Marble devices for the Base isolation of the two Bronzes of Riace: a proposal for the David of Michelangelo

Gerardo De Canio
ENEA C.R. Casaccia, Roma, Italy

SUMMARY:
New Anti-seismic basements made by marble for earthquake protection of the two statues known as "Bronzes of Riace" at the Archaeological Museum of Reggio Calabria (Italy) have been developed. The use of marble for the semi passive anti seismic basements is useful for earthquake protection of movable and semi movable Cultural Heritage objects like museum showcases and/or slender statues with a reduced surface at the basis such as the Bronzes of Riace and the Michelangelo's David. Basements of the same type, made by granite, are also used for the base isolation of the "Annunciazione" by Francesco Mochi at the Opera del Duomo Museum of Orvieto (Italy). The new basements can be also made by ceramic or steel/ceramics and used to protect delicate instruments for hospital and control centers too.

Keywords: Bronzes of Riace, Semi-passive devices , marble anti seismic basements.

1. INTRODUCTION

This paper describes the new anti-seismic basements made by marble for earthquake protection of the two statues known as "Bronzes of Riace" at the Archeological Museum of Reggio Calabria (Italy). The new basements provide the seismic isolation of the 3D horizontal and vertical earthquake components and the design approach was to confer the seismic isolation property by means of the geometrical properties of the basements, according the following design targets: maximum seismic isolation of the three components of the earthquake achieved by large displacements; low stiffness and low dissipation; decouple the in plane horizontal components and the vertical component of the motion of the basement; reversibility of the intervention; fully compatibility of the materials; easy maintenance. Analogous basements are used for the "Annunciazione" by Francesco Mochi at the Opera del Duomo Museum of the Orvieto Cathedral, Italy and are also useful for other high vulnerable statues standing on their legs without any support such as the David of Michelangelo in Florence. The basements can be configured as fully passive and "semi-passive" seismic isolators: the first provide a permanent passive base isolation, the second means they are blocked in normal conditions and unblocked by a Seismic Early Warning signal, therefore have been named "semi-passive". They are very low stiffness rolling double pendulum type, provided by dissipative cables. The number of cables and the geometry of the rolling surfaces allow the tuning of the energy dissipation, the stiffness and the resonance frequency of the basement. These parameters depend on the object (statue, potteries, showcases) to be protected and the energy content of the horizontal and vertical seismic spectra at the floor where the object is located in the museum. The new basements can be also made by granite, ceramic or steel/ceramics and used to protect delicate instruments for hospital and control centers too.

2. THE ANTI SEISMIC BASEMENTS FOR THE BRONZES OF RIACE

The two bronze statues known as "Bronze A the young" and "Bronze B the old" were previously located at the ground level of the museum and provided by laminated rubber anti seismic devices.

Moving the statues from the ground level to the new exposition room at the first floor of the museum required an upgrading of the anti seismic basements according the new seismic classification of the site and the change in the maximum hazard floor spectra due to the floor amplifications of the horizontal and vertical earthquake components. The previous devices provided a seismic isolation coefficient value of 2.5-3 and, to avoid overtourning, the statues where anchored with strengthening forces of 1800N applied at each shoulder by means of steel cables inserted in the cave legs. The necessity to reduce the strengthening anchoring forces, together with the new expected seismic demand due to the new seismic classification, induced to re design the anti seismic basements to increase the isolation coefficient reducing the risk of exceeding the seismic capacity of the two statues. The design of the new basements was finalized to the following performance results within the framework of compatible materials and reversibility of the intervention:

1. Maximum X,Y and Z seismic isolation
2. Easy maintenance
3. Durability

To achieve these results the design approach was to confer to the basements in their expositive configuration the function of seismic isolators. Therefore have been studied an architectonic geometry having the structural function of seismic isolation, in other words a geometry conferring the following characteristics:

a.) Low stiffness and dissipation,
b.) Large horizontal displacements,
c.) Seismic isolation index equal to 15-20 in horizontal X,Y directions and 2.5-3 in vertical direction.

