# 3D motion capture application to seismic tests at ENEA Casaccia research center: 3DVision system and DySCo virtual lab

G. De Canio, M. Mongelli & I. Roselli
*ENEA, Italy*

## Abstract

In the last 4 years, a high-resolution 3D motion capture system named 3DVision was installed at ENEA Casaccia as integration to more conventional instrumentation for measuring motion parameters during seismic tests, such as accelerometers, LVDTs, wire transducers and laser displacement sensors. In the present paper, some examples are illustrated to show the ENEA experiences with this relatively new technique in comparison to the other consolidated measurement systems. 3DVision is described in terms of flexibility and accuracy and specific potentialities are stressed. The main peculiarities of the 3DVision system derive from its capability of monitoring in real-time the absolute 3D position of more than a hundred measurement points without locating any active sensor or cable on the studied structure and on the shaking table, but only by means of cheap passive markers. Consequently, any risk of instrumentation damage in case of destructive tests is intrinsically avoided and the acquisition of hundreds of channels is guaranteed. Within the DySCo virtual lab, the 3DVision friendly graphical interface for real-time monitoring and its synchronous overlay function between markers wireframe and tests movies revealed particularly effective for remote sharing of the experimental campaigns with research partners via the internet. Also a remarkable contribution is given by the possibility of integrating and comparing experimental data with FE results at the same positions, calibrating FEM boundary conditions (materials properties, model constraints, loads etc.) in order to improve the simulation significance and reliability for similar cases. Through the DySCO web portal such numerical simulations and computations can be carried out exploiting the software and hardware resources available in the ENEA-GRID.
*Keywords: 3D motion capture, shaking table test, displacement measurement.*

 
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SAFE130711

# 1 Introduction

In recent years, remarkable advances in opto-electronics led to a tremendous improvement of digital vision applications, not only in the commercial implementation of cameras and ICT devices, but also as properly scientific measurement systems. Even in the field of earthquake engineering, digital vision techniques are increasingly utilized for laboratory testing as innovative instrumentation for motion capture and analysis [1, 2]. In particular, one of the first applications in Italy of this type of measurement approach to shaking table tests is represented by a high-resolution 3D motion capture system, named 3DVision, installed at ENEA Casaccia.

In the following, the 3DVision system is described and its potentialities in comparison with conventional instrumentation are illustrated. To this purpose, examples of application in experimental campaigns conducted during the last four years are shown.

ENEA also makes an important effort to foster scientific collaboration using information technology through the development of virtual labs. The integration between the 3DVision and the DySCO virtual lab represents the latest innovative solution in seismic tests at ENEA Casaccia RC.

# 2 3DVision system

The 3DVision is a 3D motion capture system based on Vicon technology [3]. It is made up of 9 near infrared (NIR) digital MX cameras for markers acquisition and 4 DV cameras for movies recording.

The actual sensors in the system are the CMOS mounted on board of the MX cameras. They have a full-frame resolution of 4 megapixels at 370 fps (frames per second of capture speed, which corresponds to the system sampling frequency in Hz) and are capable of increasing their frame-rate to up to 2000 fps by partializing the sensors scan. The system is currently set to acquire at 200 fps, which is an optimal compromise between oversampling frequency and hardware resources.

Cameras' strobes are equipped with powerful Light Emitting Diodes (LEDs) that emit NIR light onto the measurement volume in which retro-reflecting markers are placed on the mock-up to be tested.

MX cameras can be either installed onto the lab walls by means of bolted brackets or they can be mounted on tripods when required for particular geometric test configurations. Position and orientation of each camera must be planned so that each marker is viewed by at least two cameras.
An on-board processor is implemented with sophisticated algorithms for grayscale extraction and calculation of markers centers on each frame. Therefore, triangulation of such data is performed in real time on the host PC in order to obtain the markers trajectories.

The 3DVision can acquire a maximum number of 136,000 markers per second, which means 680 markers at 200 fps. This implies 2040 output channels, as each marker's trajectory is provided with x, y and z coordinates. Obviously, in

 
www.witpress.com, ISSN 1743-3509 (on-line)

most cases less than a hundred markers are sufficiently abundant for monitoring all the required measurement points in ordinary shaking table tests without uselessly stressing the system's hardware resources (Figure 1).

