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SHAKING TABLE TESTS ON C-SHAPED MASONRY WALLS: DISPLACEMENT FIELD DATA DETECTED BY 3D MOTION CAPTURE SYSTEM AT ENEA CASACCIA RESEARCH CENTER

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Abstract. *This paper describes the results obtained by shaking table tests on unreinforced and reinforced full scale C-shaped masonry walls performed at the Qualification of Materials and Components Laboratory (UTTMAT-QUAL) at ENEA Casaccia research center. Firstly the experimental campaign was carried out on an unreinforced masonry macroelement made up of a façade, connected with two lateral walls through a layer of mortar. The goal of the experimentation was to study the out-of-plane dynamic behavior of the façade under seismic input, especially in terms of evaluating the rocking and overturning critical accelerations. Subsequently, the damaged structure was consolidated and reinforced by SRG (Steel Reinforced Grout) technique. The reinforced masonry model was tested again by shaking table in the second experimental campaign. Besides traditional sensors, such as accelerometers and wire transducers, a 3D motion capture system named 3DVision installed in the laboratory acquired and processed displacement data. The system is able to track the absolute coordinates of several selected points of the structures during the shaking table tests. It is a 3D light-based system made up of near infrared (NIR) digital cameras for data acquisition and it is able to detect the complete motion of many spherical retro-reflective markers placed on the structure subjected to experimental tests. During the shaking table tests, the trajectory of hundreds of markers placed on the structure are tracked, the tri-axial absolute displacements x(t), y(t), z(t) with easy and fast test set-up are obtained. The 3DVision monitoring methodology, focusing on the parts of the model where deformation energy concentration can be very dangerous, allows to measure the development of the cracks in terms of displacement in several parts of the masonry tested while they are going on.*

1 INTRODUCTION

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 [1][2]. Effectively, current displacement instrumentations, such as LVDTs and laser sensors, provide a very precise measurement of motion in only one direction. Hence, three sensors for complete motion acquisition of each measurement point are needed, implying difficulties in location and attachment, considering the typical range and encumbrance problems of conventional sensors. Consequently, the common choice is to monitor only few points, limiting the interpretation of large-scale and complex mock-ups dynamics. Such inconveniences become negligible with the use of optical motion capture systems that acquire the mock-up motion by means of cameras located around the shaking table.

The optical motion capture is a vision-based tracking technology that may be classified as either image or light-based [3]. Image-based tracking relies on feature detection between frames of a color or monochrome texture map, while image processing and 3D reconstruction is conducted [4]. This is a very challenging task for real-time monitoring, given the computational resources required. On the contrary, light-based systems are very promising, as cameras acquire only a narrow band of radiation wavelengths emitted (active systems) or retro-reflecting (passive systems) by apposite markers, which helps the recognition algorithms optimizing cameras resolution and computational power. In particular, passive systems, acquiring up to more than a hundred small light wireless markers, are able to provide a very detailed description of 3D motion with much easier installation [5].

One of the first 3D motion capture systems applied to shaking table tests in Italy started operating at ENEA Casaccia, near Rome, Italy. This 3D optical movement detection and analysis tool was named 3DVision and it is specifically configured at the purpose of tracking the dynamic displacements of numerous points of specimen under dynamic testing simulating natural (earthquake) and artificial (mechanical) induced vibrations.

2 EXPERIMENTAL FACILITIES

The main technical specifications of the experimental facilities for vibration and seismic tests at the Qualification of Materials and Components Laboratory (UTTMAT-QUAL) at ENEA Casaccia research center are shown in Table 1. They consist of two electrodynamics shakers and two high performance seismic tables. The research activities are principally devoted to the experimental studies of innovative systems for the seismic isolation and retrofitting of civil, industrial, and historical buildings. Also seismic tests of substructures and scaled mock-ups are executed. Experimental campaign usually focus on the evaluation of specimen dynamic behavior, the performance of anti-seismic devices (especially in terms of isolation and dissipation properties) and the failure modes of structural elements.

Table 1: Test facilities at UTT MAT-QUAL Laboratory.