The necessity to reduce the accelerations in Z direction is due to the amplification of vertical component at the first floor within the frequencies 8-12 Hz which are critical for the two statues. The design results are, for each statue, a basement made by two blocks made by marble type "Carrara" showed in figure 1, the surfaces of the blocks are modelled as ellipsoid of revolution where 4 spheres made by the same material of the blocks are located. The two blocks are connected by dissipative device made by stainless steel cables for horizontal displacement limitations and recentering; in the upper block is located a device made by stainless steel for vertical isolation. In short, the basement is made by the following elements: *BI= marble lower block*, *S= marble spheres*, *DO= Horizontal displacement limitation and recentering device*, *BS= marble upper bloc*k, *DV=vertical isolation device* inserted in the BS upper block.

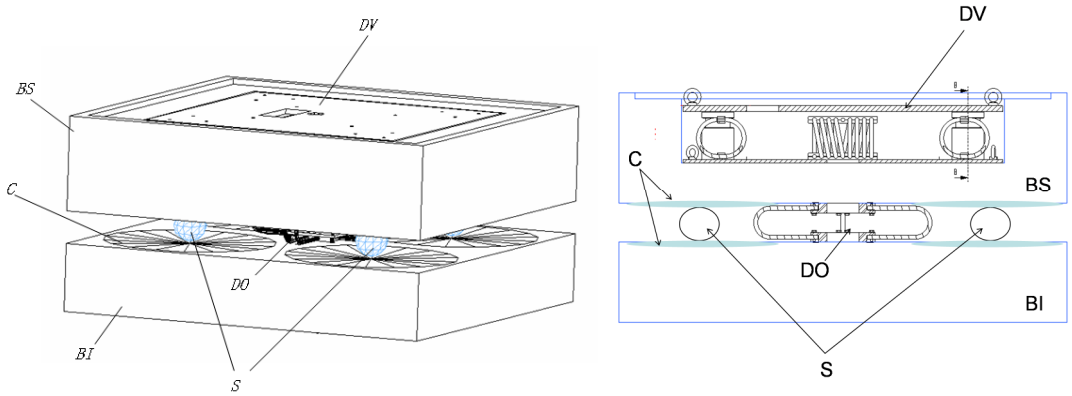


Figure 1. Marble anti seismic basement provided by spheres + horizontal limitation device + vertical isolation device inserted in the upper block.

The design parameters of the rolling surfaces are: a= 300mm, b=10mm, where a and b are the semi axes of the ellipsoid of rotation, *W* is the total weight of the upper block comprehensive of the weight of the statues. However stiffness and principal frequency of the basement are not constant due to the elliptical geometry of the rolling surfaces, the principal frequency are ranging from 0.015Hz to 0.025 Hz depending on the position along the surface, with zero value at the centre, where the recentering function is demanded to the element *DO*.

$$K = W \cdot \frac{b(1-\sqrt{1-\frac{x^2}{a^2}})}{x^2}$$

basamento Bronzi di Riace
Materiale: Marmo di Carrara
tipo: pendolo inverso
Geometria: ellissoide di rotazione

