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SEISMIC AND VIBRATION PROTECTION OF THE STATUE "PIETA' RONDANINI" BY MICHELANGELO

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Abstract

The paper describes the innovative system that protects the statue "Pietà Rondanini" by Michelangelo Buonarroti from both earthquake and traffic-induced vibrations. The marble statue was the last incomplete job by Michelangelo Buonarroti (1475-1564), housed in the Sforza Castle in Milan. This statue, as many artifacts in our museums, is facing problems related to traffic induced vibrations in cities that are becoming more and more crowded. Italy is a well known seismic-prone country, so this adds the need to protect these artifacts from earthquakes. The relocation of the statue to a new room of the Castle, would have exposed the masterpice to an important vibration dose produced by the underground trains running underneath. Therefore it was decided to develop a base able to protect the statue from traffic vibrations and earthquake, avoiding any possible marble damage.

The solution consisted in a special base, equipped with both a seismic isolation device (guides with recirculating steel balls which converts a mechanical linear motion into a rolling motion) and rubber bearings, to reduce the effects of traffic induced vibrations. A steel cylinder has been mounted on the top plate of the isolation base, which hosts an internal safety retaining system to preserve the statue from possible rocking. This system allows the oscillation of the statue when the horizontal actions are above a predetermined threshold. In the case of displacements greater than those anticipated in the design, a stopping system equipped with fuse dissipation devices ensures a base movement limit, due to a progressive energy dissipation. These systems have produced a redundant protection against seismic action and any other exceptional events, in order to ensure a safety level fit for the high "cultural" value of the statue within the Italian and the world heritage. The base isolation system was tested on a shaking table up to twice the code seismic action to verify the protection against the earthquake. The capability to filter lower vibrations produced by traffic was also tested. Shaking table tests were carried out on a copy of the real statue made of marble as the original. Tests were performed on a multi axes shaking table and the tests were: sweep sine tests, tri-axial seismic tests, uniaxial vibration tests, manual impacts. The tests show the effectivness of the designed innovative system that protects the statue "Pietà Rondanini" by Michelangelo Buonarroti from both earthquake and traffic-induced vibrations. The system implements a solution that shifts the natural frequencies of the structure in frequency ranges where the excitation due to underground traffic and earthquakes is the lowest.

Keywords: marble statue, traffic vibration, earthquake protection, cultural heritage, base isolation

1. Introduction

This work refers to the last incomplete marble statue by Michelangelo Buonarroti (1475-1564), that he worked on from the 1550s until the last days of his life, in 1564. The masterpiece is housed in the Sforza Castle in Milan, built in the 15th century by Francesco Sforza, Duke of Milan, renovated and enlarged, in the 16th and 17th centuries. The unfinished sculpture of the artist, folds the body of the Virgin into that of the dead Christ.

Our cities are becoming more and more crowded and the problem of traffic vibrations on artifacts is becoming critical. Many large cities, home to important museums are located in seismic-prone countries, so this adds the need to protect these artifacts from earthquakes. This project was originated after the Municipality of Milan decided to relocate the “Pietà Rondanini” marble statue in a new room, specially created inside the Castello Sforzesco in Milan. In the new location, if properly mitigating actions had not been taken, the statue would have been subjected to an important vibration dose produced by the underground trains running right underneath. Therefore it was decided to develop a base able to protect the statue from vibrations, avoiding any possible marble damage due to running trains continuous excitation. An adequate protection from earthquake was also required. This project aims to preserve a marble statue, world heritage, from earthquakes and traffic vibrations, simultaneously: this is something happening very seldom.

The knowledge of the eventual damage of natural marble subject to continuous vibrations is very limited, so we have opted for a system that can limit the vibrations on the statue at a value deemed safe.

Several innovative solutions and techniques were introduced:

- linear motion guides isolation devices were used for seismic isolation;
- rubber bearing isolators were used for traffic vibration;
- new dissipative fuse system to prevent overturning of the statue were designed and built;
- special safety devices made up of composite fibers were bonded to the statue.

The first step consisted in defining the correct input; this was achieved by measuring and analyzing the vibrations induced by the underground trains and going to the national standards to get the site seismic risk. The project of the protection system has been matched to the architectural design of the support, which was developed to place the statue at a height of approximately 1 meter from the floor. As a result, the base isolated support allows a significant reduction of the acceleration reaching the statue, due the train pass-by traffic; the good performance of the system was confirmed by the vibrational measurements carried out after the statue was placed in its final position. The adopted design is characterized by the innovative solutions used in order to ensure, for the first time, the simultaneous protection of a marble statue from both earthquakes and traffic-induced vibrations.

This project is considered a pilot project by the Italian authorities dealing with the protection of artistic and cultural heritage, and it has been followed with great interest, with the intention to replicate the obtained results and apply these benefits to other parts of the immense Italian and world heritage.

The innovation consists in having designed a system that can protect the statue from vibrations of different nature, with different dynamic features and effects.