	Table 1	Table 2	Shaker 1	Shaker 2
Table size [m]	4 x 4	2 x 2	1.5 x 1.5	0.6 x 0.6
Degrees of freedom	6	6	1	1
Frequency Range [Hz]	0-50	0-100	5-2000	5-2000
Acceleration [g]	3 (peak)	5 (peak)	125 (0-peak)	100 (0-peak)
Velocity [m/s]	0.5 (0-peak)	1 (0-peak)	2 (0-peak)	1.2 (0-peak)
Displacement [m]	0.25 (0-peak)	0.3 (0-peak)	0.025 (peak-peak)	0.25 (peak-peak)

3 THE 3DVISION SYSTEM

The 3DVision is currently used for 3D motion measurement during the execution of shaking table tests. 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.

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.

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. 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.

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 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 (Figure 1).

Figure 1: 3DVision system: typical configuration of NIR cameras in the lab (left); detail of a NIR camera (right).

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.

The 3DVision system 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 system was tested during several shaking table experiments on a masonry buildings representative of the historical houses still used for civil habitation in Italy and for the dynamic characterization of structures and components prior the seismic qualification tests of systems and components for mechanical, transportation and nuclear industry.

The possibility to synchronize visible and infrared cameras allows the remote participation and control of the shaking table tests in a networking configuration of distributed experiments. In the following figure is showed the conceptual structure of this networking configuration within the virtual laboratory DySCo (structural Dynamic, numerical Simulation, qualification tests and vibration Control) [6].

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 [7]. 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.

4 SHAKING TABLE TESTS ON MASONRY WALLS

External walls are one of the most vulnerable elements of historical masonry building because seismic action can induce the detachment from transversal walls and activate a rocking motion up to the out-of-plane overturning. For this reason the experimental campaigns were carried out on masonry full scale C-shaped macroelement, made up of a façade, connected with two lateral walls through a layer of mortar.

Firstly the unreinforced specimen was tested by shaking table (Figure 2) to study the seismic capacity of the masonry walls until the out-of-plane overturning mechanisms was activated [8]. Then the damaged structure was repaired and strengthened by Steel Reinforced Grout (SRG) [9] with ultra high strength galvanized steel cords (GeoSteel®) and natural hydraulic lime mortar (GeoCalce®) and a second experimental campaign was executed (Figure 3) [10].

Figure 2: Unreinforced specimen: before shaking table tests (left) and out-of-plane collapse of the façade (right).

Figure 3: SRG-reinforced specimen: façade (left) and back view (right).

4.1 Tests set-up

Before executing shaking table tests a finite element (FE) analysis were performed. The goal was to define the more critical areas of the structure and consequently to identify the more appropriate positions for sensors and markers measures on the tested structures. The FEM was defined by 3D solid elements and the connections between the lateral walls were reproduced by 1D rod elements that supported only the axial component to study the effect on the out-of-plane behavior the façade (Figure 4). In Figure 5 the concentration of strain energy is depicted in false colors from light blue to red .

Besides conventional accelerometers and wire transducers, the 3DVision system was used to detect the complete motion of 45 markers. The positions of the markers are shown in Figure 6. Markers on the south wall are labeled with S, on the north wall are labeled with N, while the ones on the façade are labeled with E. Figure 7 displays an example of real-time monitoring of a selected marker in terms of x, y and z components during a shaking table test. The intervention aimed at preventing the activation of out-of-plane mechanisms and at improving the seismic capacity provided by the reinforcement and the resistance towards vertical bending induced by seismic transverse loads.

The experimental campaign was real-time remotely shared through the DySCo Virtual lab. The remotisation of experimental tests for seismic and vibration tests was developed exploiting the multimedia technologies available in ENEA-GRID, which is the infrastructure providing the access to the computational resources of ENEA.