$$T = \frac{1}{2\pi}\sqrt{\frac{g \cdot x^2}{b(1-\sqrt{1-\frac{x^2}{a^2}})}}$$

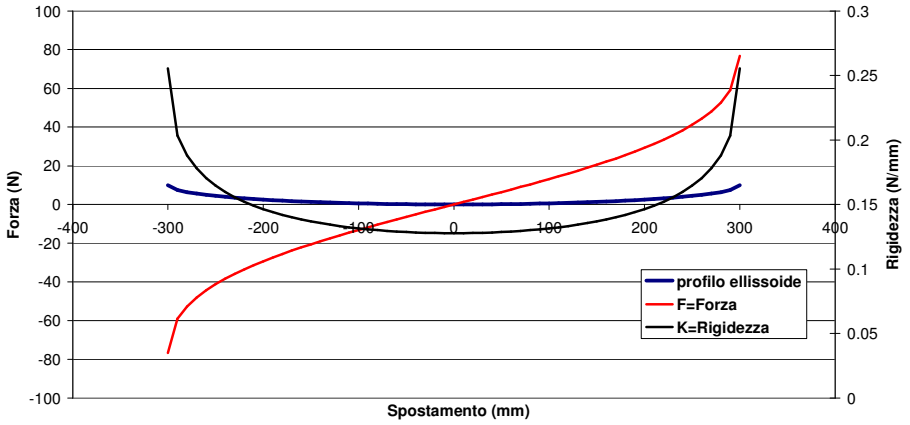
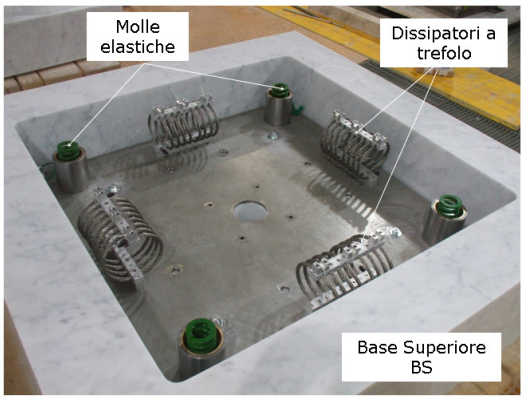
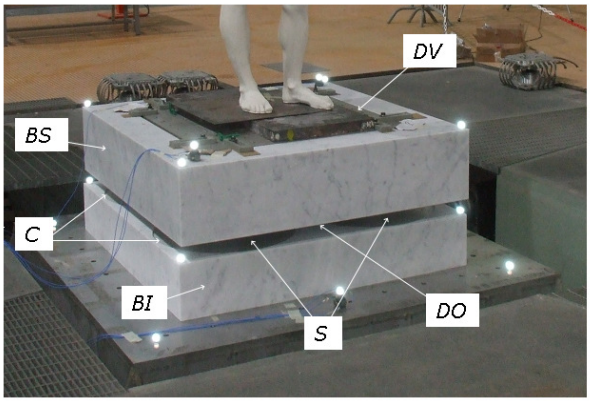


Figure 2. design parameters for the sliding surfaces: K=stiffness, W=weight, T=period

The vertical isolation is provided by two stainless steel plates connected by four shock absorbers made by dissipative cables plus four springs inserted in piston guides confining and de-coupling the vertical and the horizontal motion, therefore the simultaneous X,Y,Z seismic isolation is possible because the horizontal isolation is demanded to the basement geometry and the vertical isolation is demanded to the shock absorbers inserted in the upper basement. As anti seismic device, the basement is logically divided in three parts: marble basement, recentering tool and vertical isolation device. They can be used single or combined. In the actual configuration the basements are passive seismic isolators. When configured as "*semi passive*" they are blocked in normal conditions and unblocked by a seismic early warning signal anticipating the earthquake.



a)



b)

Figure 3. marble basement for the bronzes of Riace: a) details of the vertical isolation device inserted into the upper block, b) basement ready for the shaking table tests

3. SHAKING TABLE TESTS

The shaking table tests on the basements have been performed at the Qualification of Material and Component laboratory of ENEA Casaccia Research Center, Roma (Italy); test set up and details of the basements are showed in figs. 4-a,b,c,d and fig.5:

