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Experimental tests of reinforced concrete buildings and ENEA DySCo Virtual Laboratory

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In the present paper, an innovative methodology for an integrated use of three-dimensional Finite Element Model (FEM) analysis and motion capture data from shaking table tests is proposed.
Recently, a high-resolution 3D motion capture system named 3DVision was installed at ENEA Casaccia Research Center as an alternative to conventional displacement instrumentation for shaking table tests, such as LVDTs and laser sensors. Among the advantages of the 3DVision system, there is the possibility of monitoring the complete motion of more than a hundred markers on the structure and on the table during tests. Moreover, the 3DVision system allows sharing the experimental results in real time, via the DySCo Virtual Laboratory (Structural Dynamics, numerical Simulation, Qualification tests and vibration Control).

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ABSTRACT In the present paper, an innovative methodology for an integrated use of three-dimensional Finite Element Model (FEM) analysis and motion capture data from shaking table tests is proposed. Recently, a high-resolution 3D motion capture system named 3DVision was installed at ENEA Casaccia Research Center as an alternative to conventional displacement instrumentation for shaking table tests, such as LVDTs and laser sensors. Among the advantages of the 3DVision system, there is the possibility of monitoring the complete motion of more than a hundred markers on the structure and on the table during tests. The 3DVision system allows sharing the experimental results in real time, via the DySCo Virtual Laboratory (Structural Dynamics, numerical Simulation, Qualification tests and vibration Control).

1 INTRODUCTION

Research activities at the ENEA Materials and Devices Qualification Laboratory (UTTMAT-QUAL) are mainly devoted to experimental tests on innovative systems for seismic isolation and retrofitting of civil, industrial, and historical buildings by shaking tables.
Seismic tests of sub-structures and scaled mock-ups are executed in order to identify the failure modes of the building structural parts. Moreover, new reinforced systems and isolation/dissipation performance of anti-seismic devices are evaluated.
Before testing the structures, finite element analysis is carried out, to understand the dynamic behavior and obtain a map of stress and strain distribution, frequencies and modal shapes. These are used to set the position of traditional sensors and of many "markers" of the 3D motion capture innovative system named 3DVision.

Furthermore, material properties are very often unknown: destructive and non-destructive (sonic and ultrasonic) tests are executed before, during and after the shaking table experimental campaign to assess the mechanical properties and validate the numerical model. Therefore, it is necessary to validate the finite element models by updating and refining them step by step by the experimental results which came from the shaking tables and non-destructive tests.
Design of FE models is an important step to study the dynamic behavior of the structures to be tested. In this study FE analysis is integrated with the new 3DVision monitoring methodology, focusing on the parts of the models where the stress or strain concentration can be very dangerous, and allowing validating the numerical model with experimental results.
The 3DVision system used at ENEA is the first example in the world of 3D optical movement detection applied to shaking table experiments: together with traditional sensors (accelerometers, LVDT), it tracks the dynamic displacement of several selected points of the structures during the dynamic tests of natural (earthquake) and artificial (mechanical) induced vibrations [1][2]. The synchronization of visible and infrared cameras of the 3DVision system allows, within the virtual framework DySCo (Structural Dynamics, numerical Simulation, Qualification tests and vibration Control) laboratory, the remote participation and control of the shaking table tests in a networking configuration of distributed experiments [3]. Results are shared in real time by the Internet among the partners of the experiment and stored in ENEA web pages for future use and for remote users. In this paper, the 3DVision system and DySCo Virtual laboratory are described, showing and comparing the experimental results obtained by shaking table tests to study traditional and non-traditional technologies for seismic protection and rehabilitation of movable and immovable structures for civil, industrial and cultural heritage applications.

2 FINITE ELEMENT METHOD AND THE 3DVISION SYSTEM AT CASACCIA R. C.

Finite element (FE) analysis showed in this paper is used to predict the structural behavior of buildings and other structures to seismic attack, to support new monitoring methodologies, and to test the effect of new devices or techniques to consolidate and protect them. Simulations allow to decrease the number and the cost of prototypes and experimental tests, fix the research activities especially in areas where the stress or strain concentrations can be very dangerous, and allow comparing modal shapes and frequencies numerically obtained with experimental results.
Numerical methods, which include FE methodology, can solve a broad range of problems because they can approximate the behavior of any arbitrarily shaped structure under general loading and constraint conditions with an assembly of discrete finite elements which have regular geometric shapes and known solutions. The FE method is a numerical approximation method. It is a method of investigating the behavior of complex structures by breaking them down into smaller, simpler pieces. These smaller pieces of structure are called elements. Moreover, finite element analyses decrease the number and the cost of prototypes and experimental tests. Eurocodes [4] and Italian guidelines [5] for seismic verification of new and existing structures support the finite element approach and suggest linear static, dynamic and non linear analysis.

