QUASI-STATIC AND DYNAMIC TESTS FOR THE SEISMIC ASSESSMENT OF AN INNOVATIVE CLADDING SYSTEM

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Abstract

External thermal insulation composite systems are conventionally designed to provide environmental protection for building occupants. More recent research has been conducted to study also the seismic behavior of this kind of nonstructural components in order to enhance the building resilience against natural hazard like earthquakes. As a matter of fact, it is already well known that the damage of nonstructural elements due to earthquakes, even for low intensity events, can have significant consequences on the operability of strategic buildings, on the human life safety, but can also have a relevant economic impact related to post-earthquake retrofitting actions. The above mentioned issues paved the way to the development of several innovative solutions also for cladding systems, suitable to withstand seismic actions with little damage, in view of increasingly resilient buildings. This paper presents the results of experimental tests carried out on an innovative composite cladding system specifically designed to accommodate in-plane and out-of-plane displacements due to seismic motion of the main structure, exhibiting very low or even no damage, in addition to ensure proper thermal and acoustic properties. Full scale tests were carried out on cladding panels by means of an innovative testing facility equipped with two beams that can be moved, through six hydraulic actuators, in the plane and out of the plane direction to simulate seismic actions. In particular, quasi-static cyclic tests, both in plane and out of plane of the cladding system, are performed according to American standard FEMA 461 (Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components) in order to evaluate the development of damage as the inter-story drift increases. Furthermore, bidirectional dynamic tests are carried out following the provisions of AC156 (Seismic Certification by Shake-table Testing of Nonstructural Components) to assess the seismic behavior of the system also in dynamic conditions.

Keywords: cladding systems; quasi-static tests; dynamic tests; seismic assessment; building resilience.

1. Introduction

Cladding systems represent the elements enclosing a structure and defining the aesthetic aspect of the building. Their primary function concerns several architectural features influencing both interior and external space, such as thermal, acoustic and weathertight performances, where the latter refers to the cladding's ability to be both airtight and watertight [1]. The airtight performance is an important metric determining the energy efficiency since it represents the rate of heat loss, thus it is directly linked to the thermal transmittance. Differently, the watertight performance mainly influences the system's durability. Cladding elements are the foremost responsible of adequate and comfortable internal environmental conditions for the occupants, preventing air leakage, controlling the passage of light and heat and avoiding thermal bridges. For this reason, a great attention is given to achieve a proper design, taking into account these issues. In addition, the increasing global interest towards sustainable buildings with reduced energy dispersion incentives the development of innovative thermo-acoustic technologies for modern cladding systems.

In earthquake-prone areas a special effort is also devoted to the analysis of cladding system's seismic performances. As a matter of fact, since San Fernando earthquake in 1971, it emerged the substantial impact of non-structural components, such as façade systems, in the definition of economic losses [2]. This is definitely due to their damageability for low seismic demand levels, also caused by the dynamic amplification of seismic actions with respect to the ground they are typically subjected [3], and to the significant associated repairing of replacing costs, representing the largest portion of a building construction [4]. In more recent seismic events, such as Canterbury earthquakes sequence in 2010-2011 (New Zealand) and Emilia earthquake in 2012 (Northern Italy), the important role of non-structural components in the framework of the Performance-Based Earthquake Engineering (PBEE) was evidenced. In particular, many buildings in the Christchurch CBD suffered severe non-structural damage, causing the business interruption and consequent indirect losses [5]. As well, in Emilia main cause of fatalities was the failure of cladding panels in precast structures [6]. These events highlighted the significant incidence of non-structural components in determining total losses, commonly identifiable as the 3Ds, i.e. Dollars, Deaths and Downtime. This result is also confirmed by numerical loss assessment analysis [7]-[9]. Accordingly, harmonization of the seismic performance levels between structural and non-structural components in the PBEE approach becomes vital [10].

