3D motion capture and FEM Analysis for Shaking Table Tests at ENEA Casaccia Research Center

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ABSTRACT:
An innovative high-resolution 3D motion capture system named 3D-Vision is operating at ENEA Casaccia research center replacing conventional LVDTs and laser sensors for displacement measurement. The 3D-Vision system can detect the complete motion of up to hundred markers located on the tested structure. A Finite Element Analysis (FEA) is initially executed for the first estimation of dynamic behavior of the structure in order to identify the most adequate nodal points where markers should be placed. At this stage, the Finite Element Model (FEM) is affected by remarkable uncertainties about material properties and structural nonlinearities. 3D-Vision data provide the real seismic input for FEM non-linear static and transient analysis. The motion of any point of the structure is simulated and compared with the experimental markers data. Consequently, FEM boundary conditions (materials properties, model constraints, loads etc.) are calibrated to improve the significance of next simulations and the model reliability for similar tests.

Keywords: 3D Motion Capture , Finite Element Model (FEM), Shaking Table Test.

1. INTRODUCTION

In the present paper an innovative methodology for integrated use of three-dimensional Finite Element Model (FEM) analysis and motion capture data from shaking table tests is proposed.
Generally speaking, optical motion capture is a vision-based tracking technology that may be classified as either image or light-based. Image-based tracking relies on feature detection between frames of a color or monochrome texture map, while image processing and 3D reconstruction is conducted, which is a very challenging task for monitoring earthquake motions. On the other hand, light-based systems are based on the detection of markers emitting (active systems) or retro-reflecting (passive systems) only a narrow band of light wavelengths. Since markers help cameras in measurement points detection and tracking, the complexity of live data processing in light-based systems is reduced significantly (Hutchinson et al. 2004).
Recent advances in 3D motion capture systems are making this kind of technology more and more interesting for scientific research in fields other than their typical consolidated applications, such as in biomechanics, sports and virtual reality (videogames and filmmaking industry). In particular, it is an emerging technique in experimental fields related to motion measurement.
In fact, the application of computer vision and image processing techniques to shaking table tests was lately investigated and developed by some researchers to expand the limits of conventional instruments (Beraldin et al. 2004, Doerr et al. 2005). Effectively, current displacement instrumentations, such as LVDTs and laser sensors, give a very precise measurement of only one-dimension motion. Moreover, one sensor for each measurement point is needed, implying difficulties in location and attachment. Consequently, the common choice is to monitor only few points, limiting the interpretation of large-scale and complex mock-ups dynamics. Also, conventional sensors add to small-scale models substantial mass, friction or stiffness, so as to influence the dynamic response characteristics of the studied systems.
In such context, the interest toward vision-based techniques is confirmed by some recent studies and experimental campaigns (Hutchinson et al. 2004, Fujita et al. 2005, Ray Chaudhuri et al. 2005).

Particularly promising in shake table tests are the light-based systems, which can utilize up to hundred small light wireless markers, as camera resolution and computational power are optimized.
In the present paper the use of a light-based system, named *3D-Vision*, offers the possibility of integrating motion data with three-dimensional FEM analysis to compare and update step by step experimental data and numerical simulations while the experimentation goes on.
Moreover, the numerical simulation of typical reinforced techniques are carried out by adding new appropriate elements to the original FEM.
FEM material properties and load boundary conditions are updated with the experimental results and the FEA is re-executed to optimize the FEM and to re-align it to the real structure.
The structural mode shapes and the relative resonance frequencies resulting from the experimental data and the FEA are also matched and compared.

2. THE 3D-VISION SYSTEM AT ENEA CASACCIA R.C. AND FEA

The 3D-Vision system was installed and is currently utilized at Qualification of Materials and Components Laboratory (UTTMAT-QUAL) of the ENEA Casaccia R.C. for 3D motion measurement during the execution of shaking table tests (Table 2.1). It is a 3D light-based system made up of 9 near infrared (NIR) digital cameras for data acquisition and 4 DV cameras for movies.

Table 2.1. Principal characteristics of the Qualification of Materials and Components Laboratory (UTTMAT-QUAL) facilities of the ENEA Casaccia R.C.

