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An innovative shaking table controller system by 3DVision displacement measures

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ABSTRACT

The Qualification of Component and Material laboratories at the ENEA Casaccia Research Center, Roma (Italy) has developed an innovative optical based displacement data acquisition system named 3DVision for the two 6-Degree-Of-Freedom (6DOF) shaking tables, in terms of displacement, to achieve the optimal match between commanded and achieved motion at the base of the table. The motion of the shaking table is actually controlled by servo-hydraulic control loop system based on the comparison of the combined three variable displacement-velocity-acceleration feedback signals from transducers positioned on the shaking table actuators with the reference time history, so that adjustments can be made when the measured response does not match the commanded shaker input motion. The indirect measurement of the velocity feedback is an important contributor to the difference between the reference and achieved motion. Among the conventional measurement instrumentations like accelerometers, strain gauges, optic fiber sensors, laser displacement sensors and LVDTs, the laboratory is equipped with a recently installed high resolution 3D motion capture system named 3DVision. It is an optical system for 3D motion measurement exploiting a constellation of 9 near infrared (NIR) digital cameras for data acquisition and 4 DV cameras for synchronized movies. Retro-reflecting markers are positioned on the tested structure and their trajectories are reconstructed by spatial triangulation of NIR cameras rays. The 3D-Vision system can detect the complete motion of up to hundred markers fixed on the shaking table and on the specimen, therefore it is able to directly measure the displacement of every marker and can provide the achieved signal of the specimen motion in order to implement control of the shaking table in active mode.

Keywords: *Shaking table tests, Control technologies, displacement measure*

1 INTRODUCTION

Large scale test facilities for vibration and seismic tests are available at the ENEA-Qualification of material and technologies laboratories of the Materials and New Technologies Technical Unit at the Casaccia Research Center of Roma, Italy. They consist of two electro dynamic shakers and two high performance seismic shaking tables for three axial seismic tests of structures up to 10 ton mass and 3g acceleration applied at the G.C. (Gravity Center) at 1m from the base table, or, equivalently, 30 ton mass and 1g acceleration applied at G.C.

Table 1. Test facilities at ENEA C.R. Casaccia laboratories

	Table 1 (Master)	**Table 2**	**Shaker 1**	**Shaker 2**
Table size	4m x 4m	2m x 2m	1.5m x 1.5m	0.6m x 0.6m
Degree of Freedom	6DOF	6DOF	1DOF	1DOF
Frequency range	0-50 Hz	0-100 Hz	5-2000 Hz	5-200 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/Force **G.C. height**	10ton 1m g.c. height	1 ton 1m g.c. height	145 KN Force 1m g.c.height	27 KN Force 1m g.c.height

The shaking table tests can simulate the real stress fields in structures due to dynamic loads induced by wind, traffic and earthquakes. Beside the traditional sensors (accelerometers, LVDT, strain gauges) normally used in dynamical tests, the data acquisition are also performed by the high resolution 3D optical movement detection and analysis tool named "3DVision" [1]. It is a 3D light-based system and its purpose is to track the dynamic displacement of several selected points of the structures during the dynamic tests of natural (earthquake) and artificial (mechanical) induced vibrations. It is composed of 9 near infrared (NIR) digital cameras for data acquisition and 4 DV cameras for movies. 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 1.

Table 1. Main technical specification and performance of the NIR cameras of the 3D-Vision system

Specifications	**Camera performance**
Camera maximum frame rate at full resolution	370FPS Hz
Camera maximum rame rate at partial scan	2000 FPS Hz
Max markers /sample rate	680 /200Hz
Sensor resolution	2352 x 1728
Sensor grayscale depth	10 bit

Cameras are installed on 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.). 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.

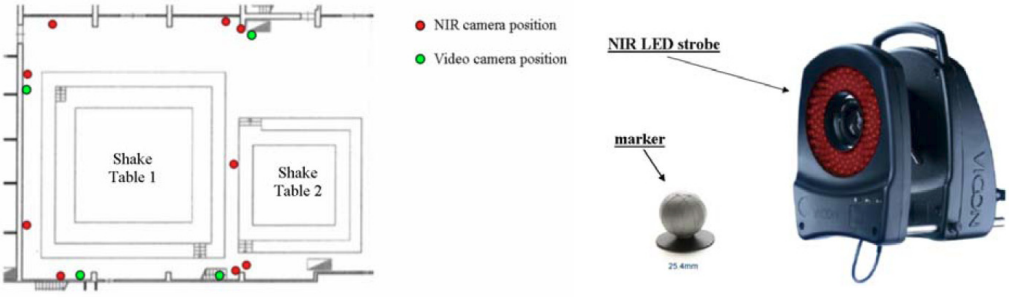


Fig. 1 Plan view of the shaking tables and default position of the 3D-Vision cameras (left). Marker and NIR camera (right).