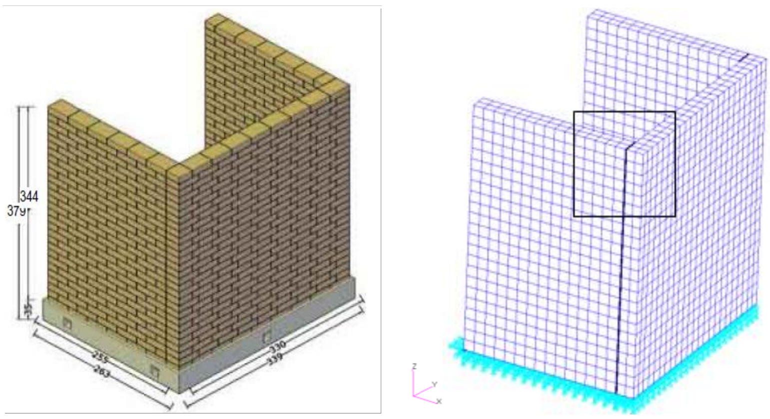

Figure 4: Design of the structure (left) and FEM (right).

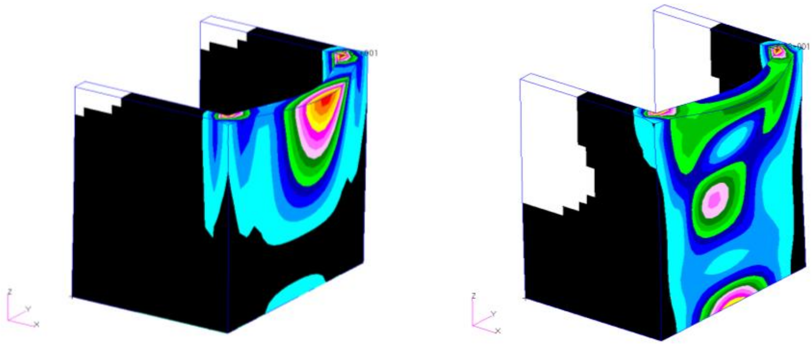

Figure 5: FE Model (left), first modal shape (center), second modal shape (right).

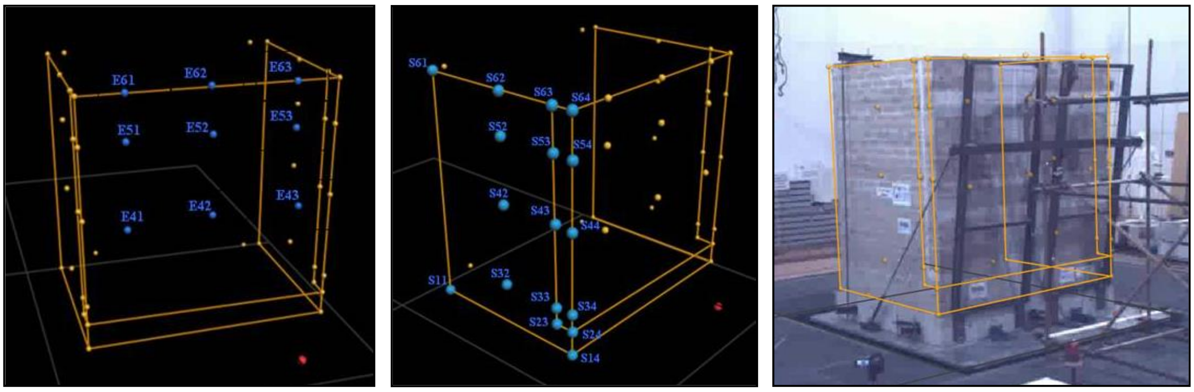

Figure 6: Positions of 3DVision markers: façade (left), south wall (center) and 3D Overlay (right).