	Shake Table 1	**Shake Table 2**	**Shaker 1**	**Shaker 2**
Table size	4m x 4m	2m x 2m	1.5m x 1.5m	0.6m x 0.6 m
Degree of Freedom	6 DOF	6 DOF	1	1
Frequency range	0-50 Hz	0-100 Hz	5-2000 Hz	5-2000 Hz
Acceleration	3g peak	5g peak	125g (0-peak)	100g (0-peak)
Velocity	0.5 m/s (0-peak)	1 m/s (0-peak)	2 m/s (0-peak)	1.2 m/s (0-peak)
Displacement	0.25 m (0-peak)	0.30 m (0- peak)	0.025m (peak-peak)	0.025m (peak-peak)
Mass and G.C. height for rigid specimen	10 ton mass 1 m c.g height	1 ton mass 1 m c.g. height	145 KN Force	27 KN Force

Furthermore, remote users have the possibility to connect to DySCo virtual laboratory by ENEA-CRESCO facilities (Computational RESearch center on COmplex system) during tests: acquired data and movies can be viewed in real time via the Internet by the experimentation partners and stored in the ENEA archive accessible by a web page for future use by authorized remote users (De Canio et al. 2008). The ENEA grid and the CRESCO systems also give the remote users the opportunity to run heavy finite element structural analysis codes from powerful software packages available on CRESCO exploiting its parallel computation capabilities.
The NIR cameras are mounting a CMOS sensor with a full-frame resolution of 4 megapixels up to 370 fps (frames per second of capture speed, which corresponds to the system sampling frequency in Hz). In fact, the NIR cameras capture speed can be increased up to 2000 fps by partializing the sensors scan, which would imply a sensible reduction of image resolution. But, since earthquakes main spectral content is commonly below 20 Hz, shaking table tests do not usually need to exceed the sampling frequency limit of 370 Hz (in most tests conducted the sampling frequency is set at 200-250 Hz). Consequently, partial scan of cameras sensors is generally unnecessary for seismic application. The main specifications of the NIR cameras are shown in Table 2.2.

Table 2.2 Main technical specifications and performance of the NIR cameras of the 3D-Vision system.

Specifications	**Performance**
camera maximum frame rate at full resolution	370 fps (Hz)
camera maximum frame rate at partial scan	2000 fps (Hz)
max markers per second	136,000 markers/s (680 at 200 Hz)
sensor details	Vicon VEGAS-4 CMOS
sensor resolution	2352 x 1728
sensor grayscale depth	10 BIT

Cameras are installed onto the lab walls by means of bolted brackets provided with removable camera heads so that, alternatively, they can be mounted on professional tripods when required for particular geometric test configurations (Figure 2.1). By default, cameras are oriented in a way that the whole 3D measurement volume (including the shaking table and up to 5 m in height) is covered.

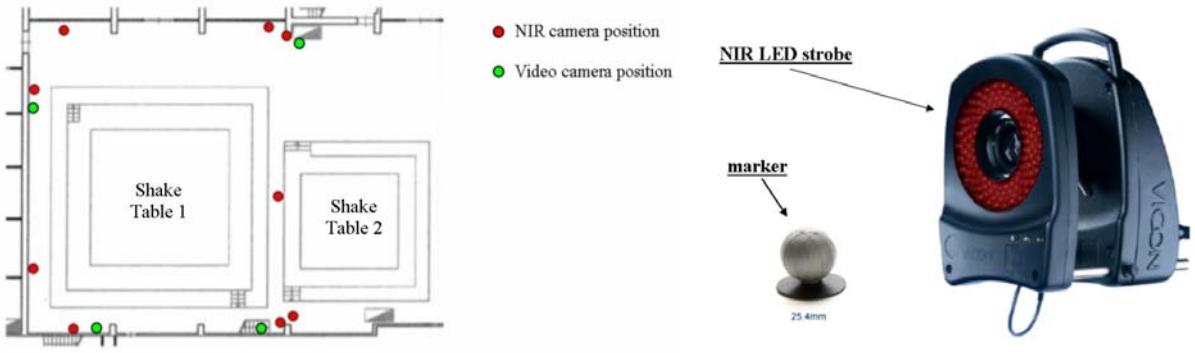


Figure 2.1. Plan view of the shaking tables and default position of the 3D-Vision cameras (left). Marker and NIR camera (right).