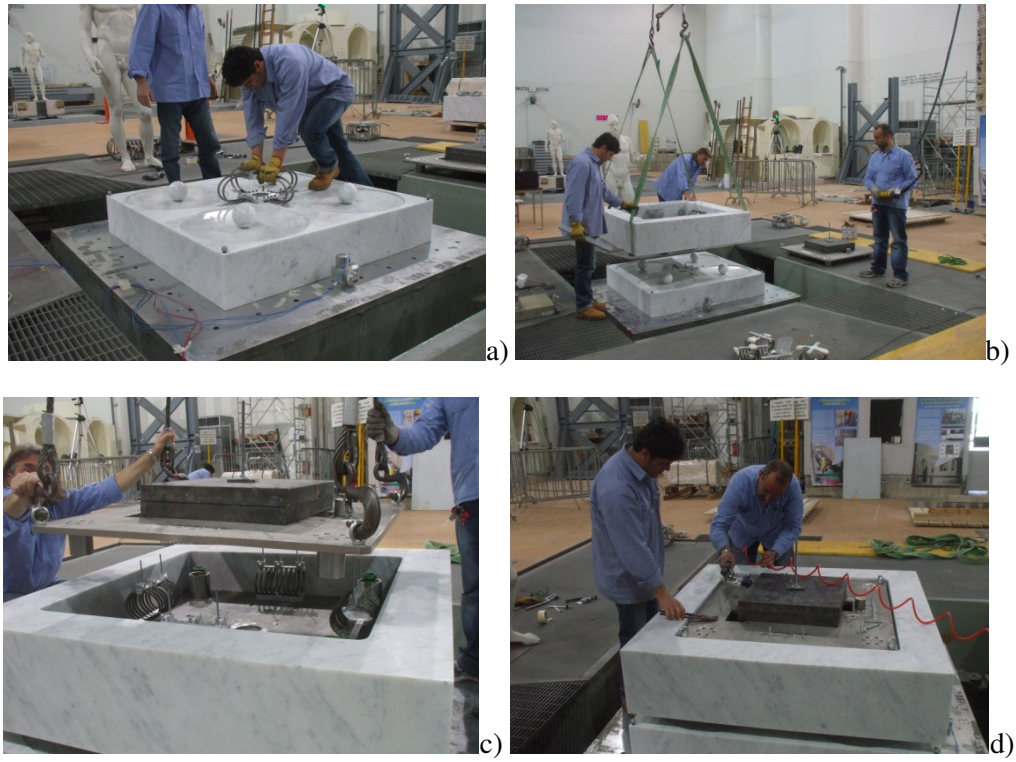


Figure 4. a) lower block and recentering device, b) upper block with vertical isolation c) upper plate, d) basement ready for the shaking table tests

Figure 5. Shaking table tests of the marble anti seismic basements for the Bronzes of Riace

The input time histories were natural accelerograms from strong motion data base normalized and rescaled to the max hazard of Reggio Calabria, return period of 2475 years, amplified at the first floor of the museum; the selected earthquakes were Irpinia (stat. 198 X,Y,Z) and Gilroy (Loma Prieta X,Y,Z). In addition to natural earthquakes, three series of X,Y,Z artificial accelerograms were applied, compatibles to the Ultimate Limit State of the museum amplified at the first floor at different damage conditions of the building: no damages, medium damages, high damaged. At the end of the test campaign was also applied an X,Y,Z earthquake compatible with the RRS (Required Response Spectrum) for NPP (Nuclear Power Plant) class 1-E equipment (essential for the safety) according the IEEE-344 specifications. All tests reached the reduction coefficient of 15-20 for the horizontal accelerations and 2.5-3 for the vertical accelerations; the overall maximum acceleration measured on the basement in all the tests was 0.08g.