3 3DVISION SYSTEM AND DYSCO LABORATORY AT ENEA CASACCIA R.C.

The 3DVision 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 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 1. Technical specifications of the Qualification of Materials and Components Laboratory UTT MAT-QUAL facilities at ENEA Casaccia R.C.

	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 0.6 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 1m c.g height	1 ton mass 1 m c.g.height	145 KN Force	27 KN Force

Furthermore, remote users can connect to DySCo virtual framework by ENEACRESCO facilities (Computational RESearch center on COmplex system): 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 [6]. 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 mega pixels up to 370 fps (frames per second of capture speed, which corresponds to the system sampling frequency in Hz). In most tests conducted the sampling frequency is set at 200-250 Hz [7] [8]. The realization of FE models is an important step to study and simulate the dynamic behavior of the structures to be tested. 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 [9]. 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 retro reflecting markers are used to reflect the NIR radiation. Such markers are located in the points of measure on the prototype structure. 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 [10] [11]. 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.

4 CASE STUDY: TRADITIONAL AND NON TRADITIONAL CONCRETE STRUCTURES SEISMICALLY ISOLATED AT THE BASIS

The ENEA and The “Filippo Brunelleschi” Technical School of Acireale (Italy) signed an agreement titled “Diffusion of the culture to prevent the seismic risk and to test new systems for

building protection" where the most important public and private subjects involved in the project were: the University of Catania, the University of Potenza, the CEFME (Centro di Formazione Maestranze Edili), the AIPND (Italian Association of Non Destructive Tests), the SICILFERRO and TIS S.p.A. The goal of the project was to involve the students to the experimental activities of large scale laboratories for seismic rehabilitation of buildings. The seismic tests was performed on two 2:3 scaled mock-ups, with the same geometry built by Sicilferro Torrenovese Company. One of them was executed with traditional methodology (TCs); the other was built with Non Traditional (NTCs) anti-seismic techniques by "light reinforced roofs" called "Plastbau Metal", that uses polystyrene strengthened by steel elements. The NTCs also includes beams built according to a technique named "Reticular Beam", designed to bear high load with low thickness, and reduce building cost. The mass of 800 kg was applied on each roof due to compensate the effect of the scaled mock-up. A 3D FE model with hexa-elements (Figure 1) and FE static, modal and non linear analysis were executed to set the areas where traditional (accelerometers) and innovative (markers) sensors had to be conveniently positioned in the structure. During the experimental campaigns a series of Non-Destructive Testing (NDT) for material characterization was performed after each seismic test to measure the effect of the damage produced on materials properties. Calibration steps of FEM boundary conditions in terms of material properties, model constrains, loads etc can be implemented and few iterations are carried out until minimization of node-marker displacement difference. In the first part of the experimentation, the dynamic behaviour of both structures was verified by shaking table tests, to obtain a first damage. Then, the innovative structure with seismic light reinforced roofs was isolated at the basis with traditional anti seismic devices and new tests were executed.