2. Analysis of traffic vibrations

At the very beginning the main concern was related to traffic induced vibration (here also referred to as ambient vibrations): the new museum was in a fascinating room, unfortunately close to four subway tracks. Though being both vibrations, tremors from earthquakes and trains are quite different. Ambient vibrations are almost continuous, while the earthquake is random, vibrations induced by traffic are much lower than those originated by an earthquake and also the frequency band is different: 20-100 Hz for the ambient vibrations, 0.5-20 for the earthquake. In the end, while seismic mitigation devices usually work in the horizontal plane, ambient vibration ones may be required to work also in the vertical direction.

A preliminary survey of the ambient vibrations was screened by means of a monitoring system measuring both the old site and the new one (Fig. 1), the main problem being the almost complete lack of standards or reference values to properly fix a "safety level" [1]. The only limits provided by national and international standards refer to buildings, and no literature is available about a continuous vibration (Fig. 2) dose for marble statues.

Fig. 1 Dynamic survey of the statue and the new site

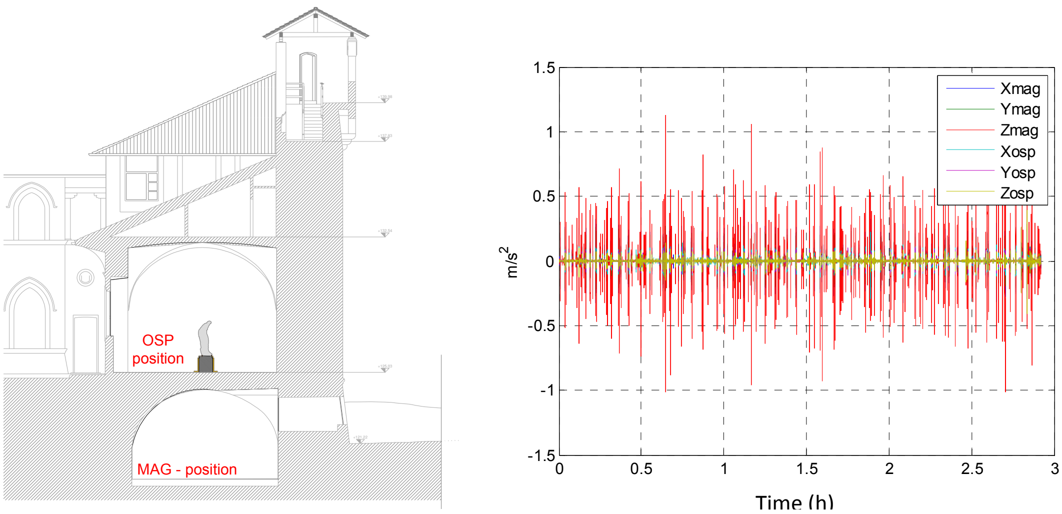


Fig. 2 Vertical section of the building and example of recorded acceleration

The usual approach for this kind of input consists in the creation of a 1 degree of freedom system exhibiting a natural frequency well below the lowest input frequency: this requires a relatively low stiffness, a high mass and a controlled damping: this in turn brings to rather high static deflection, with the requirement to stabilize the whole system, avoiding a static pitch which cannot be tolerated (this means a good knowledge of the mass distribution).

3. Seismic risk and design of protection system

Milano isn't located in a high seismic risk area in Italy, but the recent earthquake in the region Emilia, in 2012, affected an area considered with low risk, not far from the town. The 2012 earthquake hit mainly historical and industrial buildings with the difference that the first type cannot be replaceable. In this area historic buildings have showed a high vulnerability, due to the lack of any seismic countermeasures related to long earthquake return periods. In the same region an earthquake of similar intensity has been reported about 500 years ago. At present the seismic risk level is still considered low in this area, but an earthquake is considered as a possible event.

The seismic protection of statues and similar objects, that can't be exposed to high seismic stresses, can be achieved through seismic isolation, being this the most common approach [2]. The seismic isolation is realized by inserting devices that allows the relative displacement between the statue and the ground, with the goal to decuple the ground motion from that of the statue, which remains still [3].

An isolated statue has a natural period that is far from the maximum spectral acceleration in the seismic response spectra expected at site (Fig. 3).