Each NIR camera is equipped with a strobe provided with powerful surface-mount Light Emitting Diodes (LEDs) emitting NIR light in order to illuminate the field of view as evenly as possible (Figure 2.1). Spherical retroreflecting markers with a diameter of 25 to 40 mm are used to reflect the NIR radiation. Such markers are located in the points of measure on the prototype structure under test by either hot glue or bi-adhesive strips, depending on the prototype surface material and smoothness.
NIR cameras are equipped with on-board processors for grayscale markers extraction and markers centers and radii calculation. These data are triangulated and processed in real time on the host PC by the motion capture software in order to obtain the markers trajectories. After post-processing, trajectory data are archived along with movies and available for analysis.
Precision in light-based systems depends on several aspects, such as camera resolution and speed, cameras geometry configuration (implying camera-marker distance, camera rays intersection angle, etc.), cameras calibration, markers size and reflectance (including the effect of dirty or occulted markers), overall scene lighting and non-marker reflections (erroneous detection can occur in case of too strong or weak light intensity or when objects in the scene reflect light similarly to markers).
In experimental campaigns conducted at ENEA Casaccia laboratory, precision of less than +/- 0.05 mm in terms of RMS error can be obtained (Figure 2.2.).

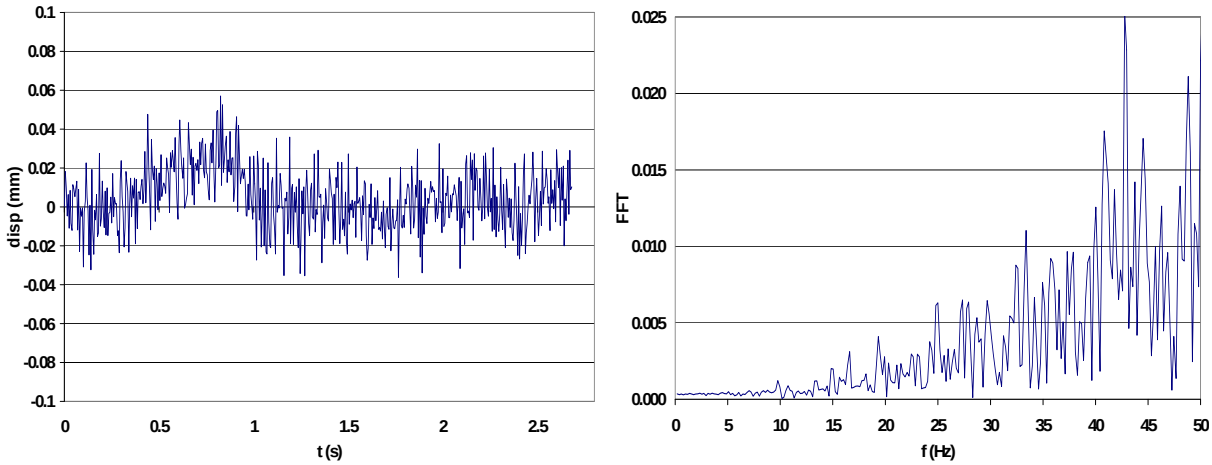


Figure 2.2. Typical 3D-Vision marker displacement error in time domain (left) and calculated acceleration error in the frequency domain (right).