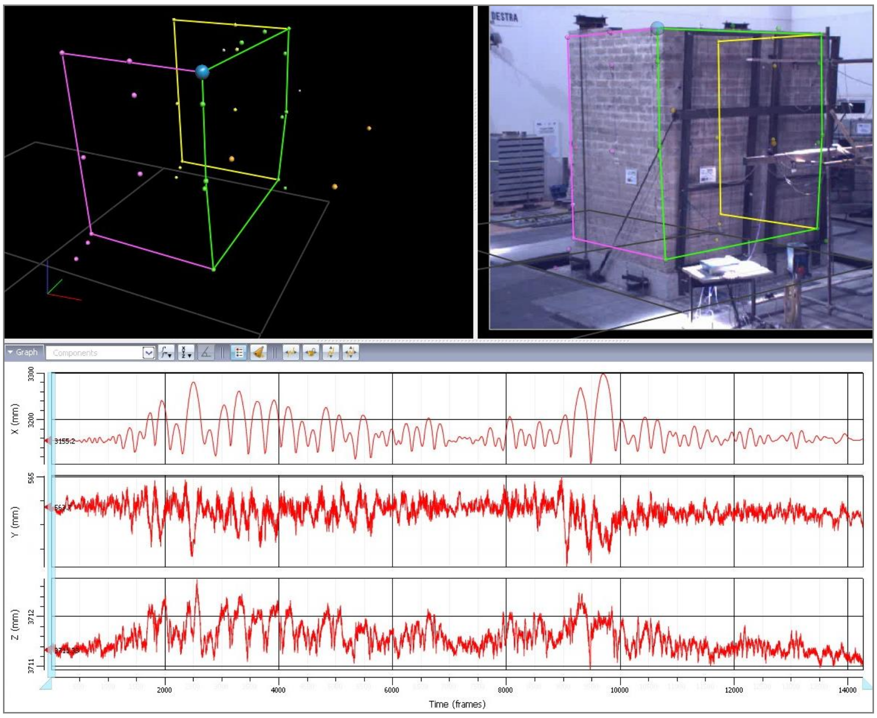

Figure 7: Real-time monitoring of a 3DVision marker: x, y and z trajectory components (bottom graphs) of the selected marker (enhanced in blue in top left and right).

4.2 Seismic input definition

Input signals were imposed with increasing scaling factor up to collapse. All tests were based on the records of the main Italian Earthquakes of the last 30 years: Irpinia (1980), Umbria-Marche (1997), L'Aquila (2009) and Emilia (2012). The effect of the different seismic signals was compared through the Housner Intensity (HI) defined, as usual, according to the general following equation [11]:

$$HI = \int_{t_1}^{t_2} Sv(t,\xi)dt \qquad (1)$$

where Sv is the velocity spectrum in function of time t and critical damping ξ (usually 5%). Original version of HI considers the limits of the integral t_1 = 0.1 s and t_2 = 2.5 s. In general, HI is considered a good measure of the earthquake potential to cause damage to the structures whose fundamental period of vibration is included in the considered range.

In particular, the input R1168EW, based on a EW record at Nocera Umbra during the September 1997 Umbria–Marche earthquake (Figure 8), resulted the most dangerous for the tested structures whose first two modal frequencies were in the range of 8-16 Hz, according to the preliminary FE analysis. The comparison of the seismic signal damaging potential is displayed in Figure 8.

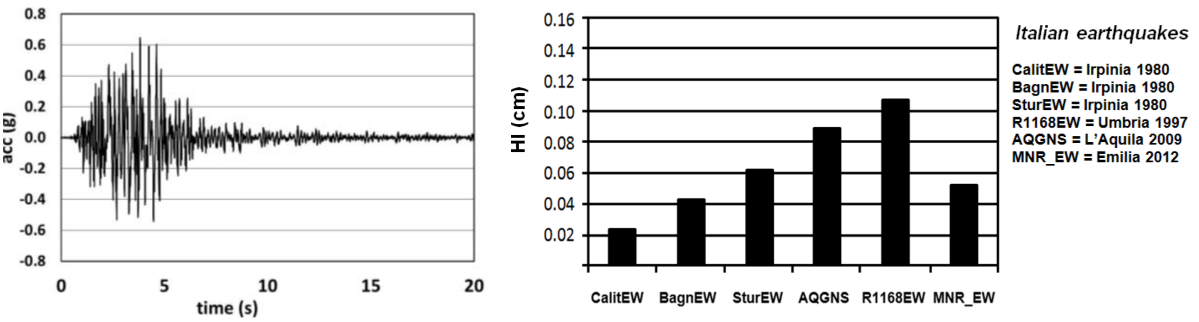

Figure 8: Input R1168EW based on Umbria–Marche earthquake of September 1997 (left), and comparison of the main Italian earthquakes since 1980 in terms of *HI* computed in the range 8-16 Hz (right).

5 RESULTS

The relative displacements of markers located along the connections between the façade and the lateral walls gave information on the opening of cracks due to out-of-plane failure. Permanent deformations were monitored through the evolution of the cumulative relative displacements in function of the input HI value.