Figure 1: Detail of a marker (left); a MX camera (center); example of large number of markers acquired during shaking table tests of a 2-storey masonry building. The markers brightness in the pictures is due to the photo camera flash reflection.

The use of cheap passive retro-reflecting markers allows the 3DVision to carry out the displacement monitoring without any expensive devices to be located on the tested mock-up. In fact, the system's sensors (the MX cameras), are typically positioned at 3 to 5 m apart from the shaking table, according to common set-up configurations, avoiding any risk of instrumentation damage in case of destructive tests. In this case, the acquisition of markers data is accomplished anyway, giving the opportunity of recording motion data also in the event of collapse.

Moreover, the markers installation is wireless, very easy and quick. Their small size (25 and 40 mm of radius) and weight make them very competitive in terms of flexibility and encumbrance in comparison with conventional displacement sensors. When absolute displacement is measured using conventional devices, for example, it is generally required to attach the instrument housing to a stiff frame or support as a reference. From the housing a physical wire or a laser beam must be able to reach the measurement points within a given limited range. Also when used to monitor relative displacement, traditional instrumentation often poses problems of distance and room to be located on the tested mock-up itself at the desired positions.

Another remarkable feature of the 3DVision system is the possibility of synchronizing the acquisition of other analog devices and DV cameras with the markers trajectories. DV cameras can be calibrated in accordance to the markers reference origin in order to record a 3D-overlay movie. Such possibilities of devices integration and visualization are very interesting for sharing the experiments via web, as will be illustrated in the next paragraph.

 
www.witpress.com, ISSN 1743-3509 (on-line)

As is well known, vision systems' accuracy depends on several aspects related to cameras geometry configuration: camera-marker distance, cameras rays' triangulation angle, operations for internal and external orientation calibration, etc. Also important are the sensors resolution and speed, the markers size and reflectance (including the effect of dirty or occulted markers), the overall scene lighting and the presence of disturbing reflections (erroneous detection can occur when lighting intensity is instable or when objects in the scene reflect light similarly to markers). Taking into account the typical set-up and cameras configurations in the shaking table laboratory at ENEA Casaccia, the system accuracy lays between +/- 0.01 mm and +/- 0.1 mm in terms of RMS error. Even if other more consolidated displacement sensors can reach substantially higher accuracy, in our experiences 3DVision markers are effective and appropriate for most measurement purposes in seismic tests, where the input simulates moderate to strong ground motion and main frequency content is usually below 15–20 Hz.

## 3 DySCo virtual lab: real-time remote experiment sharing and FEM validation

In the last few years, ENEA has developed some virtual labs in order to keep research partners and students in contact for exchanging information on their scientific activities by means of remote technologies. Among them DySCo is dedicated to seismic and vibration tests and to related numerical simulations [4].

In particular, the web-based system is intended to allow the participation of authorized remote users to the experiments conducted at ENEA Casaccia RC by visualizing real-time videos and graphs of the tests under way, while interacting with local researchers through a chat-based session. Measurement systems capable of displaying real-time signals are very suitable and effective in such web-conference environment.

The 3DVision system is provided with a very friendly graphical interface for real-time monitoring. Moreover, test movies and the markers wireframe can be synchronized and calibrated together in order to obtain a 3D-overlay visualization (Figure 2).

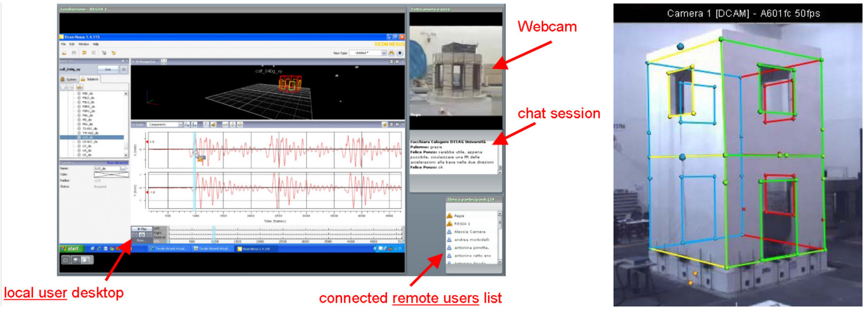


Figure 2: Real-time remote sharing of shaking table tests (left) and 3D-overlay synchronization between wireframe and movie (right).