Even if from displacement measurement the acceleration can be calculated, as well known, derivative calculation causes strong error amplification. However, as the calculated acceleration error increases with the frequency (Figure 2.2.) an accurate estimate of acceleration can still be achieved if main spectral components are at frequencies lower than 10-12 Hz, which is the case of many natural and EC8-compatible (Eurocode 8) synthetic seismic accelerograms. Noise at higher frequencies can be filtered by low-pass Butterworth (Butterworth, 1930) or by Savitzky -Golay algorithms (Savitzky et al. 1964).
The finite element method offers the possibility to study complicated structural systems using a connected collection of objects of various regular shapes and different properties called "finite elements". Any irregular geometry can be simulated by an assembly of discrete finite elements under general loading and constraint conditions by FEM analysis. The structural behaviour of the models comes from the analysis of the collective response of all elements. Moreover, finite element analysis decrease the number and the cost of prototypes and experimental tests.
Eurocodes (Eurocode 8) and Italian guidelines (MiBAC, 2006) for seismic verification of new and existing structures support the finite element approach and suggest linear static, dynamic and non linear analysis.
The realization of FE models is an important step to study and simulate the dynamic behaviour of the structures to be tested on the shaking table. More specifically FE analysis is integrated with the new 3D-Vision monitoring methodology, focusing on the parts of the models where the stress or strain concentrations can be very dangerous and allowing to validate the numerical model with experimental results.

3. THE ENEA METHODOLOGY

The methodology used at ENEA UTTMAT-QUAL is described in this paper. It can be divided into the following three steps (Mongelli et al., 2008):
1) Numerical analysis: static and dynamic numerical finite element analysis are preliminarily executed in order to obtain the stress-strain distribution and the approximate dynamic behavior of the structure to be tested. The numerical results obtained at this step allow to identify the positions where markers should be conveniently placed;
2) Shaking table tests, 3D-Vision data acquisition and Non-Destructive Testing (NDT) for material characterization: 3D-Vision system gives the possibility to measure the real seismic input to the mock-up base for FEA. At this level, the motion of any point on the tested structure can be simulated and compared to experimental data obtained by 3D-Vision markers.
Moreover, NDT is executed to measure the effect of the damage produced on materials properties during the shaking table experimentation;
3) FEM updating and FEA: during the experimental campaign, a calibration step of the FEM boundary conditions (materials properties, model constraints, loads etc.) can be implemented, with the purpose of improving the significance of next simulations along with the opportunity of increasing model reliability for similar tests. A few iterations are carried out until minimization of node-marker displacement difference.

3.1. Case study: church of St. Nicolò l'Arena

The above mentioned methodology was applied to the study of the dynamic behavior of the dome-drum system on top of the Benedictine Monastery's church of St. Nicolò l'Arena in Catania, Italy. An experimental campaign of shaking table tests was conducted on a 1:6 scaled mock-up representing the dome-drum system. The mock-up is in typical ashlar tuff masonry with a roof and a footing in R.C. (Figure 3.1). The material properties evaluated by literature and updated by non destructive sonic tests are illustrated in Table 3.1. A distributed mass of 88 KN weight was put on the top of the model.

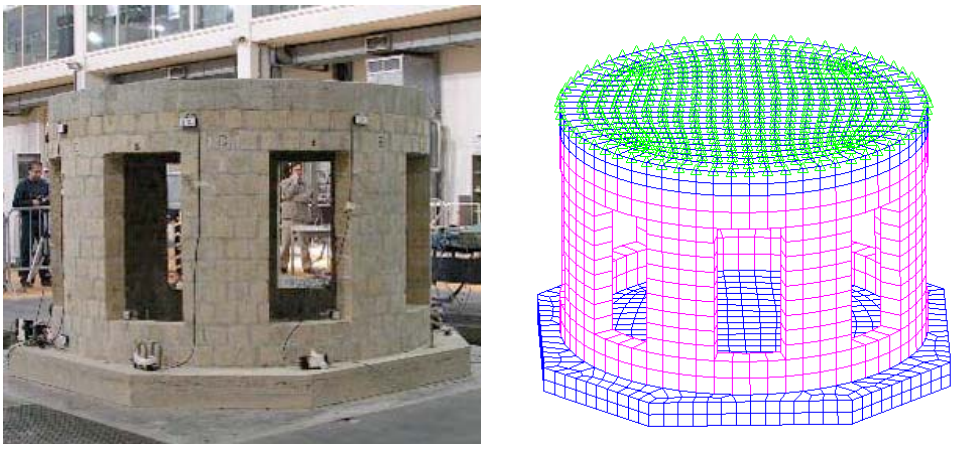
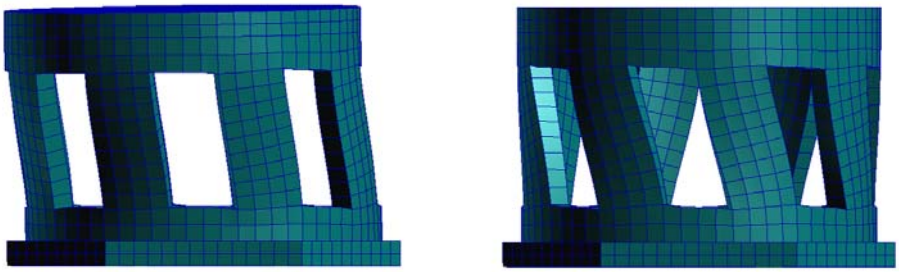