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 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 greyscale 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 archive and the evaluation of the experimental measures 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).

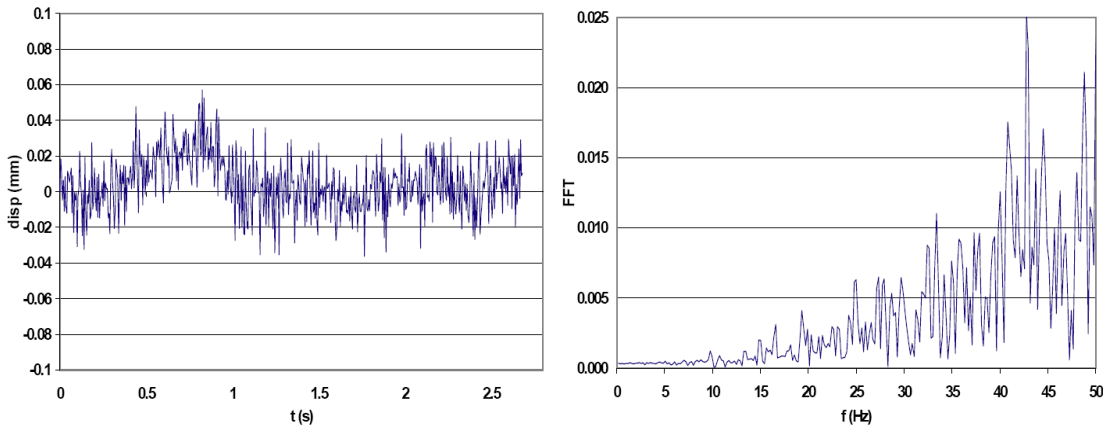


Fig.2 Typical 3D-Vision marker displacement error in time domain (left) and calculated acceleration error in the frequency domain (right).

Even if from displacement measurement the acceleration can be calculated by double derivation, it is well known the problematic related to the strong derivative calculation errors. However, as the calculated acceleration error increases with 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 the seismic accelerograms.

Noise at higher frequencies can be filtered by low-pass Butterworth (Butterworth, 1930) or by Savitzky-Golay algorithms (Savitzky et al.1964). At ENEA UTTMAT-QUAL laboratory the first step of the marker displacement data analysis consists in the time histories filtering using a Savitzky-Golay polynomial filter (SGfilter). The same filter is used for first and second polynomial derivatives (SGderiv). The choice of the most appropriate filtering parameters in SGfilter and SGderiv has been made comparing the results from different combinations of the parameters. E.G. the figure 3-b shows the effect of the SGfilter with different polynomial degree (6th and 2th) and same windowing width (129 pts).