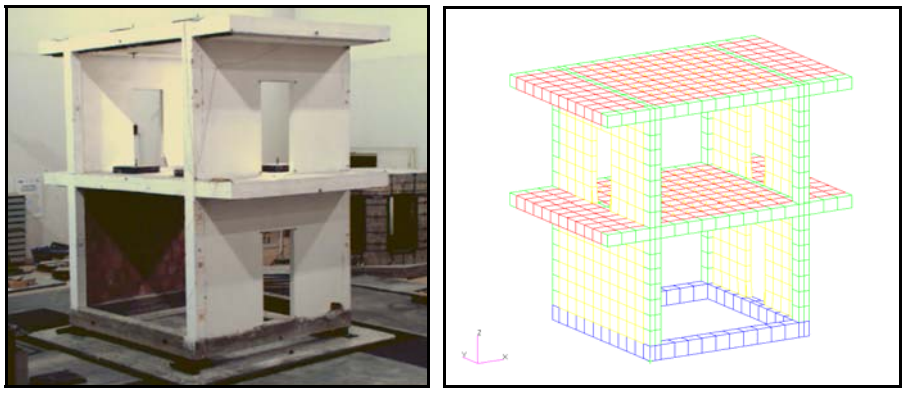


Figure 1. Mock-up and FEM

4.1 Traditional (TCs) and Non Traditional Concrete Structures (NTCs)

Before shaking table tests a preliminary 3D static and modal FEA was executed. The FEM was realized by 1100 Hexa8 solid elements to identify the resonance frequencies and modal shapes of the structure. Ultrasonic tests were executed and the estimated values of the mechanical properties were inserted in the FEM (Table 2). The centre of gravity coordinates are shown in Table 3.

Table 2: Material properties.

	E Pa	δ kg/m^3	ν -
Base (blue-Fig. 1)	3.4E+10	2400	0.2
Beam and Pillar (green-Fig. 1)	2.8E+10	2400	0.2

Table 3 for TC shows that for NTs, traditional roof is heavier, so the center of gravity is higher than in NTCs, that is a disadvantage in dynamic behavior of the whole structure.

Table 3: Center of gravity coordinates.

	X m	Y m	Z m
TCs	1.49	1.50	2.77
NTCs	1.49	1.50	2.71

Table 4 shows the first two FEM longitudinal resonance frequencies for both structures.

Table 4: FEM resonance frequencies.

	TCs model	NTCs Model
I mode	2.8 Hz	3.7 Hz
II mode	6.1 Hz	7.1 Hz

Strain energies and modal shapes of the two structures are very similar, but frequencies are higher in the NTCs. The only difference in strain energies consists in lower values for the NTCs near the windows at the second level, but it is due to lesser inertia of the roof. The marker displacements (Figure 2) were measured by 3DVision System.

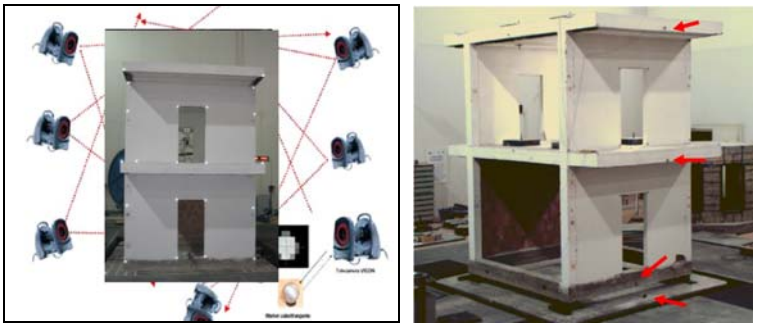


Figure 2. 3DVISION system (left), traditional sensors location and markers (right).

As the experimental campaign went on with increasing seismic input, the frequencies became lower, due to the beginning of fracture in the model. The TCs collapsed at 0.35 g, while experimental tests for NTCs continued until 0.5 g and “a first damage was verified”. The shifts of the frequencies for the first mode in the two structures are shown in Figure 3. The drift comparison was calculated in terms of displacement between two points (one at the first level and one at the second level) for the two structures as is shown in Figure 4a and Figure 4b where the drift is lower in the NTCs. The NTCs damaged structure above described was isolated at the basis by four elastomeric devices and it was subjected to a new experimental campaign. Besides 3D Vision markers, traditional sensors (accelerometers and LVDT) were applied for monitoring the behaviour of the structure too. Increasing seismic input, the frequencies decreased until 1.3 Hz (PGA 0.7g) for the NTCs seismically isolated at the basis, as it is shown in Figure 5 for the first mode. Markers accelerations obtained by 3DVision system are shown and compared in Figure 6a and Figure 6b for the structure fixed and isolated at the basis.