Figure 3.1. Mock-up (left) and FEM (right).

Table 3.1 FEM Material properties.

Properties	**R.C.**	**Masonry**
E [Pa]	3.8 E+10	2.4 E+8
ρ [kg/m^3]	2400	1600
ν	0.2	0.2

Before experimental tests a 3D static and modal FEA was preliminarily executed. The FEM was realized by Nastran code with 2648 exa8 solid elements to identify the resonance frequencies and the modal shapes of the structure (Figure 3.2).



I-II Mode: 3.8 Hz III Mode: 6.9 Hz

Figure 3.2. FEM resonance frequencies and modal shapes.

A shear-type mechanism at the top and bottom of wall of the piers and a twisting mechanism has been resulted by FEM analysis. The stress-strain distribution resulting from the executed FEA allowed to identify the most adequate positions for the markers as it is shown in Figure 3.3.
The Umbria-Marche earthquake registered in Colfiorito in September 1997 (Sabetta et al. 1999) was considered as reference for the scaled input time history. Displacements of mock-up footing, acquired by the 3D-Vision markers during shaking table tests, were inserted in the load boundary conditions of FEM and applied at the basis of the model for the execution of a linear transient FEA: the Figure 3.4. shows superimposition of the measured x, y displacements of the marker D1S at the base of the mock-up during the shaking table test and the x, y displacements input at the node 4841 of the FE calculation (see also Figure 3.5).

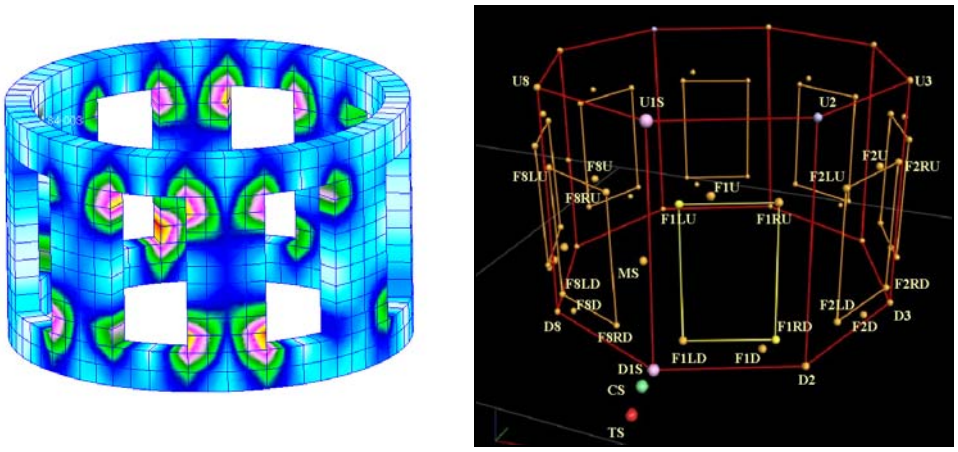


Figure 3.3. FEM stress-strain distribution (left) and 3D-Vision markers position (right)