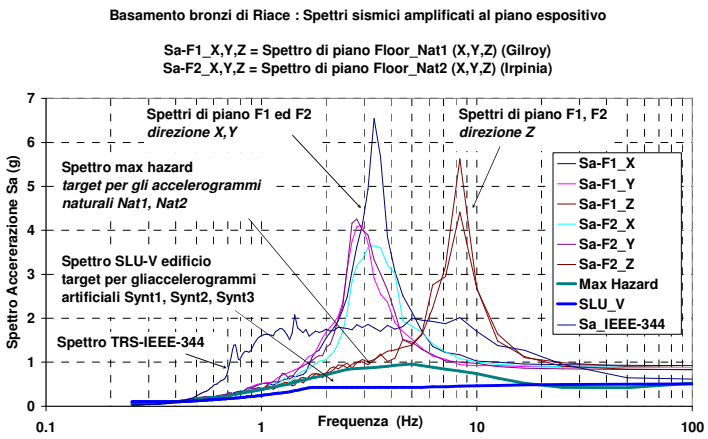


Figure 6. Floor spectra at the first floor of the museum

During all the tests with natural earthquake the isolation coefficient was 15-20 and the max acceleration peak on the basement was 0.062g. In the vertical direction, with Peak Floor Acceleration PFA=2g, the isolation coefficient was 2.4 and the max basement vertical acceleration of 0.86g. The graphs in figs.7,8,and 9 represent the results of the shaking table tests with Floor-Nat1 (rescaled Irpinia) and Floor-Nat2 (rescaled Gilroy) both amplified at the first floor of the museum. The Blue lines Tx, Ty, Tz are the Horizontal base table accelerations and the red-yellow lines Bx, By, Bz are the accelerations measured on the basement.

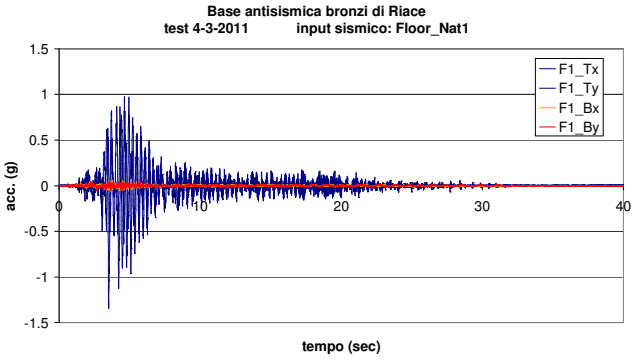


Figure 7. shaking table test Floor-Nat1: F1_Tx,y= base table, F1_Bx,y= basement. Isolation Coeff.= 22.

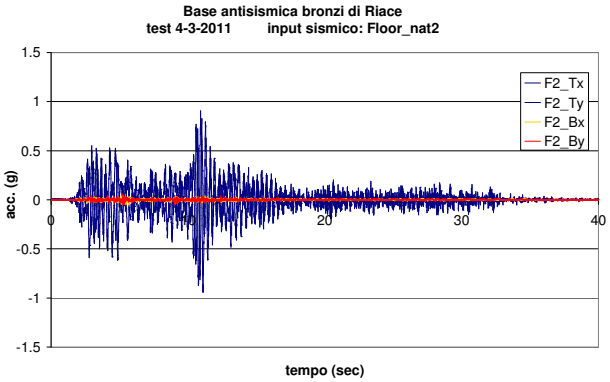


Figure 8. shaking table test Floor-Nat2: F2_Tx,y= base table, F2_Bx,y= basement. Isolation Coeff.= 20.

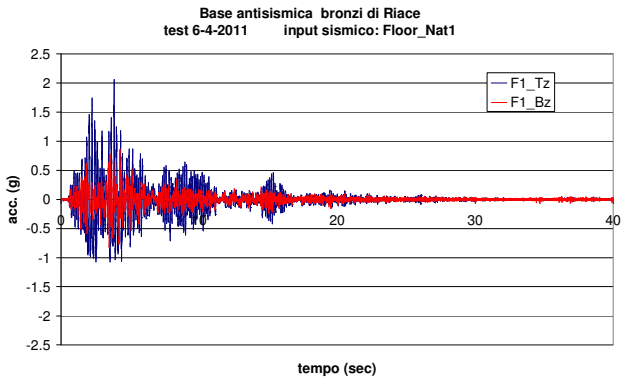


Figure 9. shaking table test Floor-Nat1: F1_Tz= base table, F1_Bz= basement. Isolation Coeff.= 2.4