In last years, considerable attention has been paid to develop a better understanding of the seismic behaviour of non-structural components. Specific testing facilities for experimental evaluation of non-structural components under full-scale floor motions have been realized, thus assessing both drift-sensitive and acceleration-sensitive systems [11]-[12] -[13]-[14]-[15] . In order to enhance buildings seismic resilience, several innovative low-damage non-structural components able to accommodate and/or dissipate the seismic action have been proposed. In the perspective of analysing the overall seismic behaviour of structural and non-structural components, shaking table tests of integrated low-damage building systems have also been performed [16]-[17]. Tasligedik et al. [18]-[19] proposed and tested a damage-resistant solution for both unreinforced masonry infill walls and drywall partitions consisting in the assemblage of smaller vertical panels, thus concentrating inelastic behaviour in correspondence of the internal gaps. In the case of precast concrete cladding systems, the use of U-Shape Flexural Plates (UFPs) as dissipative connection to the bare frame was investigated by Baird et al. [20]. Pourali et al. [21] proposed the use of an elastic isolation foam into the lateral gap of fully floating suspended ceilings, experimentally proving its seismic performances. Sivanerupan et al. [22] introduced a K-type spider connector for spider glazing façades as damage-resistant solution.

In the present work, an innovative cladding system able to contemporarily achieve very satisfactory thermo-acoustic and seismic performances is presented. A wide description of this new product and the experimental tests assessing its seismic behaviour are provided in the next sections.

2. Description of the innovative composite cladding system

An innovative thermo-acoustic insulation composite cladding system is represented in Fig. 1. It can be used in order of enhance both thermal and acoustic performances of existing façades made of bricks, concrete or stone cladding or infill systems, by means of external dry jointed installation. The main components of this new system are listed below:

- thermo-reflective insulation panel, externally characterized by pure aluminium layers, that is directly fixed to the existing façade through a bolted connection and a wood spacer, thus creating a first cavity;
- zinc-coated aluminium framing system, composed by vertical U-shaped cross section uprights and horizontal C-shaped cross section elements, realizing a 400x700 mm mesh;
- fiber-reinforced cement composite panels, characterized by high weathertight performances, that are screwed to the framing system creating a further cavity.

The final thickness of the whole cladding system is 8.7 cm.

The innovative composition of the system allows high thermo-acoustic performances. Moreover, the thermo-reflective insulation layer provides protection from irradiation, while fiber-reinforced cement composite panels ensures significant resistance to freeze/thaw cycles. The peculiar framing system supporting the external panels makes the whole cladding configuration seismically protected. As a matter of fact, the C-shaped beams are able to slide in correspondence of the U-shaped uprights, thus allowing free lateral displacements and preventing from damage.

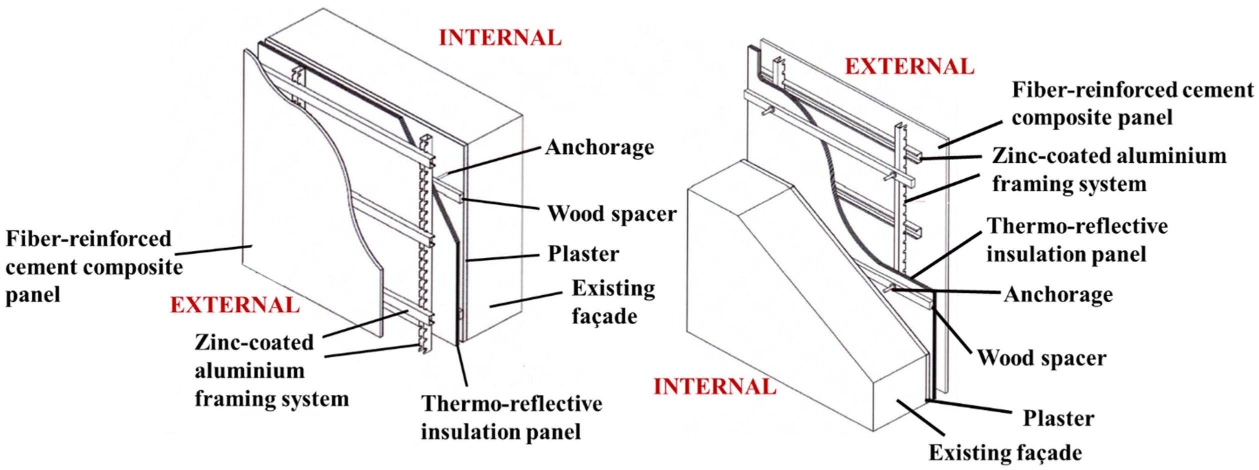

Fig. 1 – Innovative thermo-acoustic insulation composite cladding system schematic views.