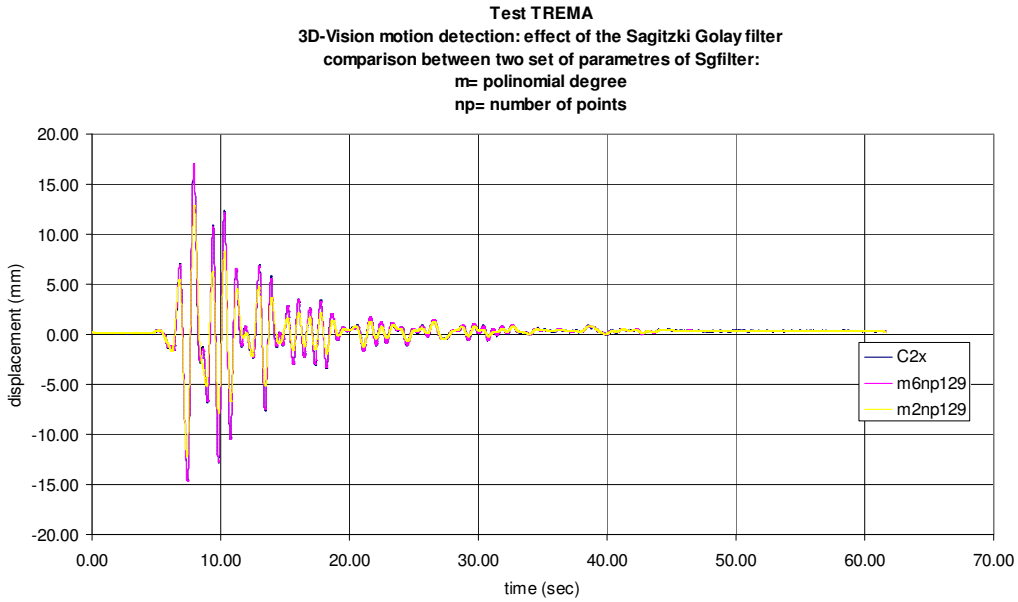


Figure 3a. effect of the polynomial degree values in the Savitzky Golay filter of the Displacement time histories detected by the 3D-Vision motion detection system.

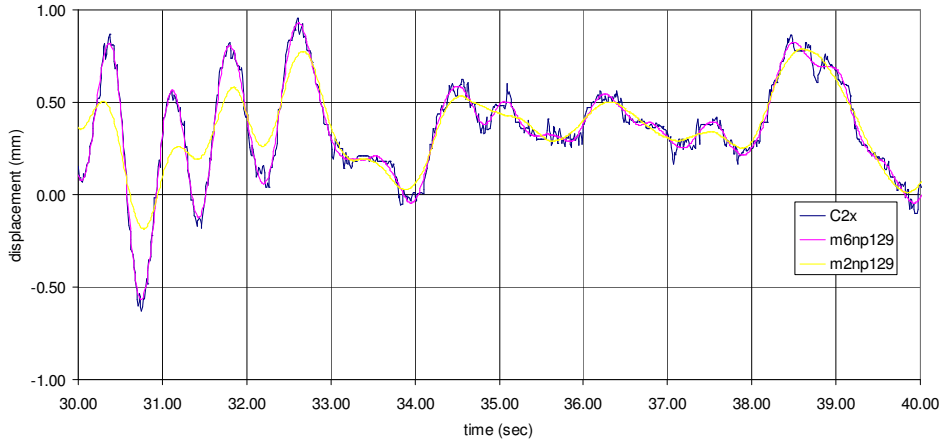


Figure 3b Zoom window of 10 seconds in the interval 30-40 sec

The 3D-Vision system allows to make movies during the tests superposing the numerical model to the imaging detected by two high resolution visible cameras (figure 4). It is able to measure accurate 3-D positions of hundred retro-reflecting markers placed on the structure during the seismic tests, their trajectory is reconstructed by spatial triangulation of NIR cameras rays (Figure 4). The resulting graphic reconstruction (a friendly wireframe) of the tested mock-up is shown to the remote users, along with graphs for monitoring the motion of one or more selected markers. Synchronized movies of the test, optionally with the wireframe overlay, can be also viewed in the case of figure Figure 5.

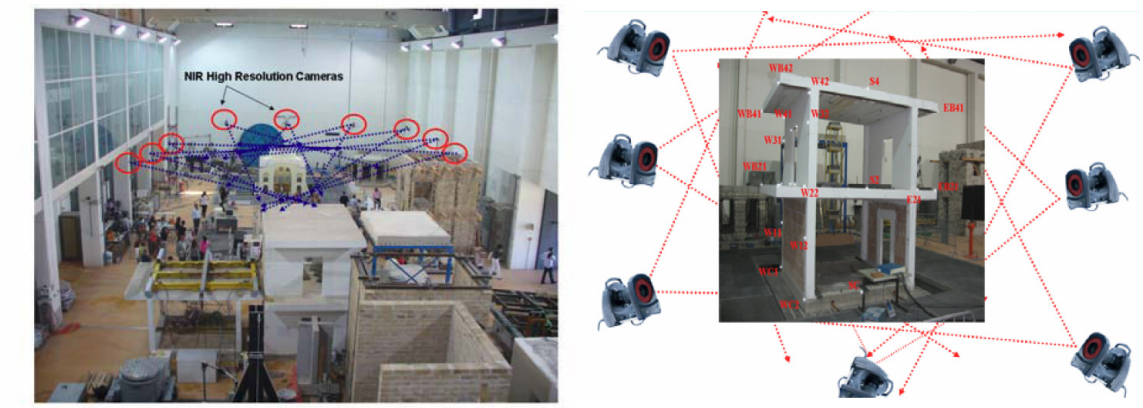


Figure 4 VISION of the system: position of the cameras to detect the motion of the markers.