The unreinforced specimen showed crack formation at the top of the south connection after the test with HI equal to 40 cm (Figure 9, top left). When HI reaches 60 cm most of the south connection is already failed (Figure 9, top center). On the contrary, at such HI values the SRG-reinforced specimen revealed no permanent deformations yet. Only at HI over 100 cm evidence of failure started appearing in the south connection of the reinforced model (Figure 9, bottom center, and Figure 10, right). In addition, even after crack formation the damaged connection displayed quite moderate opening (only 0.3 mm at the top for HI = 120 cm), much less than the unreinforced model. The confining effectiveness of the SRG stripes is even more evident in the last three steps before final collapse (Figure 11). In fact, relative displacements between markers located in correspondence of the two SRG stripes are more limited than on top and below the protected part of the connection.

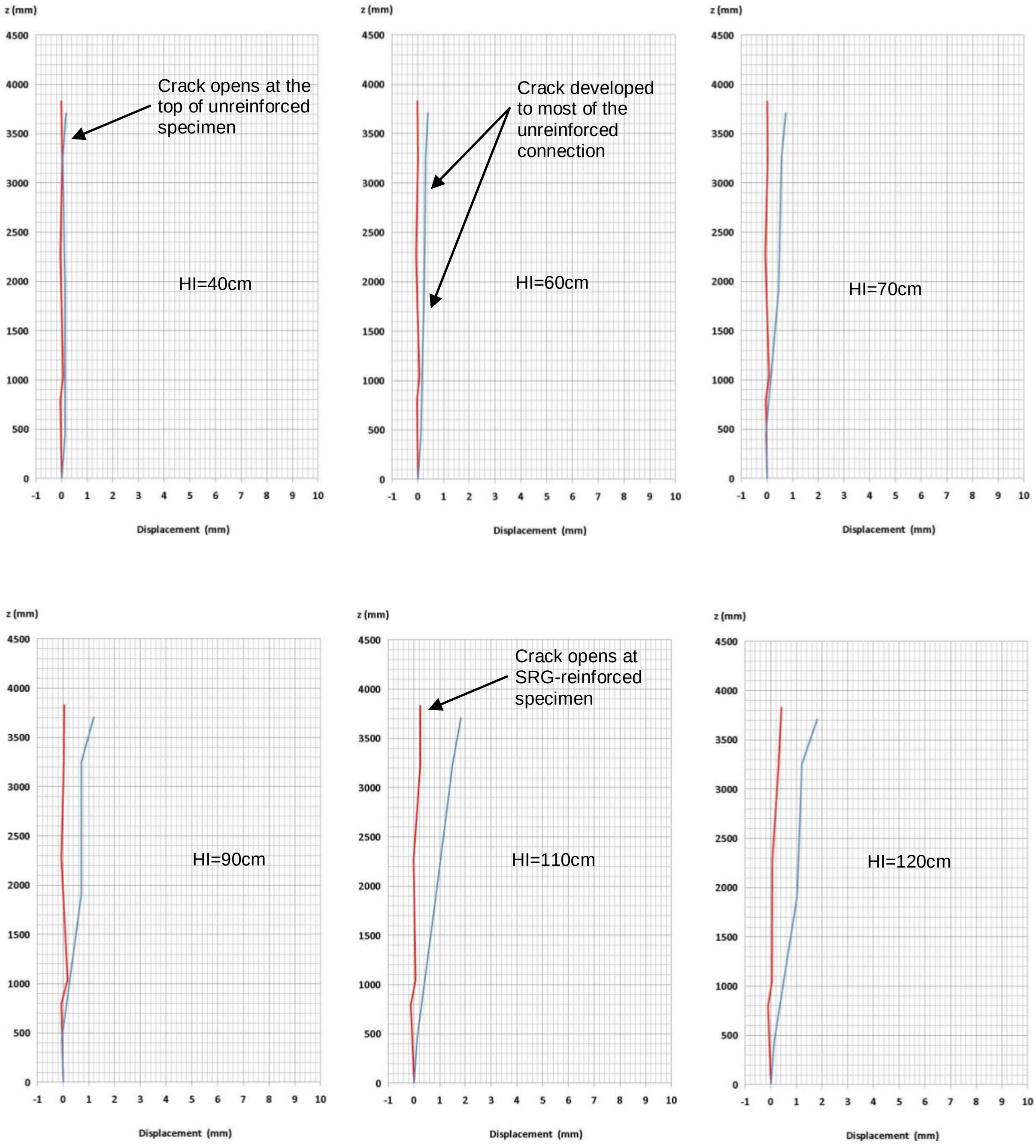

Figure 9: Evolution of south wall-façade connection after shaking table tests at different HI values: Red profiles correspond to SRG-reinforced specimen