## 4 Case 1: crack monitoring at masonry wall connections

This first example is interesting to compare the use of conventional sensors with 3DVision data for absolute and relative displacement. An experimental campaign was conducted on the dynamic resistance of masonry wall connections and, subsequently, on the out-of-plane behaviour of the façade [5]. A mock-up, made up of a masonry façade (named E in the following) connected to lateral walls (named S and N in the following), was built for shaking table tests.

Displacement wire transducers and accelerometers were installed at the same positions on the façade for a refined description of its out-of-plane dynamic behaviour. Markers were located on the lateral walls, at façade connections and at the mock-up base (Figure 3).

The wire transducers set-up required, as usual, to attach the sensors housing on a stiff frame in front of the façade as a reference for the out-of-plane absolute displacement (Figure 3). A protection net was added to the mock-up to avoid the façade crashing down after the collapse and damaging the instrumentation and the reference frame. In Figure 4 the absolute displacement time-history from a marker and from a wire transducer can be compared.

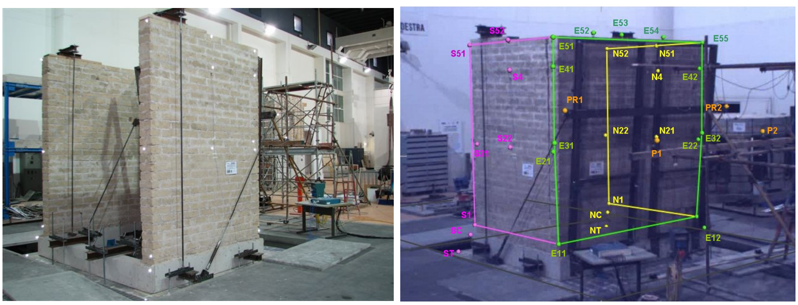


Figure 3: Masonry mock-up and steel frame scaffolding in front of the façade for displacement sensors set-up (left). 3DVision markers (right).

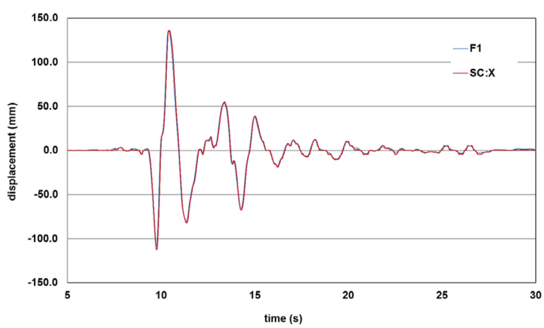


Figure 4: Comparison between marker SC and displacement wire transducer F1.

In particular, markers were able to measure relative displacements at connections between lateral walls and the façade, which allowed us to monitor the cracks evolution during the tests. The graphs in Figure 5 show that S-E connection fails at the early steps of the tests sequence and gradually opens, while N-E connection remains in place until the late tests before the façade collapse. This asymmetric behaviour was also investigated by analysing the RMS of the relative displacement at both wall connections. Such RMS values indicate the oscillation of cracks openings during the seismic excitation. In Figure 6 it is evident that some damage appears in the early tests along the N-E connection as well, but the crack propagation did not reach to the top of the wall until the test before the final collapse.

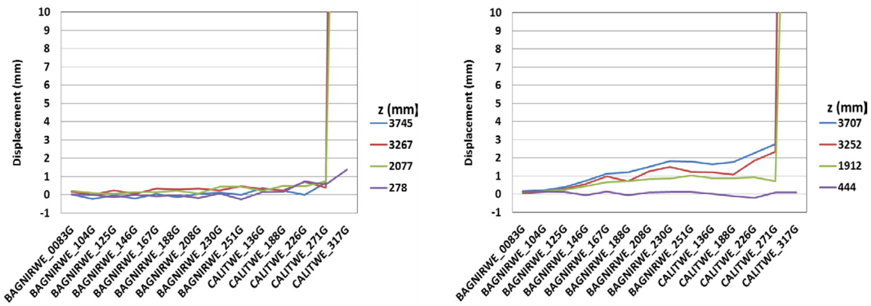


Figure 5: Relative displacement after each shaking table tests at N-E (left) and S-E (right) wall connections at different height z along the façade.