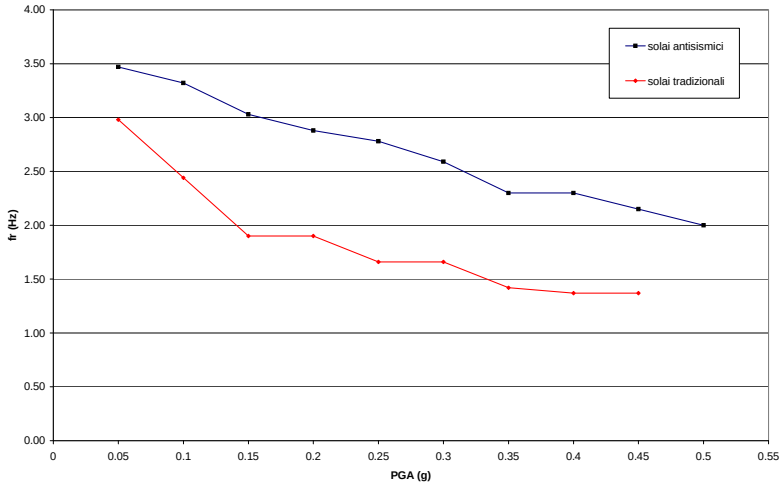


Figure 3. Frequencies [Hz] vs seismic input in TCs (red) and NTCs (blue).