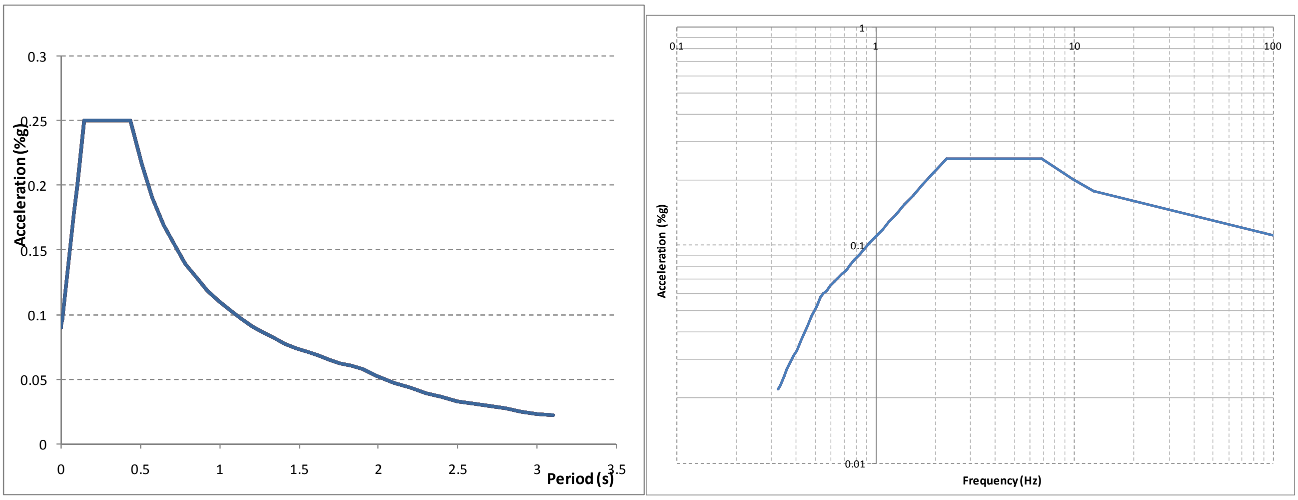


Fig. 3 Acceleration site spectra (Tr=2475 yrs), acceleration vs period (on the left); acceleration vs frequency (on the right)

For aesthetic reasons the Pieta Rondanini statue had to be placed on a base higher than the ground level, therefore increasing its seismic vulnerability. According to the interior designer the base of the statue has a cylindrical shape made of steel. The architect in charge of the setting up of the museum placed the on the steel support, so that the center of mass of the statue has 53 cm eccentricity on the support itself, to maintain the center of mass aligned with the geometrical centre. The weight of the statue is 780 kg and the weight of the steel support is 1700 kg, hence the steel support was positioned with an eccentricity of 16mm on the base isolation system to eliminate eccentricity between the two systems and load all the devices in the same way, preventing from the already mentioned risk of static rotation. All the devices designed for vibrations and seismic isolation were inserted into the steel cylinder and below it.

Looking at devices usually designed for seismic isolation of buildings, those most used are rubber bearings and friction pendulum bearings. Rubber bearings have a stiffness that, related to the isolated mass, leads to a period increasing that reduces seismic forces for buildings but not for relatively light objects like statues. On the opposite friction pendulum bearings have a frequency that is not dependant from mass but their friction is not negligible [4]. Seismic protection of statues poses the problem that devices available for building isolation are not adequate for this artifacts [5].

To find devices that can be used for statues, the reference activity has been the seismic protection of electronic devices, that are light and sensitive to accelerations. Sliding devices equipped with linear rolling motion have been considered suitable for this purpose, due to their low friction. Available devices are usually completed by springs to add an elastic restraint and dampers to reduce displacements. With this configuration is possible to change each parameter that influencing the dynamic behaviour of the isolated system for a proper tuning the device performances. For the Pietà Rondanini TGS devices made from THK company has been chosen.

Considering the elevation of the center of mass of the statue, a preliminary analysis was performed to check that the base isolation system activation without statue overturning. The amplification due to elevated position of the statue was calculated with the equations provided by the Italian seismic code for parts and components. Acceleration was amplified 4 times, even under the most unfavorable condition, when the statue has same vibration period of the isolation system. Since the isolation system activates at a=0,017g (as specified by the manufacturer), the lateral load on the statue is 0,133 kN, which is below the overturning force of 0,765 kN, even if amplified by the factor of 4.

A second insulation stage was added to the seismic part, to limit traffic induced vibrations; this was made up of rubber elements with relative low vertical stiffness. To tune the statue-spring vertical frequency, the mass of the base has been modified, filling the steel cylinder with sand. The base vertical frequency has been changed to get out of the traffic induced frequency band.

The whole isolation system is made of linear rolling motion with a steel slab on top supporting the rubber bearings; on top of these there is the steel base of the statue.

The system to isolate the statue from the traffic-induced vibrations is made of 5 rubber isolators THK SWCC R-100 and 8 rubber isolators THK SWCC R-065. The properties of such devices are shown in the table 1.

Table 1: Stiffness of rubber isolators

THK SWCC DEVICES			
Device	Number	Horizontal rigidity (N/mm)	Vertical rigidity (N/mm)
R-65	8	59	371
R-100	5	320	975
Total		2072	7843

Considering the cultural and economical value of Pieta Rondanini, the vibration protection system has been equipped with other devices assure a damage risk reduction in case the isolation system doesn't work properly. To ensure an adequate robustness, other devices are used to mitigate events leading to uncontrolled displacements and of lack of sliding. Dissipative end stop devices have been used to limit the maximum displacement of the linear rolling device motion. These elements, made by REGLASS, are used as impact absorber in automotive and army industries and were designed for the force estimated to lead to overturning.