Regarding the vertical component in fig.9, the basement should provide an isolation coefficient sufficient to limit the vertical accelerations when vertical components are amplified by the dynamics of the building. The usual anti seismic devices do not isolate the vertical component of the earthquake, nevertheless, near fault earthquakes have strong vertical components which, in case of floor amplifications, can increase the risk of overturning due to the reduction of the normal forces. During the shaking table tests the values of vertical isolation obtained by the vertical device inserted in the upper block was 2.4. The test with natural (rescaled) earthquakes was followed by the tests with artificial earthquakes amplified at the first floor of the building and in different ductility factors. The graphs in figure 10 represents a summary of the results of the three earthquakes Synt1, Synt2 and Synt3. During all the tests with synthetic earthquakes the maximum acceleration peak measured on the basement was 0.066g

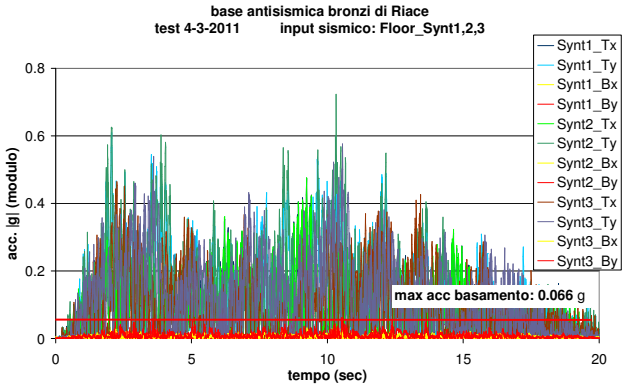


Figure 10. shaking table test Floor_Synt1, Floor_synt2 and Floor_synt3: T= base table, B= basement

The last tests was performed using accelerograms compatible with Required Response Spectrum according the IEEE-344 specifications for NPP component of class 1-E.

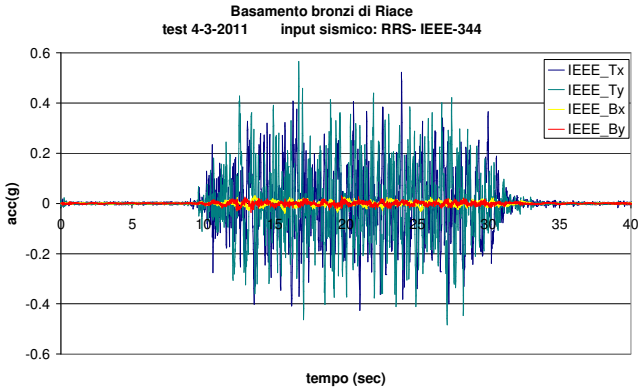


Figure 11. shaking table test IEEE-344: T= base table, B= basement

The reduced accelerations at the base of the statues allows to reduce also the strengthening forces.
The new basements made by marble provide a seismic isolation coefficient of 25-30 and the strengthening forces was not yet necessary to prevent earthquake induced overturning. Therefore the two forces of 1800N have been reduced to the values of 600N and 300N just to replace the strengthening due the weight of the shield on the left arm and the lance on the right arm and to fix the statues preventing man made actions. The same type of basement can be useful for the David of Michelangelo, in this case, due to the whole mass of the actual basement and statue, we should use a marble basement with 25 spheres as shown in figure 12.