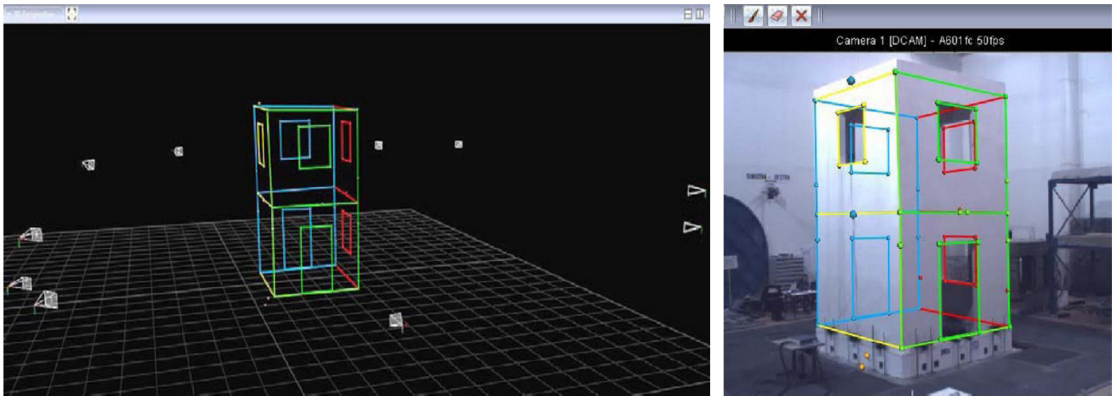


Fig. 5 constellation of NIR cameras of the 3DVision system and wireframe reconstruction (left) and 3D overlay synchronization of wireframe and visible images (right).

This monitoring technique allows measuring 3 axial absolute displacements with easy and fast test set-up, high accuracy and the possibility to link the 3D-motion time histories of the tracked markers with CAD drawings of the structure and validate the FE models in real time experimental data assimilation. The direct measure of the displacement is very strongly supported for the structural design in earthquake engineering by Eurocodes and Italian guidelines (MiBAC, 2006). Moreover it is suggested the approach of finite element analysis (linear static, dynamic and non linear analysis) to study the dynamic behaviour of new and existing buildings. For this reason the 3DVision system is commonly used during all the shaking table tests carried out in the laboratory and many structures involved in different application fields are experimentally verified. More specifically FE analysis is integrated with the new 3DVision monitoring methodology, focusing on the parts of the models where the stress or strain concentrations can be very dangerous and allowing validating the

numerical model with experimental results [2]. The possibility to synchronize visible and infrared cameras of the 3DVision System allows the remote participation and control of the shaking table tests in a networking configuration of distributed experiments The conceptual structure of this networking configuration within the virtual framework DySCo (structural Dynamic, numerical Simulation, qualification tests and vibration Control) is shown in the Figure 6. As the experimentation goes on, remote users have the possibility to interact step by step with the operator [3]. The connection to DySCo is provided by the ENEA grid of numerical computation, the results are shared in real time via Internet among the partners of the experiment. The possibility to synchronize visible and infrared cameras allow the remote participation and control of the shaking table tests in a networking configuration of distribuited experiments. In the following figure is showed the conceptual structure of this networking configuration. This test facility is nested within the ENEA Grid of computational and experimental facilities: the Tokomak particle accelerator at the ENEA Frascati Research center, the ABI Prism 3700 DNA sequence system at the ENEA Trisaia Research Center, the 300 KeV Electron microscope at the ENEA Brindisi research center and the (future) CTM test facility for simultaneous mechanical-Climatic experiments at the ENEA Portici Research center.