They act as energy absorber at the level of the horizontal force before that this can cause dangerous actions to the statue. The dissipation effect works with a plastic behaviour for a displacement of about 2 cm, and after this it works as a rigid end stop.

Due to the shape of Pieta Rondanini that has a centre of gravity at about 0,857 m from the base, a lock device has been placed between the statue and base (Fig. 4). A carbon fiber plate , provided from KIMIA, has been glue with epoxy resin, after protecting the marble. Both elements, the epoxy resin and the carbon fiber device have been tested by means of a loading machine with different marble and protection primers, to check the weakest element of the whole chain.

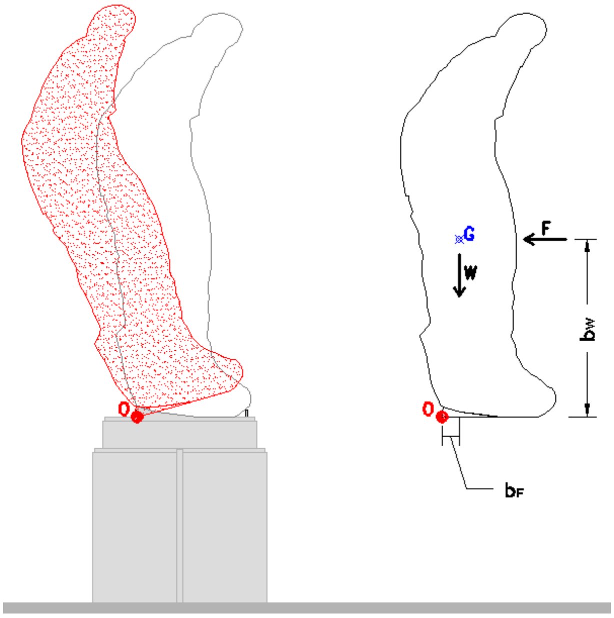
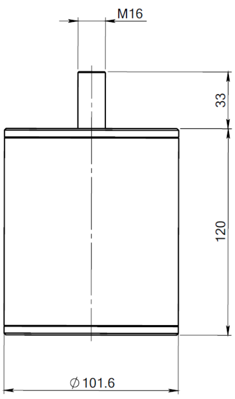


Fig. 4 Scheme for the overturning check (left); positioning of the statue with lock device (right)

The lock at the statue bottom has been equipped with a dissipative device, with an activation force that is proportional to the force which can lead to overturning, and considering the different lever arms, this force was estimated 8,0 kN (Fig. 5). The dissipative device provides a full stroke stop after 15 mm, to allow the statue movement without overturning. This limited displacement was fixed to allow rocking movement of the statue, being this device the last dissipative mechanism reducing seismic stresses on the statue [6].



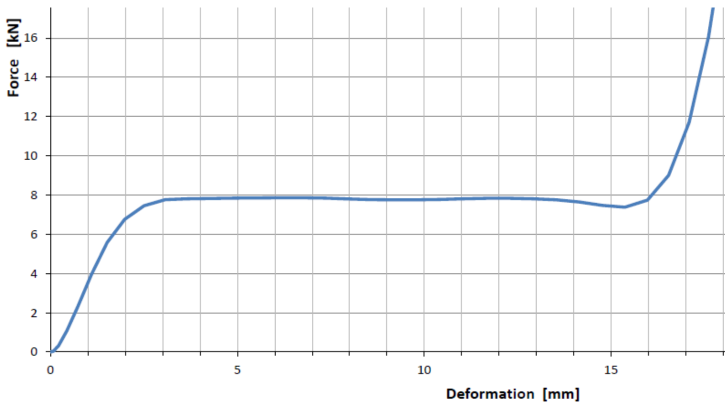


Fig. 5 Dissipative device dimensions and force/displacement curve

By coupling various elements, a seismic protection is obtained, not only ensuring the statue isolation from earthquakes and traffic vibrations, but also capable to mitigate the effects of possible failures of the main isolation system (Fig. 6). The seismic protection system is therefore equipped with a redundancy ensuring a high protection level, proportional to the high value of the statue.