3. Experimental campaign

The experimental tests were carried out at the Components and Building Systems Laboratory of the Construction Technologies Institute of National Research Council of Italy (ITC-CNR) in San Giuliano Milanese, by means of a special testing facility, schematically represented in Fig. 2. The machine is able to accommodate full size plane elements (partition systems, infill systems, façade systems, etc.) up to 6.3 m wide and up to 8.0 m high. The components can be anchored to the steel supporting frame by means of three beams (yellow in the picture): one fixed beam at the bottom and two moving beams at the second and third level. The intermediate and superior beams can be moved, in the plane and out of the plane direction, through six hydraulic actuators (black in the picture), to simulate seismic actions. A mechanical lift system for the moving beams allows for various inter-story heights. The moving beams are supported on low friction rollers and connected to a dynamically controlled hydraulic actuators system. The load cell and transducer of the hydraulic actuators are connected with an advanced digital controller that enables acquisition of real time load and displacement data.

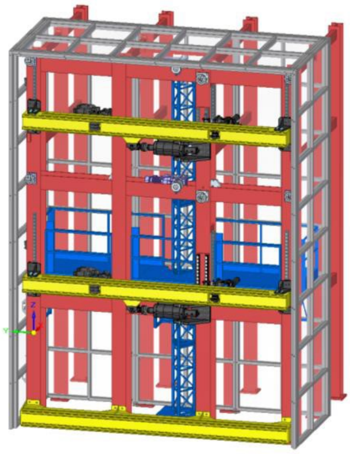

Fig. 2 – Scheme of the ITC-CNR test facility in San Giuliano Milanese for quasi –static and dynamic tests of plane components.

In order to simulate real installation conditions, the studs of the above described system are linked to a substructure consisting of five steel tubular profiles (Fig. 3), by means of fixing devices usually used to connect the cladding system to infill elements. The tubular profiles are then connected to the yellow beams of the seismic machine, in order to simulate the displacement of cladding element, to which the external composite system is attached, that follows the movements of the primary structure during a seismic event.

Fig. 3 – Test setup for connection of the cladding system to the testing machine.

The experimental campaign consisted of cyclic quasi-static tests, performed in-plane direction according to the loading procedure proposed by FEMA 461[23] and dynamic bidirectional tests performed according to the acceptance criteria provided by AC156 [24]. The loading procedures are detailed for each of the performed test in the following sections, including a description of the tested specimen.

1.1. Description of the specimen

The cladding system specimen is characterized by a total height of 3200mm and a length of 2800mm (Fig. 4), thus covering a number of sub-panels in the vertical and horizontal directions respectively equal to 8 and 4, considering the specific mesh characteristic of this element, i.e. 400x700mm.

In Fig. 5 the vertical and horizontal sections of the zinc-coated aluminium framing system is reported. This framing system is connected to the tubular substructure above mentioned, then fibre-reinforced cement composite panels are mounted according to manufacturer provisions (Fig. 6). A global view of the assembled specimen in shown in Fig. 7