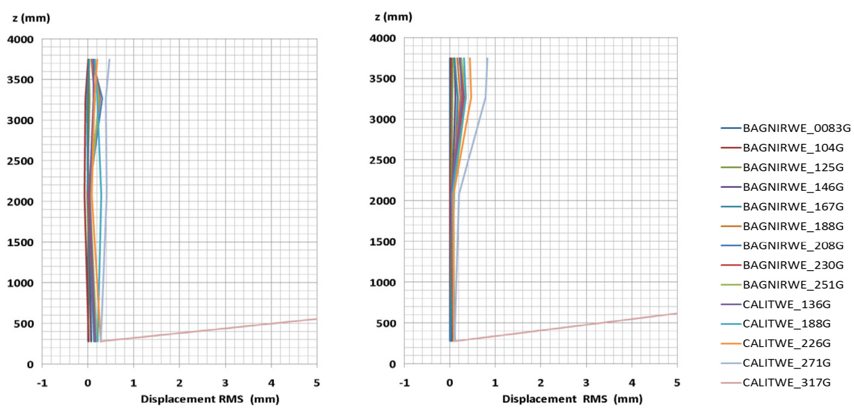


Figure 6: Profiles of relative displacement RMS at N-E (left) and S-E (center) wall connections for each shaking table test (chronological sequence in the legend on the right).

In similar cases of relative measurements between points that can suddenly fall apart, sensors requiring a physical connection (wire transducers, LVDTs, etc.) need to be used very carefully to avoid relevant risk of instrumentation damage.

## 5 Case 2: 3D dynamic behaviour of an obelisk

The present case shows an application difficult to be conducted by conventional instrumentation. Markers data proved to be very effective for the study of the dynamic behaviour of a 1:6 scaled model of the Laterano Obelisk.

The experimental study was conducted within the PERPETUATE project funded by the European Commission in the Seventh Framework Programme (FP7/2007-2013). The research project focused the attention on some relevant architectural types of the historical heritage in the Mediterranean countries.

The 5m-high model, made up of three blocks (Figure 7), as well as the original obelisk located in Rome, was submitted to shaking table and pull-release tests. The use of the 3DVision system offered the possibility of capturing the 3D rotational motion of each block in a very complete way, allowing the analysis of the precession effects on rocking phenomenon under free oscillations [6].

Given the size and the typology of the model it would be an extremely difficult task for conventional sensors to provide the needed data for a complete description of the 3D absolute displacement of each block. Besides, it would require a very engaging set-up preparation, with the use of high scaffoldings and the installation of sensors attached to 5m-high stiff frames around the obelisk. On the contrary, the markers could be located on each block on the floor before obelisk composition and test set-up.

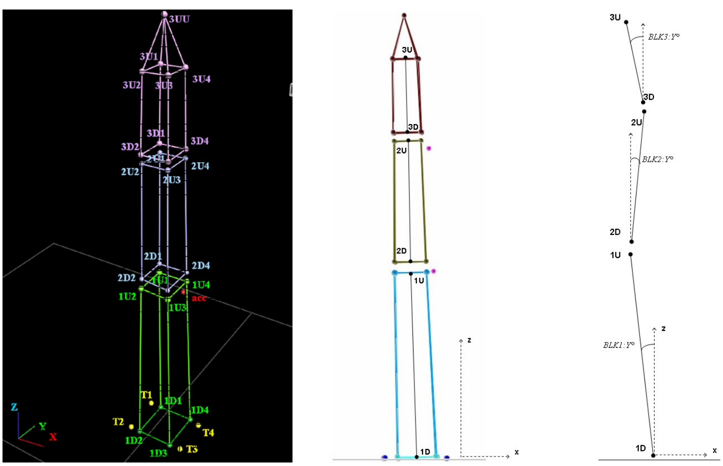


Figure 7: 3DVision markers and wireframe of the 1:6 scaled model of the Laterano Obelisk (left) and rotation angles for rocking analysis (right).

 
www.witpress.com, ISSN 1743-3509 (on-line)

Also, the real-time monitoring of the markers allowed one to guide the operator in the correct timing for pulling and release steps according to the desired initial obelisk position. For example, the vertical displacements of markers at the base of the obelisk, which are related to the release angle, were taken under control (Figure 8).