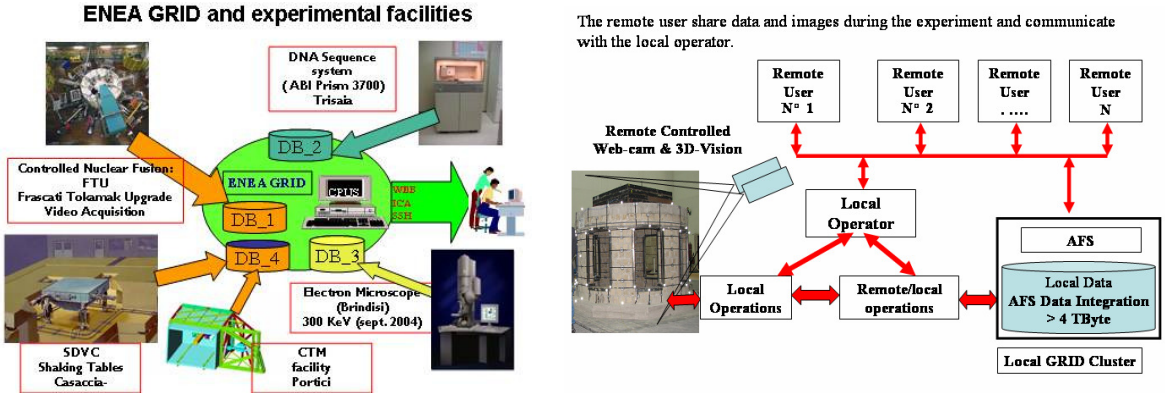


Fig. 6: ENEA Grid of remote controlled test facility

The conceptual structure of the remote shaking table operations is shown in fig. 6. At this stage the remote operator share data and image during the experiments and communicate with the local user, the only operator abilitated to drive the test. Furthermore, in the laboratory remote users have the possibility to connect to DySCo virtual laboratory by ENEACRESCO 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 [3]. 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.

2 EXPERIMENTAL DATA ACQUISITION: EVAUATION OF UNCERTAINITY IN THE MEASURES

A study was executed evaluating the Accuracy of experimental data obtained by shaking table tests with the comparison of the traditional results obtained by accelerometers (traditional sensors) and markers (3Dvision). The tests were performed using four time-histories scaled and applied along x, y and z directions: Nat1, Nat2, Pettino and Aterno. Nat 1 and Nat2 are the spectra of two natural

earthquakes from "strong motion database" scaled to the maximum values predictable for the site of Reggio Calabria with a return period equal to 2475 years. Pettino and Aterno are natural spectra recorded by seismic stations during the 2009 l'Aquila earthquake. The experimental campaigns were carried sampling the 3Dvision data at 200Hz rate. The green and blue markers of the 3Dvision system are highlighted in the yellow rectangle in the Figure 7 and are physically fixed on two accelerometers placed on the table. The graphs on the right represent the coordinates x, y and z of the trajectory of the blue marker during the test execution obtained by Nat2 input (not scaled).