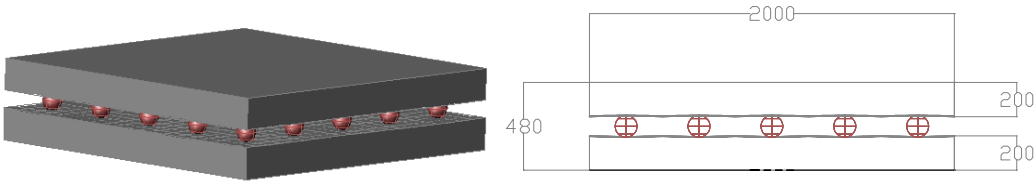


Figure 12. proposal for the base isolation for the David of Michelangelo

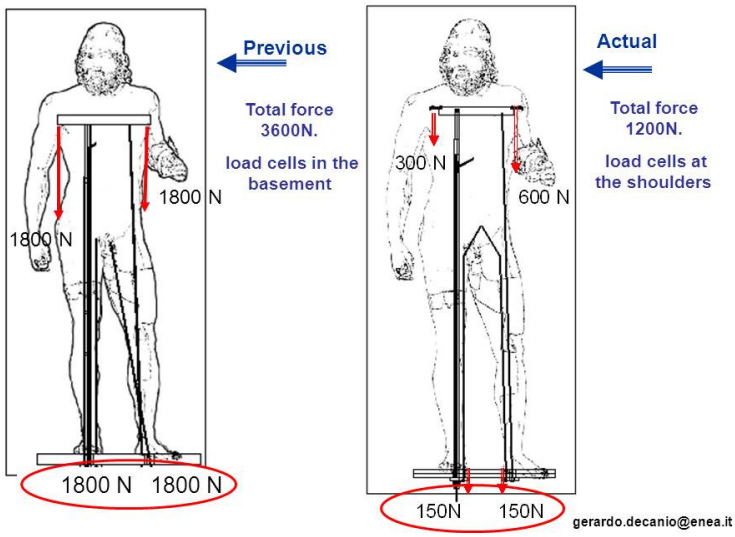
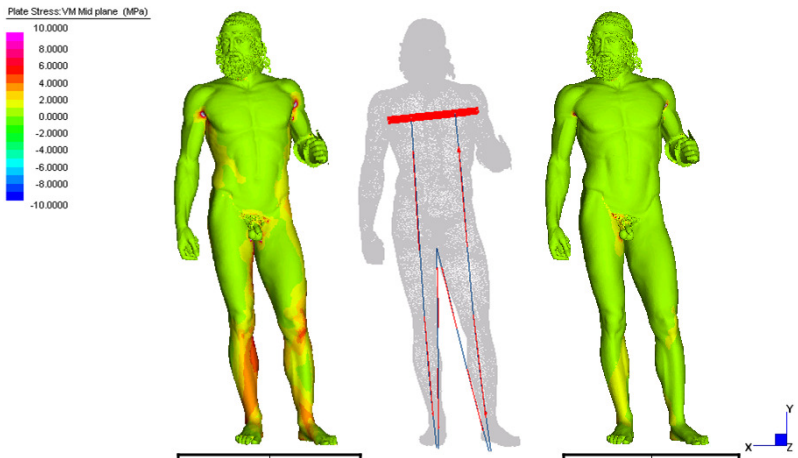


Figure 13. The previous rubber bearing devices required the application of strengthening forces



Posizione	Forza Kg
Spalla Ds	180
Spalla Sx	180
Inguine	180

Forze di ancoraggio con dispositivi in gomma vulcanizzata

Posizione	Forza KN
Spalla Ds	30
Spalla Sx	60
Inguine	30

Forze di ancoraggio con dispositivi in marmo

Figure 14. Bronze A: comparison of the stress fields induced by the new and old strengthening forces

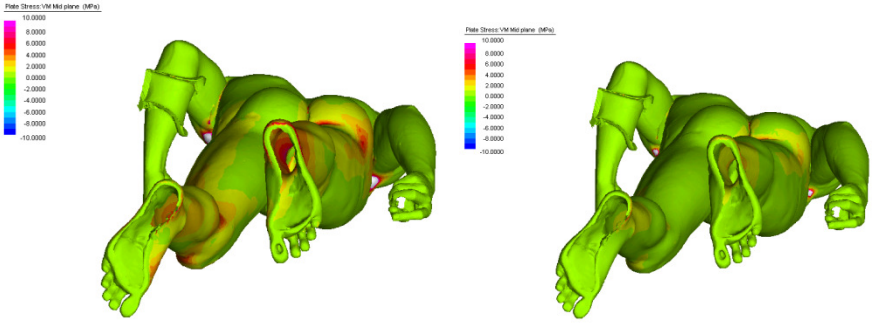


Figure 15. Bronze A: comparison of the stress fields by the old and new strengthening forces

Devices of the same family, made by granite, have been developed for the two statues known as "Annunciazione" by Francesco Mochi at the Cathedral of Orvieto, Italy (fig.16). In this case the device will be positioned on the old basement as shown in the figures 17 and 18.