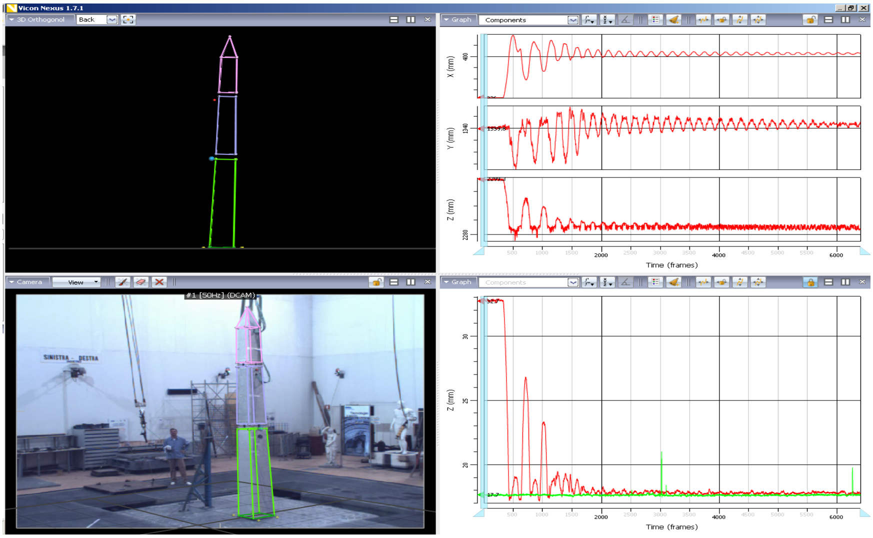

Figure 8: Real-time monitoring of obelisk pull-release tests: triaxial motion of a selected marker (top right) and vertical motion of two markers at the base of the obelisk (bottom right).

## 6 Case 3: study of a small-scale arch with tie-rod

Another experimental campaign conducted within the PERPETUATE Project focused on the effect of different kinds of tie-rods to the seismic resistance of typical historic masonry arches [7].

To this aim a small-scale model of an arch was tested on shaking table. The arch was made up of 43 small discrete blocks of plastic material with the insertion of a thin membrane of Polyvinyl Alcohol (PVA) in order to obtain the desired friction angle between the blocks.

In consequence of the small size of the arch (Figure 9), it was very difficult to use conventional sensors to monitor the relative displacement between the blocks. In effect, common displacement sensors suffer from limits in housing encumbrance and weight that would affect the results of tests on small and light models. In such circumstances, if miniaturized instrumentation can be used, remarkable additional costs must be considered. Instead, a large number of markers were placed very easily and quickly with no further expense.

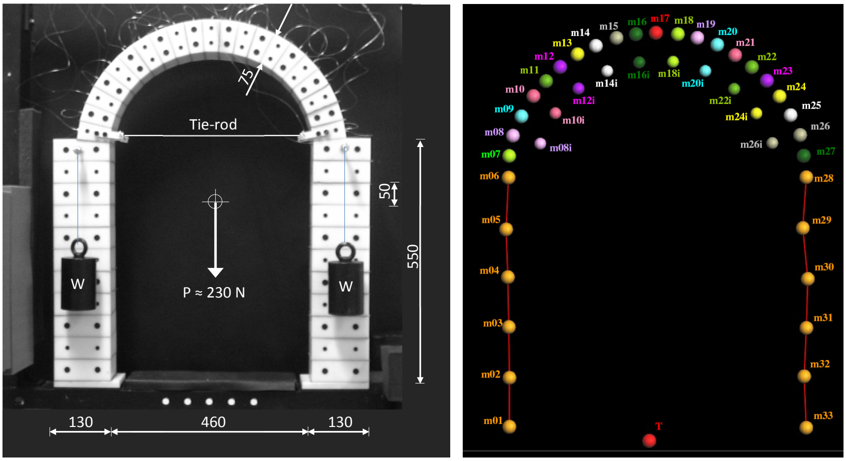


Figure 9: The arch model dimensions (left) and 3DVision markers (right).

In order to detect also the blocks sliding, two markers could be installed with no encumbrance problems on alternated blocks: variation in the angle formed by two markers on the same block and a marker on the adjacent one indicates sliding between them (Figure 10).