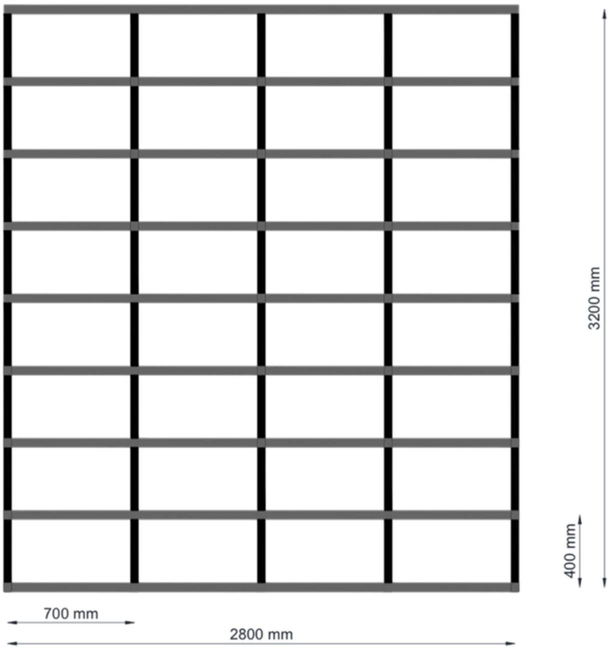

Fig. 4 – Zinc-coated aluminium framing system, composed by vertical U-shaped uprights (black) and horizontal C-shaped elements (grey).

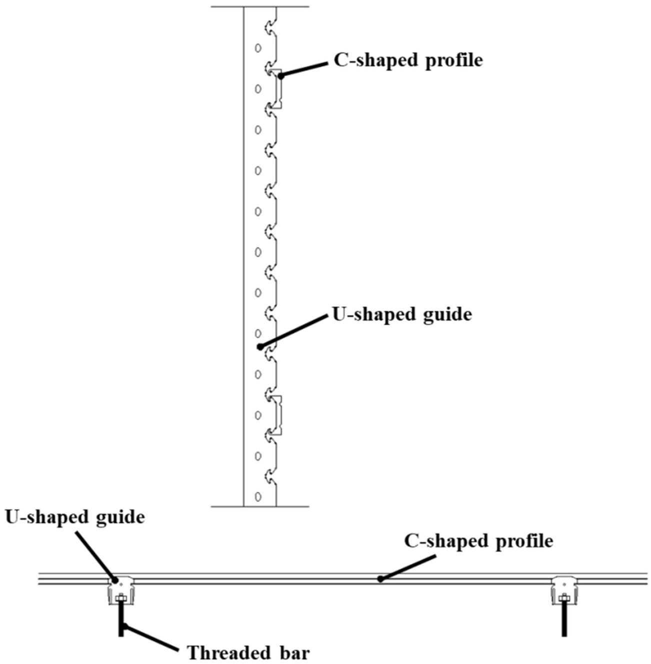

Fig. 5 – Vertical and horizontal sections of the zinc-coated aluminium framing system.

Fig. 6 – Assembly of the panels on zinc-coated aluminium framing system.

Fig. 7 – Final assembling of the tested specimen.

1.2. Quasi-static cyclic tests loading procedure

The in-plane and out-of-plane quasi-static cyclic tests are performed according to the loading procedure provided by FEMA 461. The procedure proposed by the American code, specific for seismic assessment of non-structural components, allows to identify the relevant damage states, the seismic demand parameter (for cladding systems the seismic demand parameter is usually represented by inter-storey drift) and to establish the relationship between the damage level and the related seismic demand.

Following the provisions of the FEMA 461, the displacement controlled loading protocol in Fig. 8 is proposed. The displacement amplitude is evaluated as numeric succession on two successive steps a_i and a_{i+1} as highlighted in Eq. 1, in which the value of the parameter “c” is assumed equal to 1.39. It has been calibrated to represent the response of a single degree of freedom system (mass-spring) when subjected to a set of accelerograms compatible with a Eurocode 8 [25] design spectrum evaluated on type B soil and with a peak ground acceleration equal to 0.35 g.