Figure 16. The Dom of Orvieto (Italy) and the two statues of "Annunciazione" by Francesco Mochi.

In this case the anti seismic device is made by granite, positioned on the actual basement and covered

by the same stone of the actual basement.

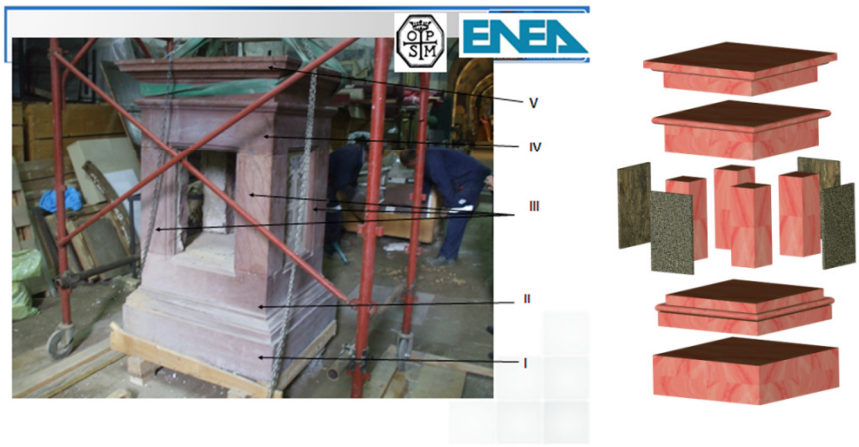


Figure 17. original basement of the statues, it is composed by several blocks.

Figure 18. The granite anti seismic basement for the "Annunciazione" by Francesco Mochi. The granite is covered by the same marble of the original basement

3. CONCLUSIONS

New anti seismic basement made by marble have been developed for high vulnerable statues, delicate objects and museum techs. They are part of the sliding/rolling family of seismic isolators, made by steel/ceramic or marble and provided with dissipative cables to calibrate the energy dissipation during the earthquake. The basement can be classified as fully passive or semi-passive, the semi-passive configuration is blocked in normal conditions and unblocked by a seismic early warning (SEW) triggering signal. A complete shaking table test campaign have been carried out using natural earthquakes rescaled to achieve the museum site maximum hazard, synthetic earthquake compatible with the Ultimate Limit State and, at the end, a series of time histories compatible with the Required Response Spectrum (RRS) according the IEEE-344 specifications for Nuclear Power Plant class 1E equipment qualification tests. The very low acceleration values at the base of the statues allows to reduce the strengthening forces to the values equivalent to the lost part of the statues, i.e. the shield on the left arm and the lance on the right hand. Basements of the same family are used for the two statues of the Annunciazione by Francesco Mochi at the Cathedral of Orvieto (Italy). The results allow to propose the same basement type for the David of Michelangelo.

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REFERENCES

De Canio, G. (2008). Seismic early warning systems for strategic infrastructures and CUHES. *The 14th World Conference on Earthquake Engineering* October 12-17, 2008, Beijing, China.

De Canio, G. (2011). Basi Antisismiche in marmo per i bronzi di Riace. *Archeomatica N°1* **6-10** Dec. 2011

IEEE Std 344-2004 " Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations" IEEE- 3 Park Avenue, New York, NY 10016-5997, USA

IEEE Std 693-2005 "Recommended Practice for Seismic Design of Substations" IEEE- 3 Park Avenue, New York, NY 10016-5997, USA 8 May 2006