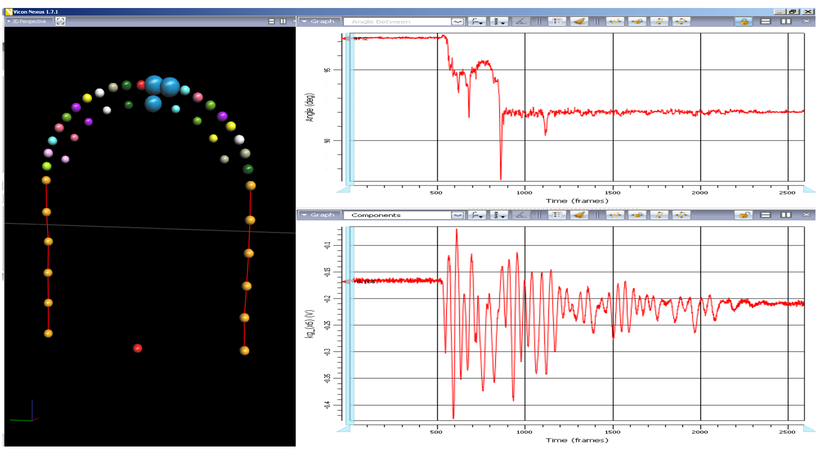


Figure 10: Monitoring of blocks sliding by angle between markers at keystone (top right) and synchronized load cell at the tie-rod (bottom right).

Also, a load cell was installed at the tie-rod and acquired by the 3DVision along with the markers, giving the opportunity of comparing synchronized load data and displacement between the arch imposts (Figure 11).

 
www.witpress.com, ISSN 1743-3509 (on-line)

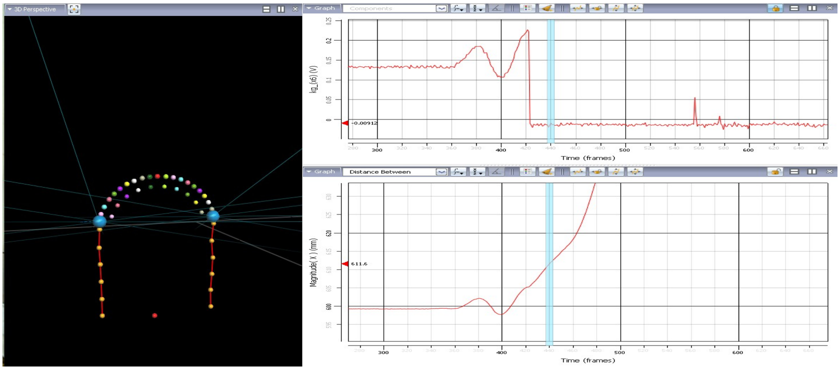

Figure 11: Monitoring of tie-rod failure during shaking table tests: load cell (top right) and distance between markers at the imposts (bottom right).

## 7 Case 4: anti-seismic devices characterization

Another application in which the 3DVision provided an interesting added value is the characterization of anti-seismic devices.

As a brief example, the characterization tests of the EARLYPROT isolators is illustrated in the following [8]. They are sliding-rolling (pendulum type) devices provided with dissipating steel cables limiting the displacements (Figure 12).

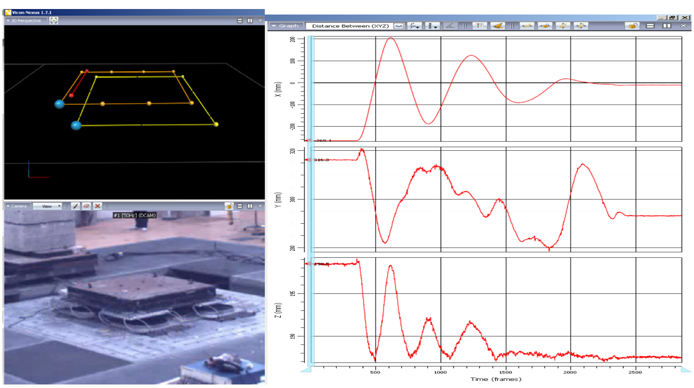

Figure 12: EARLYPROT isolators' pull-release test. Relative displacement in x, y and z directions between an isolator and the table (right).