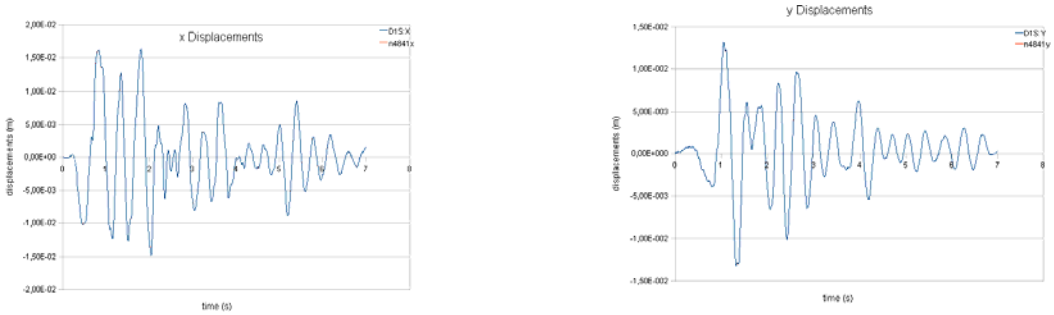


Figure 3.4. Input time history in x and y directions (FEM node 4841 and marker D1S).

Damping is assessed measuring the decay rate of mock-up free vibrations, according to the logarithmic decrement method, and with the FRF half-power bandwidth method (Chopra, 1995). The combined x, y displacements simulated by FEA in the nodes on the top (node 110), at the centre (node 1130) and at the bottom of the drum (node 4841) were post-processed and compared with 3D-Vision data (Figure 3.5).

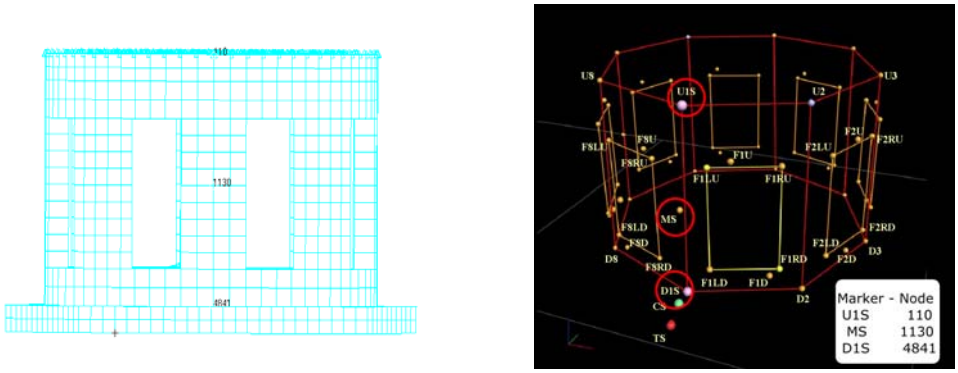


Figure 3.5. Correspondence between analyzed FEM nodes (left) and 3D-Vision marker (right).

The displacement increase of the nodes from the bottom to the top of the model agrees with experimental tests, which put into evidence the elastic-cracking behavior with limited tensile strength of the masonry and with the path of the fractures proceeding also from the bottom to the top of the mock-up (Figure 3.6).

Comparison between FEA and 3D-Vision displacements for nodes mentioned above are shown in Figures 3.7, 3.8.

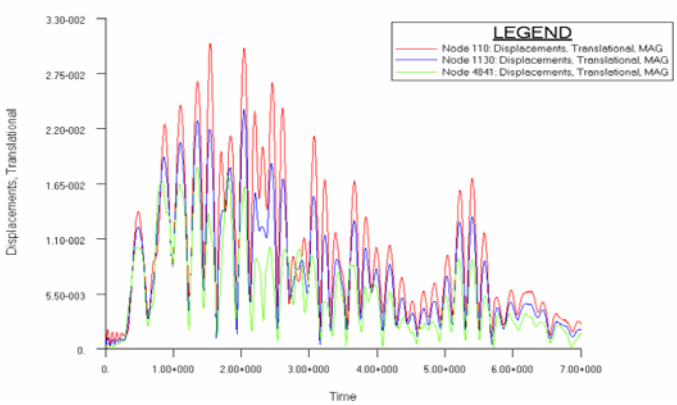


Figure 3.6. FEM absolute displacement results.