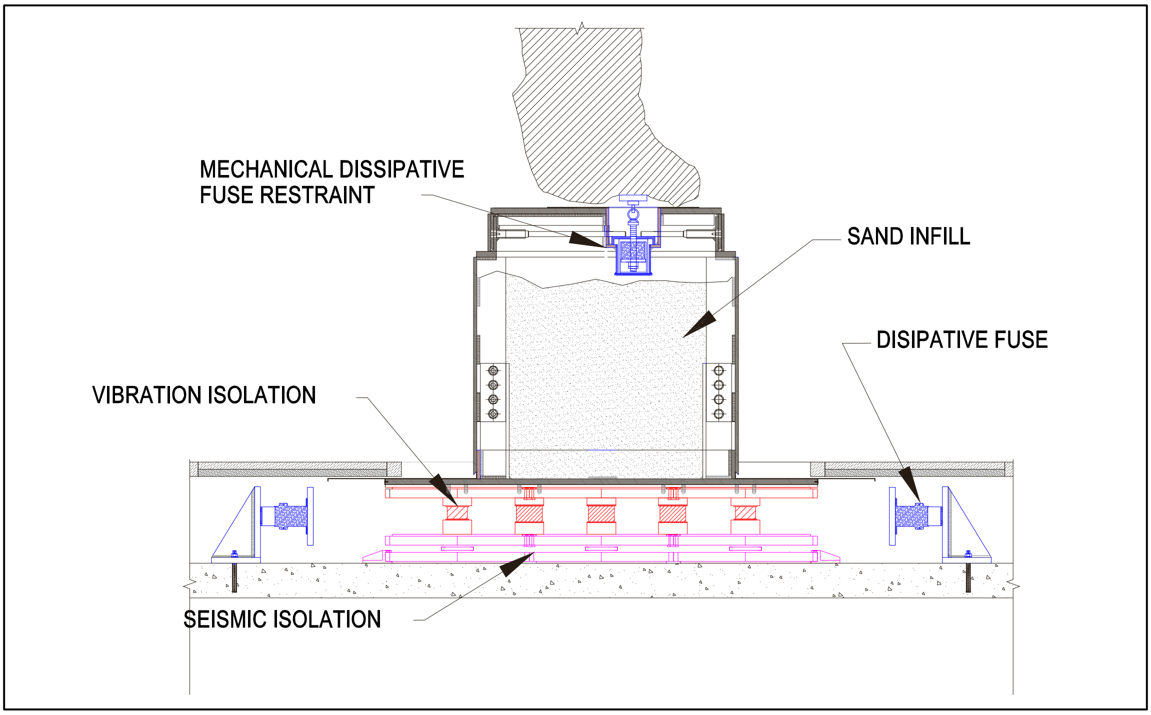


Fig. 6 Vertical section of the base with isolators and dissipative devices

4. Numerical Analyses

Before performing laboratory tests a simulation by means of a specific numerical simulation model was carried out to predict the seismic response of the isolation system.

Several models have been created, with increasing complexity, to analyze the dynamic response of the statue under ideal and real constraint conditions

In the first model the single statue was constrained with elastic low stiffness springs, to separate the rigid body motions from its own modes. The first frequency was found to be 314.9 Hz, and then outside the frequency range excited by the traffic.

To analyze the characteristics of the statue dynamic response located on the steel base and forced by traffic-induced vibrations, a model was prepared with the statue rigidly connected to the steel base, supported by the rubber isolation devices. The modal analysis showed the presence of 6 vibration modes, due to the deformability of the rubber isolation devices, with a frequency between 2.3 Hz and 9.1 Hz. The higher modes describe the dynamics of the base+statue coupled system, and the frequency of mode number 7 is 109.8 Hz (Fig. 7). Numerical analyses results of have shown that there aren't natural frequencies of the system in the range 10 Hz-80 Hz, which represent the range of frequencies excited by traffic.

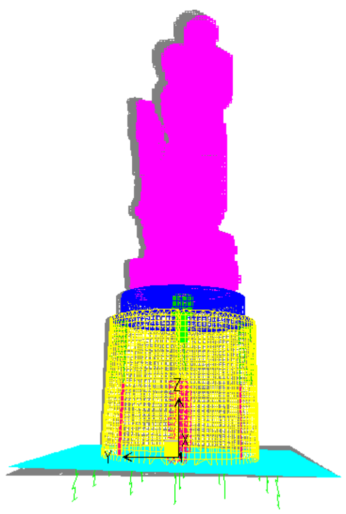
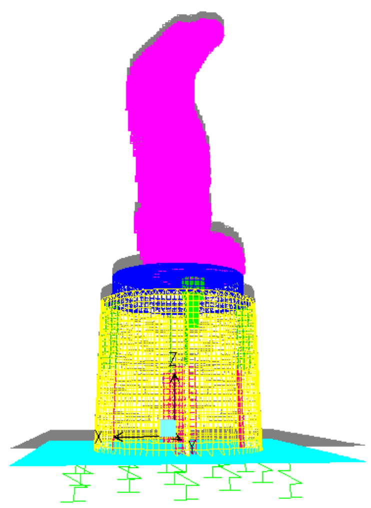
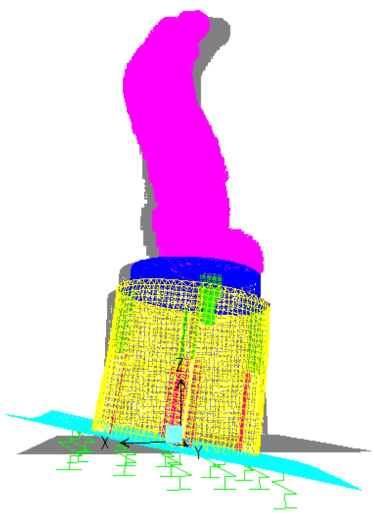
First modal shape f=2.3 Hz	Sixth modal shape f = 9.1 Hz	Seventh modal shape f =109.8 Hz
		

Fig. 7 Main numerical modal shapes and frequencies

Before testing a copy of the statue on the shaking table, some analyses have been performed on a model of the system with the statue resting on the support with a gap element (only compression) and the support connected to the base isolation system with recirculating spheres. This system is non linear, due to both damping and geometrical properties.

