the lower reductions are associated to the third vibration mode in the frequency 8.71 Hz. Nevertheless, the overall maximum vibration amplitudes are in any case substantially reduced.

Table 7 summarizes for each slab panel the theoretical results obtained in terms of *rms* acceleration for the numerical simulations of human walking load applied to the original uncontrolled structure and to the controlled structure with the MSDA system. Considering the uncertainties involved in the numerical modeling one can still note the effectiveness of the control system in attenuate the vibrations induced by human walking. As it can be seen in the last column of Table 7 the average reduction in terms of *rms* acceleration was 35.4%, somewhat close to that obtained in experimental tests (42.9%). This attenuation would be greater in resonance condition, as explained before in Section 4.

Fig. 13 presents a collection of points related to the theoretical *rms* values of vertical acceleration at the center of the slab panels obtained with numerical simulations of human walking on the uncontrolled and controlled structure. This figure also shows the two lines referred to the acceleration limits recommended by the ISO-2631-2 (1989). It can be noted in Fig. 13 that the amplitudes of accelerations of all uncontrolled panels are higher than the recommended value for conference rooms (40 mm/s²), while for controlled panels this is the case only for panel 01. With regard to the acceleration limit for offices (20 mm/s²) all four slab panels displayed amplitudes higher than the recommended one, as it was also found with the experimental measurements.

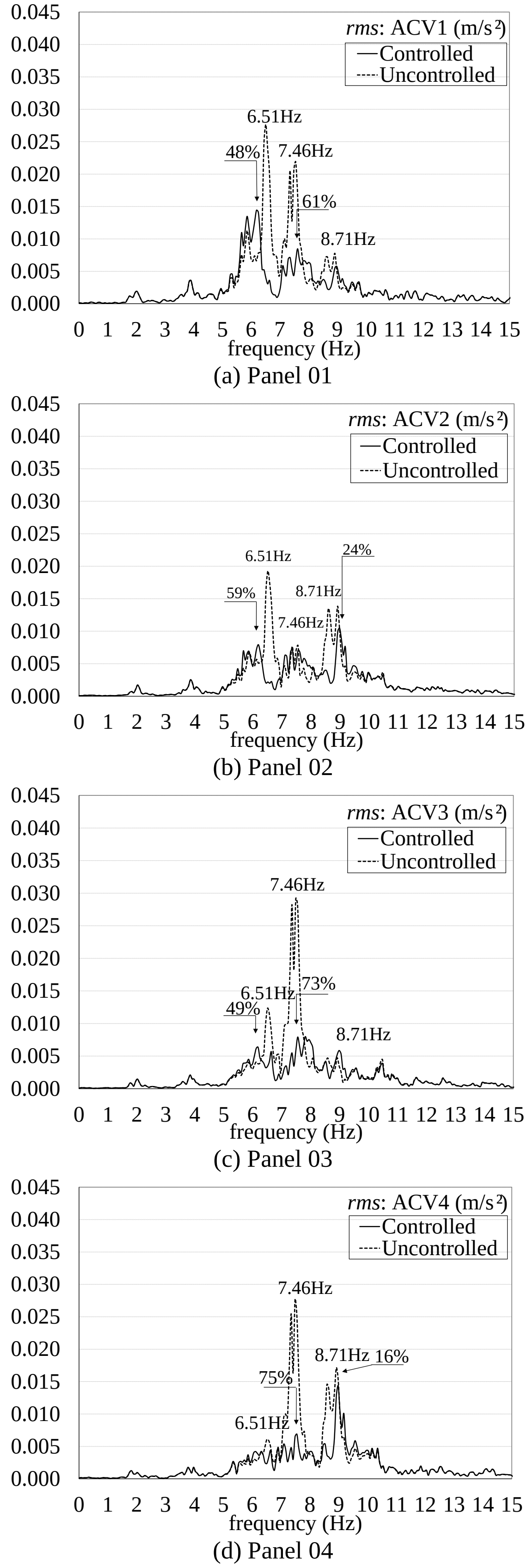


Fig. 12 Theoretical frequency responses of the four main slab panels of the uncontrolled and controlled structure subjected to human walking loading

Table 7 *Rms* values of vertical accelerations at the center of the slab panels obtained from numerical simulations

Slab panel	Uncontrolled structure (*rms* mm/s²)	Controlled structure (*rms* mm/s²)	Reduction (%)
1	70.1	48.3	31.1
2	49.3	37.5	23.9
3	58.9	33.5	43.1
4	58.3	33.0	43.4
Average	59.2	38.1	35.4

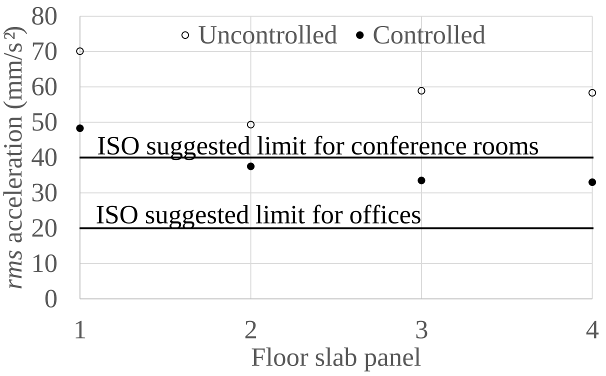


Fig. 13 Theoretical *rms* values of the vertical accelerations at the center of the slab panels in comparison with ISO 2631-2 (1989) recommendations

9. Conclusions

Mathematical models for human walking forces acting on refined 3D structural models were validated by dynamic monitoring of an actual composite floor structure and then used to design simple mechanical and easy frequency tuning multiple synchronized dynamic attenuators (MSDA) of the response amplitudes of the multipanel closed frequency space vibration modes of the floor structure.

The successful performance of the passive control system is herein demonstrated through comparisons of experimental measurements performed on the uncontrolled and controlled structure of an actual composite floor subjected to the dynamic walking loads produced by three heavy weight workers.

On can state that an optimal design of a MSDA control system can be achieved by means of mathematical-numerical models of both uncontrolled and controlled structural system. The developed mathematical-numerical models were fully validated by experimental measurements taken from both uncontrolled and controlled floor structure subjected to human walking loads.

Both theoretical and experimental values of acceleration amplitudes at the center of the four main floor slab panels decreased significantly in the controlled structure with respect to the uncontrolled one. Reduction in *rms* acceleration amplitudes reached up to 80% in frequency response domain and up to 52% in time response domain. Human comfort evaluation made accordingly to the ISO 2631-2 (1989) recommendations showed that: (i) the controlled *rms* measured acceleration values are quite satisfactory for people in conference rooms and not far above the recommended limit value regarding people in office rooms (except for panel 01). But the major feedback on human vibration perception and uneasiness came from the construction workers and the engineers who felt much more confidence in letting the building free for occupancy. The installed MSDA control system was considered by them a more efficient and cheap solution than increasing the thickness of the slab panels as it was attempted in another story of the same building.

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