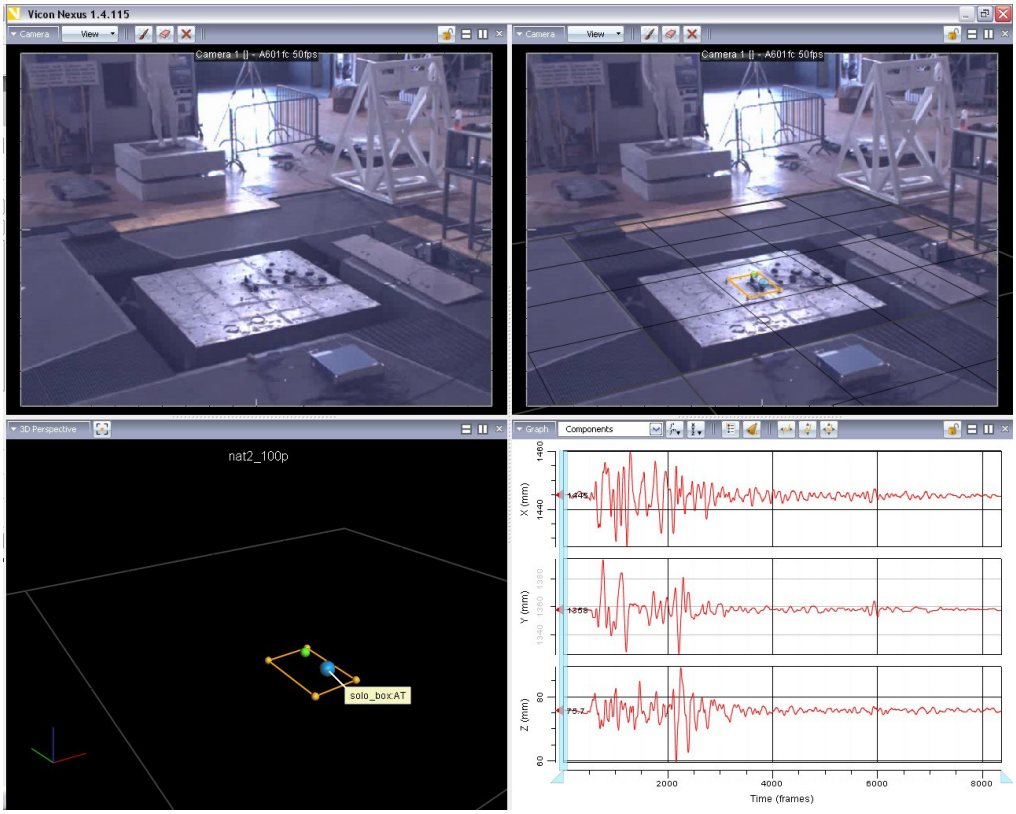


Fig. 7 Test Nat2_100p

Experimental data obtained by traditional accelerometers and 3Dvision systems were post processed and analyzed considering the following index: Amax = Max acceleration peak; Arms = average quadratic acceleration; ARIAS = Index of Arias Intensity; IC = Characteristic intensity; HI=Integral of velocity spectrum. Arms is related to the average energy contained in the accelerometric signal, it's slightly influenced by high frequency components, and does not give information about frequency content. *Ia* a scalar entity and measures total energy per mass unit transmitted by the earthquake to a battery of 1 GDL oscillators without dampening. Ic measure of potential destructive strength of the earthquake, it is the significant duration of the earthquake, defined as the time interval within which Arias Intensity goes from 5% to 95% of maximum value. Hi is the integral of velocity spectrum, it's a measurement of potential of the earthquake to cause damage to a population of structures whose fundamental vibration period is within the integral limits. It's a variant of Housner index, where limist of integral are t_1=0.1 sec, t_2=2.5 sec. Housner index gives a good correlation for structures having high period. Characteristic periods of .15sec, 0.4sec, 0.5sec, 2sec, 3sec, 4sec allow to define the seismic response spectrum for type A and type BCE terrains according to Italian laws, and to obtain the Sa acceleration spectrum and Se energy spectrum:

Table 2. Main technical specification and performance of the NIR cameras of the 3D-Vision system

Arms: average quadratic acceleration	$A_{rms} = \sqrt{\frac{1}{tr}\int_0^{t1} a(t)^2 dt}$
Arias- Arias Intensity	$Ia = \frac{\pi}{2g}\int_0^{\infty} a(t)^2 dt$
Ic – Characteristic Intensity	$Ic = (a_{rms})^{\frac{2}{3}}\sqrt{tr}$
HI- Spectral Intensity	$HI = \int_{t1}^{t2} Sv(t,\xi)\ dt$

The "Acceleration Spectrum" Sa(T,ζ) is the response of a battery of 1 GDL oscillators with own period T and dampening coefficient ζ (e.g. a structure with period T and dampening coefficient ζ subject to that specified time history would have a maximum acceleration equal to Sa). The " Energy Spectrum" Se(T, ζ) is the amount of maximum elastic deformation energy of 1 GDL oscillators subject to the earthquake.

3 CONCLUSION

The innovative monitoring technique at the ENEA laboratories allows measuring 3 axial absolute displacements with easy and fast test set-up, high accuracy and the possibility to link the 3D-motion time histories of the tracked markers with CAD drawings of the structure and validate the FE models in real time experimental data assimilation. The possibility to synchronize visible and infrared cameras of the 3DVision System allows the remote participation and control of the shaking table tests in a networking configuration of distributed experiments The conceptual structure of this networking configuration within the virtual framework DySCo (structural Dynamic, numerical Simulation, qualification tests and vibration Control)

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