The model was subject to several excitation time histories obtained from real records, properly scaled to match the design spectrum. This phase demonstrated the effectiveness of the seismic isolation system in reducing the seismic acceleration of the statue and preventing the statue from overturning.

5. Shaking Table Tests

Shaking table tests, coordinated by the Politecnico di Milano, have been carried out on a copy of the real statue made of the same marble as the original thanks to a 3D survey and to the work of an anthropomorphic robot.

These tests have allowed us to verify and fix some detail aspects of the project and its implementation, as well as to check the performances of the base in realistic vibration conditions.

Tests were performed on a multi axes shaking table for earthquake reproduction in the laboratories of CESI Ricerche Bergamo (Italy). The main features of the shaking table are: 6 degrees of freedom, frequency range 0,1-120 Hz; horizontal and vertical max stroke 20 cm; max horizontal velocity 55 cm/s; max horizontal acceleration 35 m/s^2.

The following tests have been planned and carried out:

- sweep sine tests to study the dynamic behavior of the system with uniaxial excitation along three normal directions X, Y, Z (Z vertical)
- tri-axial seismic tests (5 impulses at increasing levels of 100%, 125%, 150%, 175% and 200% of the code level)
- uniaxial vibration tests "random type", in direction X, Y, Z, 20 minutes each.

- manual impacts applied to the plate above the rubber bearings, and recording of the accelerations.

The tri-axial tests have been performed with synthetic time histories obtained from design spectra at the Collapse prevention limit state (Tr=2475 yrs) (Fig.3). The 3 time histories (with correlation factor < 0.15%) have been applied simultaneously along the 3 directions.

The base and the statue were instrumented with piezoelectric accelerometers (A) and with displacement transducers (D), placed in the positions shown in Fig. 8 (left), according to the main axes shown in the same figure.

A first round of tests was aimed at dynamically characterize the system (statue and base), sweep tests were carried out with maximum acceleration of 0.04 g and a frequency varying from 0.1 to 80 Hz (cross-over for the lowest frequencies, as the displacement limit was reached).

Fig. 8 (right) shows the sweep recording in terms of amplitude and frequency at the top of the statue along the three directions (X, Y, Z).

In order to verify the effectiveness of the base isolation system, the system was subjected to artificial time histories matching the 2475 year spectrum for Milan, applied with increasing intensity. Maximum acceleration on the shaking table was 0,21g in both plan directions, which generated a 0,38g acceleration on top of the statue (Table 2).