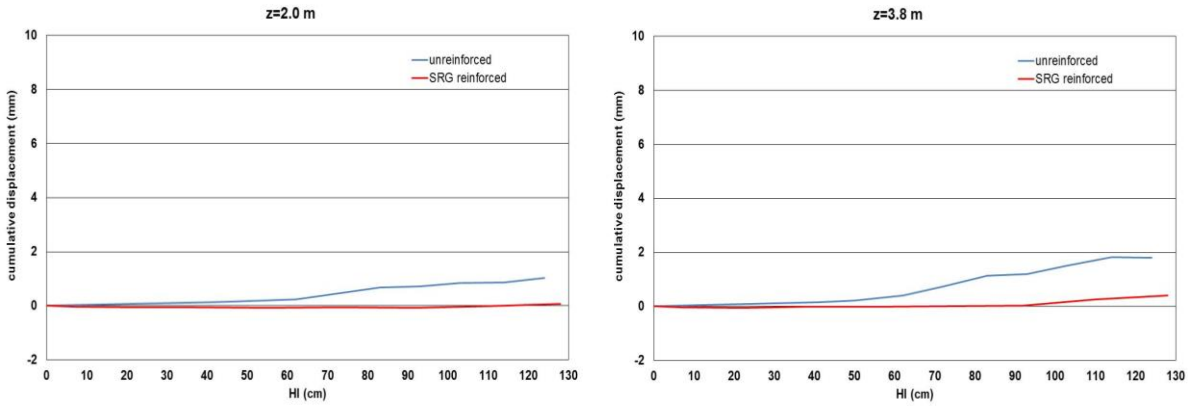

Figure 10: Evolution of south wall-façade connection at middle height (left) and on top (right) in function of the input HI along the test sequence on the unreinforced and SRG-reinforced specimen.

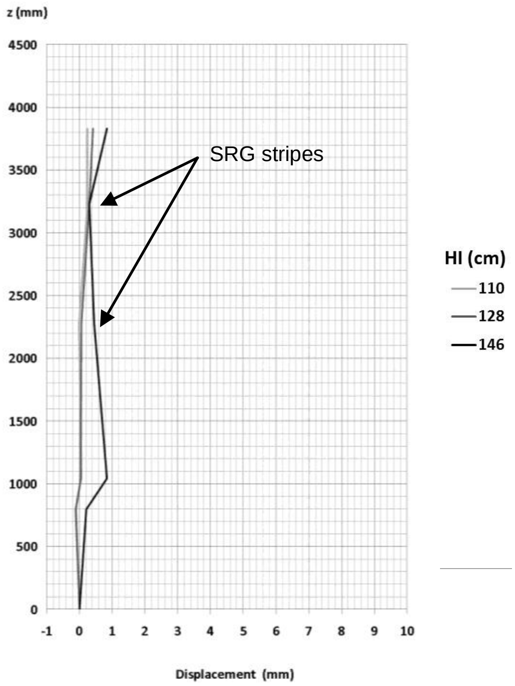

Figure 11: Evolution of south wall-façade connection in the three tests before collapse of the SRG reinforced specimen: displacements are limited in correspondence of the two SRG stripes.

6 CONCLUSIONS

The 3DVision system allowed a detailed 3D description of the evolution of permanent deformations at the connections between the lateral walls and the façade of the tested mock-ups. Cracks formation and development could be monitored along the profile of the connections in terms of marker relative displacements and the different failures mechanisms activated during the experimental sessions could be put in evidence. The above results were obtained thanks to the possibility of installing an appropriate number of markers by easy and fast set-up at all the measurement points with no range and encumbrance problems.

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