$$a_{i+1} = c \cdot a_i \quad (1)$$

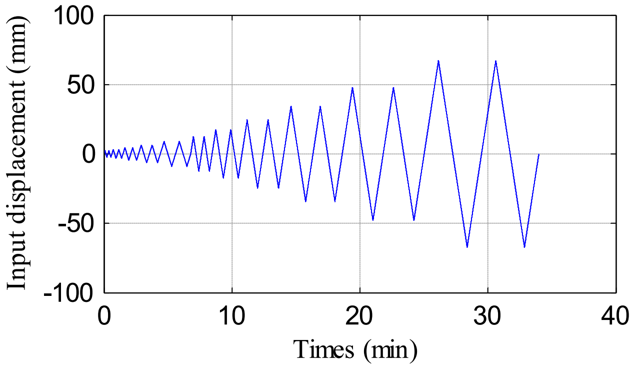

Fig. 8 - Input displacement loading protocol according to FEMA 461 in quasi static tests

The load is applied in eleven consecutives steps, with a constant rate equal to 5 mm/sec up to fifth step and 1 mm/sec from sixth to last step. The initial displacement is equal to 2.3 mm (drift=0.07%), the maximum displacement is 64 mm (drift=2.0%). The displacement time history is applied to the top yellow beam of the seismic machine in the cladding system in-plane direction.

1.3. Dynamic tests loading procedure

The dynamic tests are carried out according to the procedure proposed by the American Acceptance Criteria AC156 - Seismic Certification by Shake-table Testing of Nonstructural Components. The time histories applied both in-plane and out of plane directions during the tests are selected in order to match a reference spectrum, called Required Response Spectrum (Fig. 9).

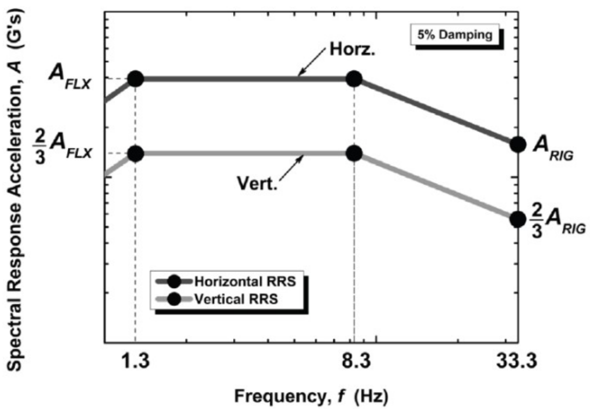

Fig. 9 - Required Response Spectra

It is developed for two horizontal directions according to AC156, as reported in Fig. 9 in which:

$$A_{FLX} = S_{DS}\left(1+2\frac{z}{h}\right) \quad (2)$$

$$A_{RIG} = 0.4S_{DS}\left(1+2\frac{z}{h}\right) \quad (3)$$

where:

- S_{DS} is the spectral acceleration factor. For the design horizontal acceleration spectrum, the International Building Code [26] defines the short period spectral acceleration as:

$$S_{DS} = \frac{2}{3}\cdot F_A \cdot S_S \quad (4)$$

  where F_A is a site soil coefficient, and S_S is the mapped maximum earthquake spectral acceleration at short periods.

- $\frac{z}{h}$ is the height factor taking into account the installation position of the nonstructural components in the main structure and varies from 0, to the foundation level, to 1 at roof level.

In this case the required response spectra are obtained considering S_{DS} equal to 1.0 g and z/h=1In details, a baseline signal is defined starting from nonstationary broadband random excitations with energy content from 1.3 to 33.3 Hz and one-sixth-octave bandwidth resolution. The selected baseline earthquake has a total length equal to 30 s and presents a rise time, a steady state and a decline time of the resultant acceleration record. Then, the signal is enhanced by introducing wavelets using the spectrum-matching procedure of RSP Match program [27] in order to make it compatible with RSS. The matching procedure is ensured over the frequency range from 1.3 to 33.3 Hz; the elastic response spectrum ordinates shall not be lower than 0.9 times RRS and larger than 1.3 times RRS (according to EC8 [25] and AC156 rules, respectively). In order to obtain a drive motion compatible with the seismic machine acceleration, velocity and displacement limits, the so obtained matched record is band passed filtered over the same range frequency . Two different time histories are defined for the two horizontal directions: shows the obtained time histories for the X (blue line) and Y (red line) directions in terms of acceleration, velocity and displacement.