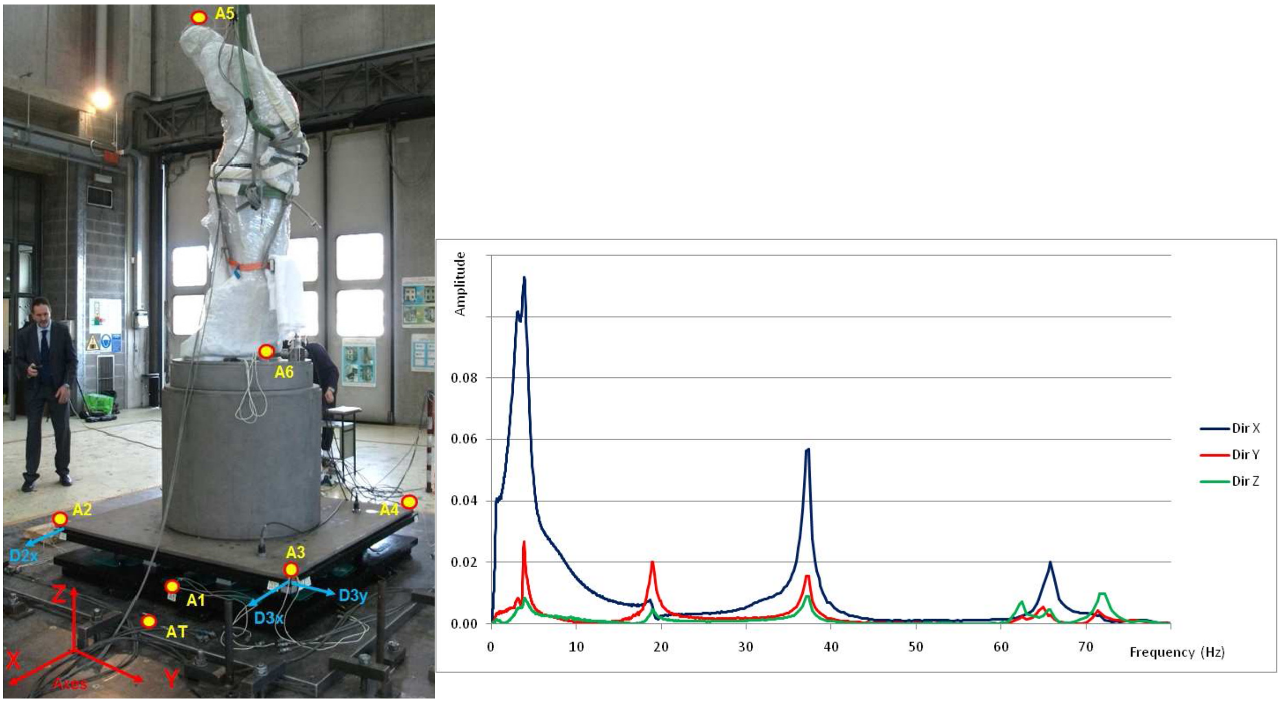


Fig. 8 Position of measuring instruments (left); amplitude of vibrations vs frequency in the 3 directions in position A5(X dir input)

Figure 9 shows the amplitude of the transfer function [7] between the “floor” and different points of the structure (see Fig. 8 for the positions of the points), in the case of sweep excitation applied to the base along the direction X. Similar results were obtained also for the direction Y (horizontal and orthogonal to X).

Point A1 is on the sliding part of the base, but it is below the elastic layer generated with the elastomeric components. This is the reason why, for frequencies above approximately 8Hz, the vibration from the ground reaches point A1 (amplitude of the transfer function close to 1). The other points, on the contrary, belong to the upper part of the base, and are therefore mounted over the elastic layer obtained with the elastomeric components. Thanks to this elastic layer, the vibration at frequencies larger than approximately 6Hz is strongly reduced, as can be deduced by the value of amplitude quickly going towards zero as the excitation frequency increases.

Table 2: Maximum accelerations and displacements recorded during seismic tests

n.		5-1	5-2	5-3	5-4	5-5
Level		100%	125%	150%	175%	200%
Position	Units					
ATx	g	0,12	0,16	0,16	0,22	0,20
ATy	g	0,11	0,14	0,17	0,18	0,21
ATz	g	0,03	0,04	0,06	0,08	0,09
A1x	g	0,08	0,09	0,10	0,13	0,14
A1y	g	0,11	0,13	0,15	0,14	0,16
A1z	g	0,05	0,06	0,08	0,09	0,11
A2x	g	0,05	0,06	0,07	0,06	0,07
A2y	g	0,07	0,08	0,09	0,09	0,10
A2z	g	0,24	0,25	0,30	0,39	0,40
A3x	g	0,06	0,06	0,07	0,06	0,07
A3z	g	0,34	0,39	0,41	0,44	0,51
A4z	g	0,25	0,28	0,36	0,40	0,51
A5x	g	0,16	0,18	0,20	0,22	0,29
A5y	g	0,15	0,29	0,36	0,36	0,38
A5z	g	0,10	0,12	0,17	0,20	0,23
A6x	g	0,08	0,08	0,10	0,11	0,13
A6y	g	0,14	0,16	0,16	0,17	0,21
A6z	g	0,08	0,11	0,16	0,19	0,20
D2x	mm	16,42	20,17	28,02	34,58	38,95
D3x	mm	16,95	21,06	29,00	35,25	39,59
D3y	mm	16,90	35,11	27,30	31,41	55,16
S long	mm	29,87	30,24	40,39	46,22	50,23
S lat	mm	26,83	33,98	41,05	45,71	47,27
S vert	mm	3,16	3,43	3,18	3,74	3,63

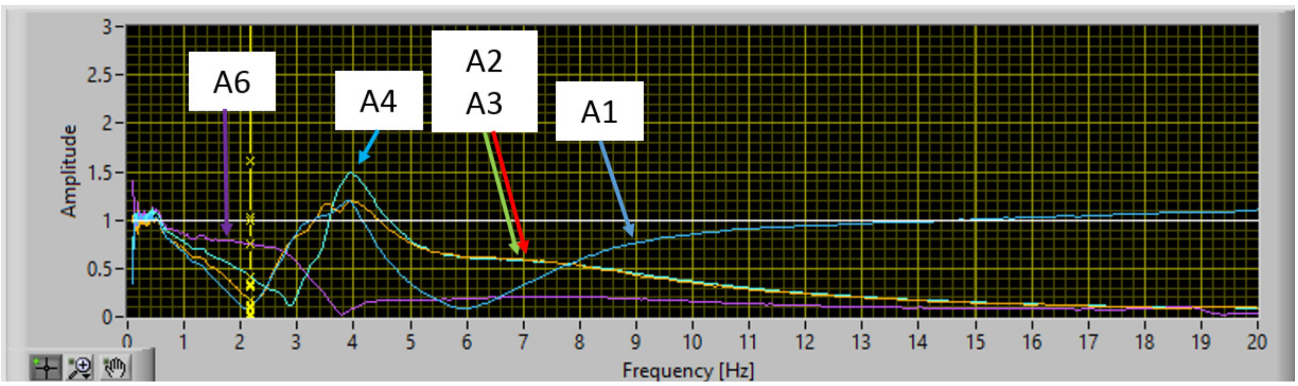


Fig. 9 Transfer function between the floor and different points on the structure in the case of sweep test with excitation direction along X