Tests were set up with four isolators linked together and loaded with a vertical mass of 17 kN and 34 kN, reproducing a realistic configuration.

Markers were located on the table, on each isolator and on the loading plates for a complete 3D motion description. A triaxial accelerometer and a laser sensor were also used as reference.

The device characterization was performed through a long sequence of pull-release, sine sweep and pure sine tests. The stiffness and the damping coefficients were calculated varying the number of steel cables.
In particular, hysteretic cycles obtained by markers data revealed interesting device properties: at low displacements, the sine sweep tests showed a constant friction coefficient of 3% in accordance with the theoretical pendulum of same geometry, while the hardening effect caused by the steel cables appeared with the increase of the displacement over 100 mm (Figure 13).

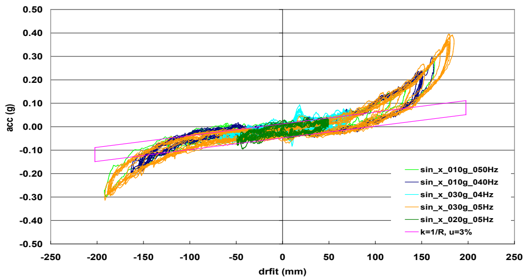


Figure 13: Hysteretic cycles of EARLYPROT isolators in several sine tests compared to the theoretical pendulum cycle with same radius at 3% friction (pink cycle).

Moreover, also the isolators' torsional and recentering properties could be effectively characterized by markers data, giving indications for possible improvements in cables designing and distribution.

## 8 Conclusions

The 3DVision showed many advantages in terms of set-up flexibility and installation facilitation. Many typical inconveniences in case of model collapse were also limited. In particular, to measure absolute displacements in high slender models (like an obelisk) and relative displacements between numerous small parts (like small arch blocks) did not represent engaging tasks. Furthermore, the 3D nature of this measurement technique gave remarkable results for a complete motion description, which is particularly suitable for 6DOF seismic tests and for integration with DySCo virtual lab in experiment real-time remote sharing and FEM validation.

On the one hand, these systems are still less accurate than more consolidated displacement sensors. However, accuracy already proved to be satisfactory for most lab applications, as shown in the above examples. On the other hand, this kind of technology is very promising in terms of performance improvement and costs in perspective.

 
www.witpress.com, ISSN 1743-3509 (on-line)

## References


[1] Beraldin, J. A., Latouche, C., El-Hakim, S. F., Filiatrault, A., Applications Of Photogrammetric And Computer Vision Techniques In Shake Table Testing, *Proc. of the 13th World Conference on Earthquake Engineering*. Vancouver, CA., 2004.

[2] Lunghi, F., Pavese, A., Computer Vision System for Monitoring in Dynamic Structural Testing. *Geotechnical, Geological, and Earthquake Engineering*, **22**, pp. 159-176, 2012.

[3] VICON, http://www.vicon.com.

[4] Roselli, I., Mencuccini, G., Mongelli, M., Beone, F., De Canio, G., Di Biagio, F., Rocchi, A. The DySCo virtual lab for Seismic and Vibration Tests at the ENEA Casaccia Research Center, *Proc. of the 14th European Conference On Earthquake Engineering*, Ohrid, Republic of Macedonia, 2010.

[5] Omar Al Shawa, Gianmarco de Felice, Alberto Mauro, Luigi Sorrentino. Out-of-plane seismic behaviour of rocking masonry walls. *Earthquake Engineering and Structural Dynamics*, **41(5)**, pp. 949–968, 2012.

[6] De Canio, G., Clemente, P., Mongelli, M., Roselli, I., Rinaldis, D., Saitta, F., Lagomarsino, S., Rossi, M., Performance based approach in the assessment of the obelisco Lateranense in Roma, *Proc. of the 8th International Conference SAHC (Structural Analysis of Historical Constructions),* Wrocław, Poland, 2012.

[7] Calderini, C., Lagomarsino, S., Rossi, M., De Canio, G., Mongelli, M., Roselli, I., Seismic Behaviour of Masonry Arches with Tie-Rods: Dynamic Tests on a Scale Model, *Proc. of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.

[8] De Canio, G., Mongelli, M., Roselli, I., Semi passive anti seismic devices for systems and components of strategic infrastructures, *Proc. of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.