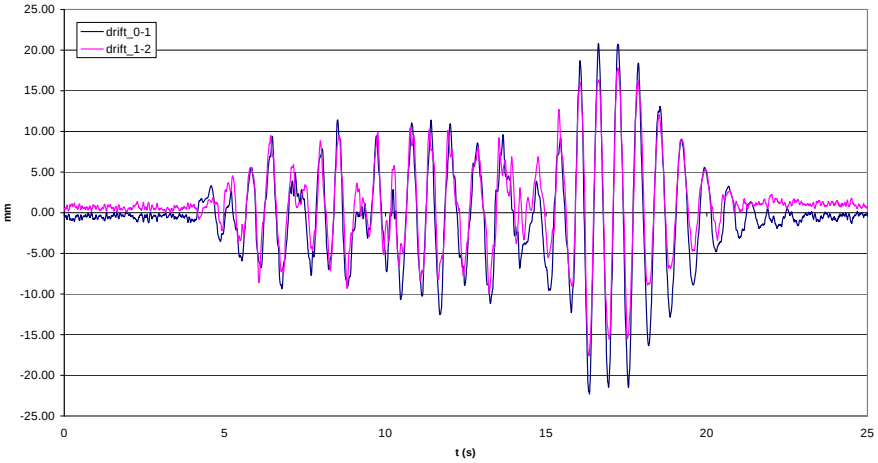


Figure 4a. Drift 0-1 and Drift 0-2 for TCs

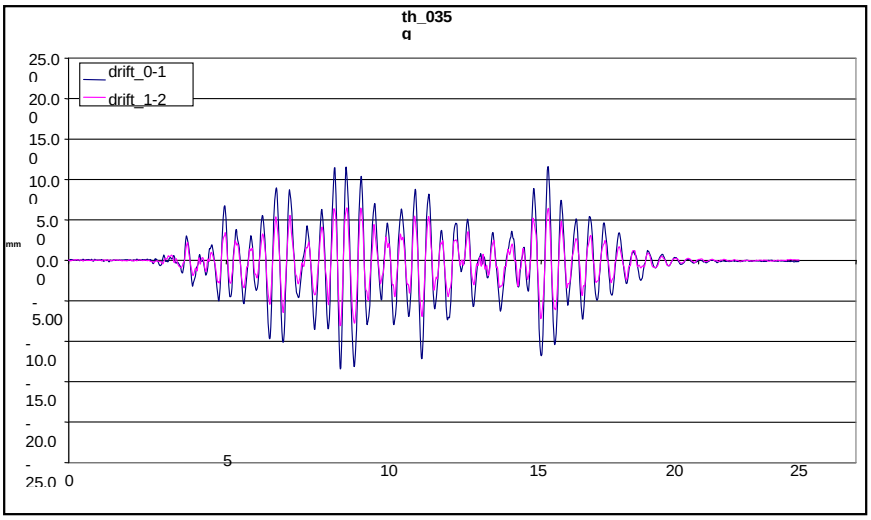


Figure 4a. Drift 0-1 and Drift 0-2 for NTCs

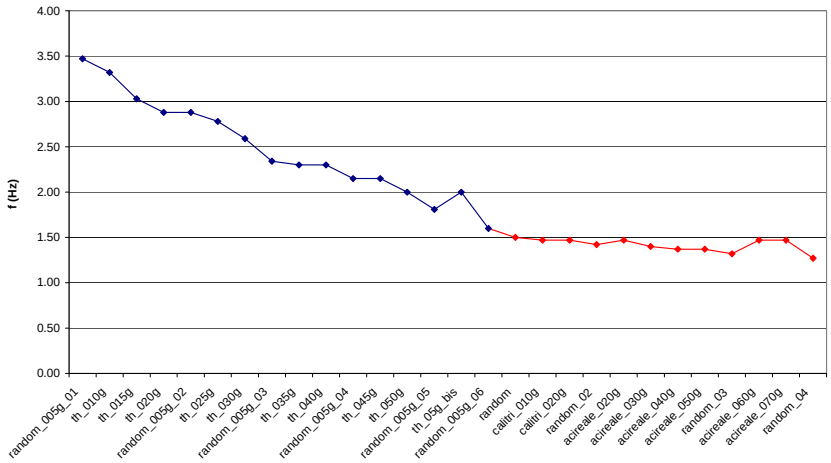


Figure 5. NTCs shift Frequencies vs seismic input fixed (blue) and isolated at the basis (red)

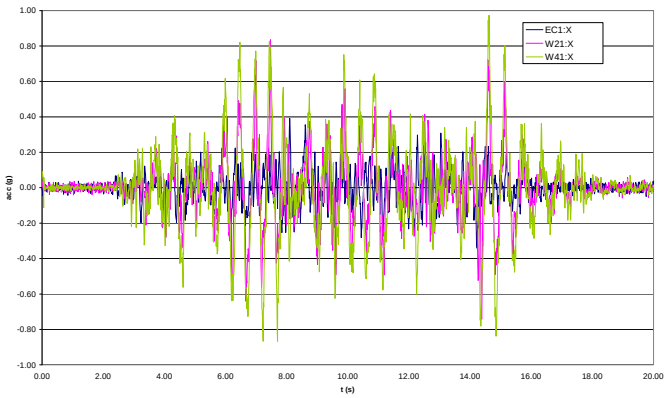


Figure 6a. Accelerations at AC Base, W21 (first level) and W41(second level) at PGA=0.5 g for NTCs fixed at the basis

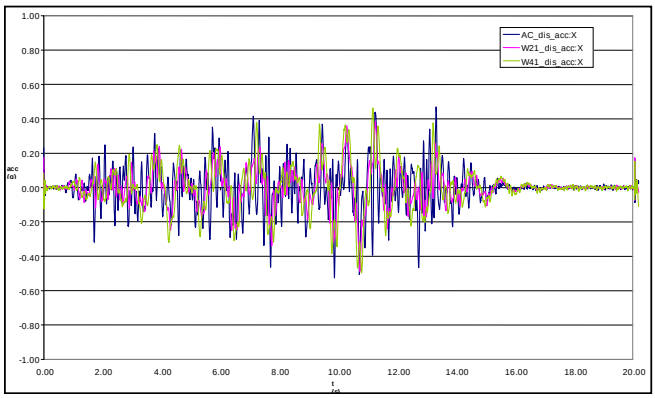


Figure 6b. Accelerations at AC Base, W21 (first level) and W41(second level) at PGA=0.5 g for NTCs isolated at the basis

5 CONCLUSIONS

Two series of experimental tests were carried out on a non traditional concrete structure (NTCs) built with the "Plastbau Metal" technique (polystyrene reinforced by metal elements) and light roof with reticular beams. The tests were performed on shaking tables using 3DVision data acquisition system and the results have been compared to those obtained on an identical twin structure built by traditional technique (TCs). In the first series of tests both structures were tested in a fixed base configuration using seismic inputs at increasing intensity until first damage was obtained. Purpose of the tests was comparing the dynamical behavior of the two structures subjected to the same sequence of seismic loads. The non traditional concrete structure showed better performance compared to the traditional one. The TCs reached the Ultimate Limit State with heavy damages and was removed, hence the second experimental campaign was performed only on the NTCs which reached only its Damage Limit State. It was isolated at the base with elastomeric devices without any repairing intervention. Even if the damages by the previous tests at fixed base were not repaired, the isolated NTCs was able to withstand much higher acceleration levels than the one in the fixed base configuration. 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. FE analyses were re-executed to optimize the FE models and to realign them to the real structure. The experimental campaign performed on the non traditional model isolated at the basis was shared in real time by Internet, via the DySCo virtual framework, and the results were stored in ENEA web pages for future use. This was one of the most important goals of this project to diffuse the seismic safety culture.

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