The frequency range around 4Hz shows a slight amplification of the vibration measured at points A2, A3 and A4, due to a natural frequency of the group composed by the statue and the base. This natural frequency corresponds to a tilt mode around a horizontal axis passing approximately at the height of point A6: in fact the amplitude of the transfer function between A6 and the ground is very close to zero. This mode is very similar to the one predicted by the numerical analysis and shown in Figure 7 on the left.

As can be seen, the base developed to isolate the Pietà Rondanini from the earthquake and from the ambient vibration, shows a significant reduction of the vibration transmitted to the statue.

Fig. 10 shows the transfer function between the floor and different points of the structure in the case of vertical excitation (i.e. along the Z axes). As can be seen, the first natural frequency in the Z direction is around 8.5Hz and it corresponds reasonably well with the mode predicted by the numerical model and shown in Figure 7 in the middle. The amplification of the vibration level due to this vertical mode is quite relevant. This type of amplification cannot be avoided in a passive system like the one developed in this work, however the design of the mass distribution and of the stiffness of the rubbers, allowed tuning this natural frequency in a range where both the excitation due to earthquakes and traffic are low. The overall vibration transmitted to the statue is therefore reduced to the minimum.

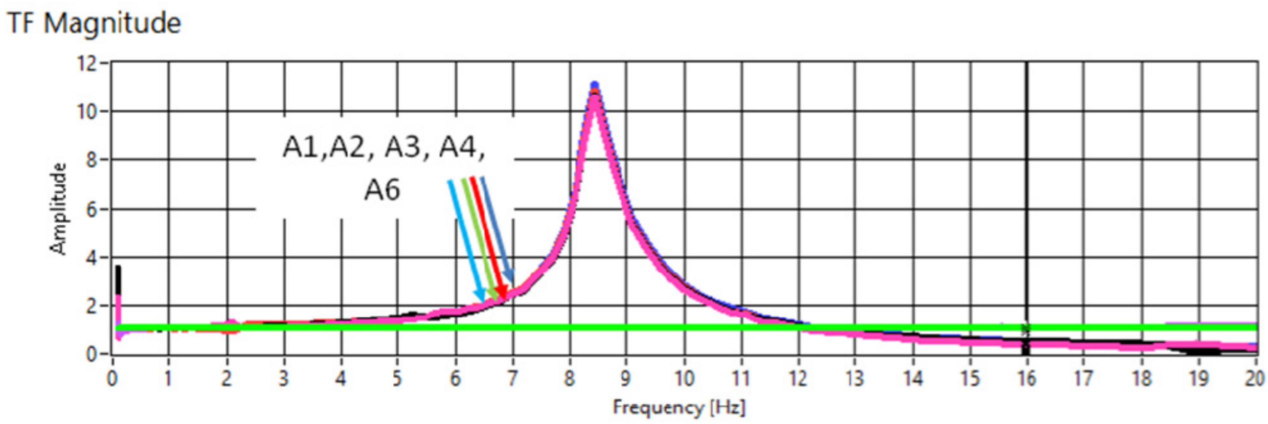


Fig. 10 Transfer function between the floor and different points on the structure in the case of sweep test with excitation direction along Z

6. Conclusions

An innovative system that protects the statue "Pietà Rondanini" by Michelangelo Buonarroti from both earthquake and traffic-induced vibrations was described. The main issue in the development of the base was the contemporary need to protect the statue from both earthquake and ambient vibration, a trade-off solution was found, tuning the first natural frequencies of the structure in frequency ranges where the excitation due to underground traffic and earthquakes are the lowest.

A special base, equipped with seismic isolation devices (guides with mechanical linear motion and rubber bearings) and dissipative devices, reduces the effects of traffic induced vibrations and prevents seismic damage. These systems have produced a redundant protection against seismic action and any other exceptional event, in order to ensure a safety level that has been tested on a shaking table up to twice the code seismic action expected in Milan. Base mass and vertical stiffness have been tuned to move the vertical first frequency at 8Hz, below the frequency amplified by traffic induced vibrations. The base is effective in reducing the amplitude of traffic induced vibrations at less than 10% of the initial value, depending on the direction and frequency, as laboratory tests have demonstrated.

Laboratory dynamic tests have shown, as expected, interaction between mechanical isolators and rubber bearings that reduce the effectiveness of seismic isolation mainly in some frequency ranges. Seismic vibration simulations, at different intensities, have shown the effectiveness of the isolation system in preventing the statue from overturning. A critical point is the connection between statue and base where a dissipative device was introduced in the lock that connects the statue to the base. In the event of an earthquake, it allows the statue to rock as the last dissipative mechanism.

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