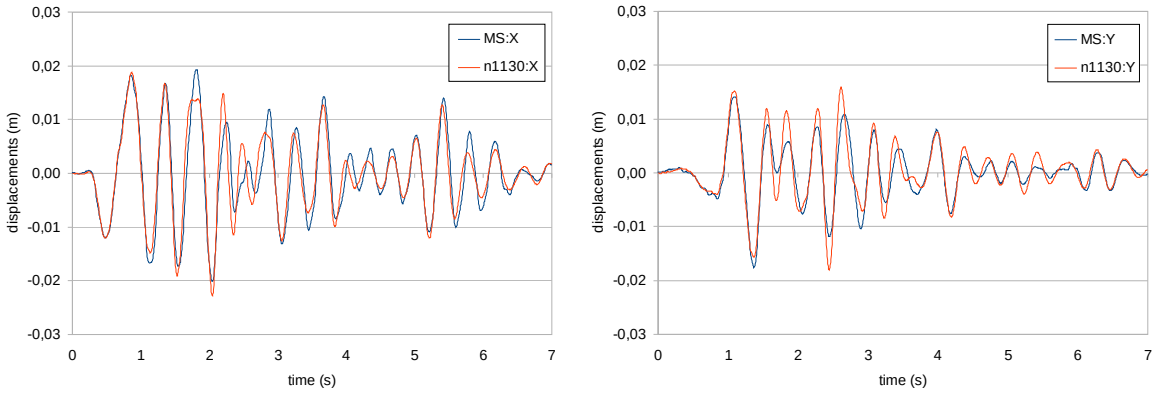


Figure 3.7. Node 1130 and marker MS (x and y displacements).

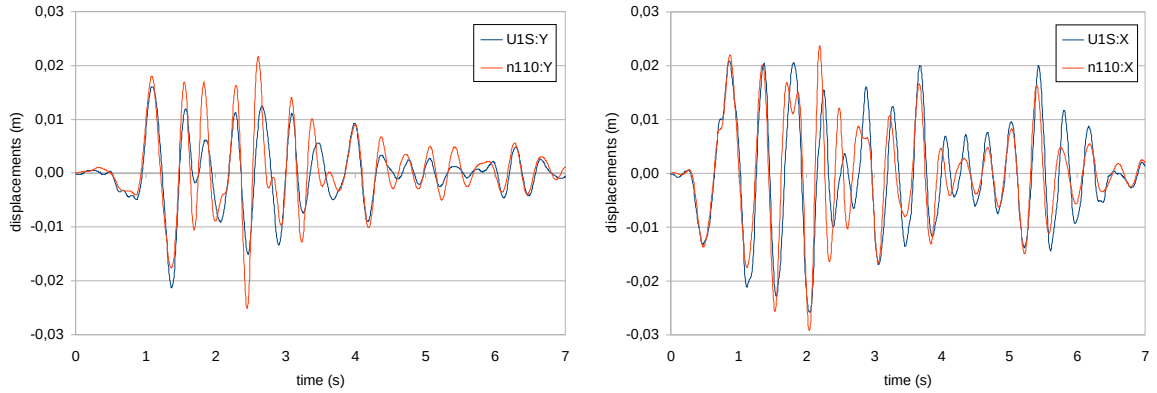


Figure 3.8. Node 110 and marker U1S (x and y displacements).

4. CONCLUSIONS

The dome-drum dynamic behavior of the St. Nicolò l'Arena was described to show the approach developed at ENEA research centre with the use of the 3D-Vision data acquisition system. Experimental results from shaking table tests confirmed a shear-type mechanism on the top and

bottom of the piers (plane sliding in the direction of the seismic input- bending behaviour) and a twisting mechanism confirmed by FEAs.
The results of the displacements evaluated in some nodes of the FEAs were compared with the real results registered by the markers located in the corresponding point on the real structure during the experimental campaign by 3D-Vision system. The results are shared in real time via the Internet while the experimentation goes on. FE analyses can be re-executed to optimize the FE models and to re-align them to the real structure. Moreover, ENEA CRESCO facilities with its capabilities of parallel computation offer the possibility of integrating 3D-Vision motion data with three-dimensional FEA analysis.

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