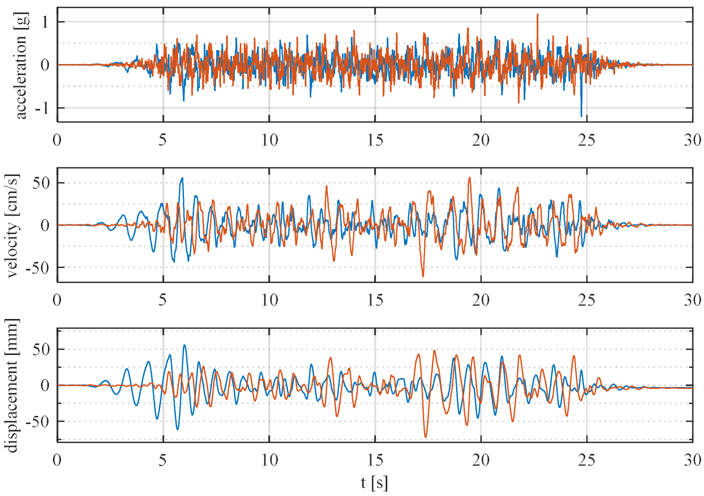

Fig. 10 - Acceleration, velocity and displacement time-history—X direction (blue) and Y direction (red);

The displacement time-histories are applied to the seismic machine in the two directions simultaneously, with increasing intensity corresponding to 25%, 50%, 75% and 100% of the maximum input in order to generalize the execution of the test, being representative of a large range of real earthquakes.

4. Results

The main goal of the *quasi-static test* performed according the FEMA 461 is the identification of relevant damage states for this kind of nonstructural component trough the observation of evolution of damage at the inter-story drift increasing, being the infills drift-sensitive components.

During the test it is observed the in-plane sliding of the horizontal C-shaped elements into the vertical U-shaped uprights: it allowed the external panels to move in independent way with respect the substructure and no damage are observed to all components of the specimen up to 64 mm displacement, i.e. up to 2% of inter-story drift. Considering that nonstructural components, like partitions and infills, are usually designed to not collapse for 0.5 – 1% of inter-story drift, a good seismic performance of the system can be observed in quasi-static conditions.

The resulting force-displacement curve, showed in Fig. 11, evidences a dissipative behavior of the system that allows large displacement (greater than 60 mm) with very low value of required forces (lower than 4 kN).

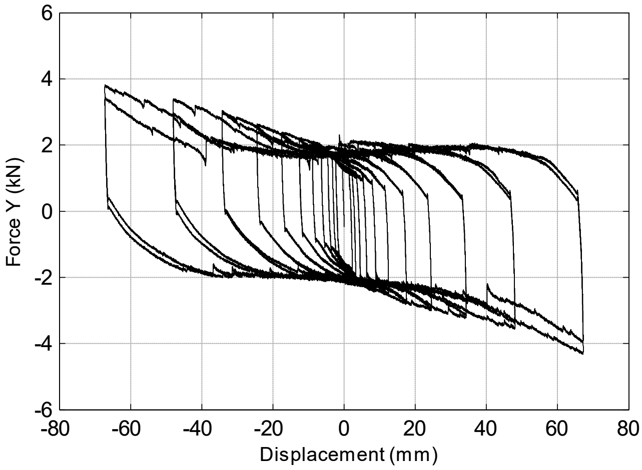

Fig. 11 – Force – displacement curve in quasi-static test according to FEMA 461

The main results of the *dynamic tests*, carried out by applying the time-histories obtained according the AC156 procedure, are shown in Fig. 12. Each graph reports the resulting force-displacement curves, recorded at the level of the upper beam at which the specimen is attached, both in y (in plane) and x (out of plane) direction, for each level of input displacement amplitude (i.e. 25%, 50%, 75% and 100%, of the maximum amplitude reported in Fig. 10). The force values recorded in y direction (in-plane) are always upper than the values of the forces recorded in x direction (out of plane): they increase up to 10 kN.

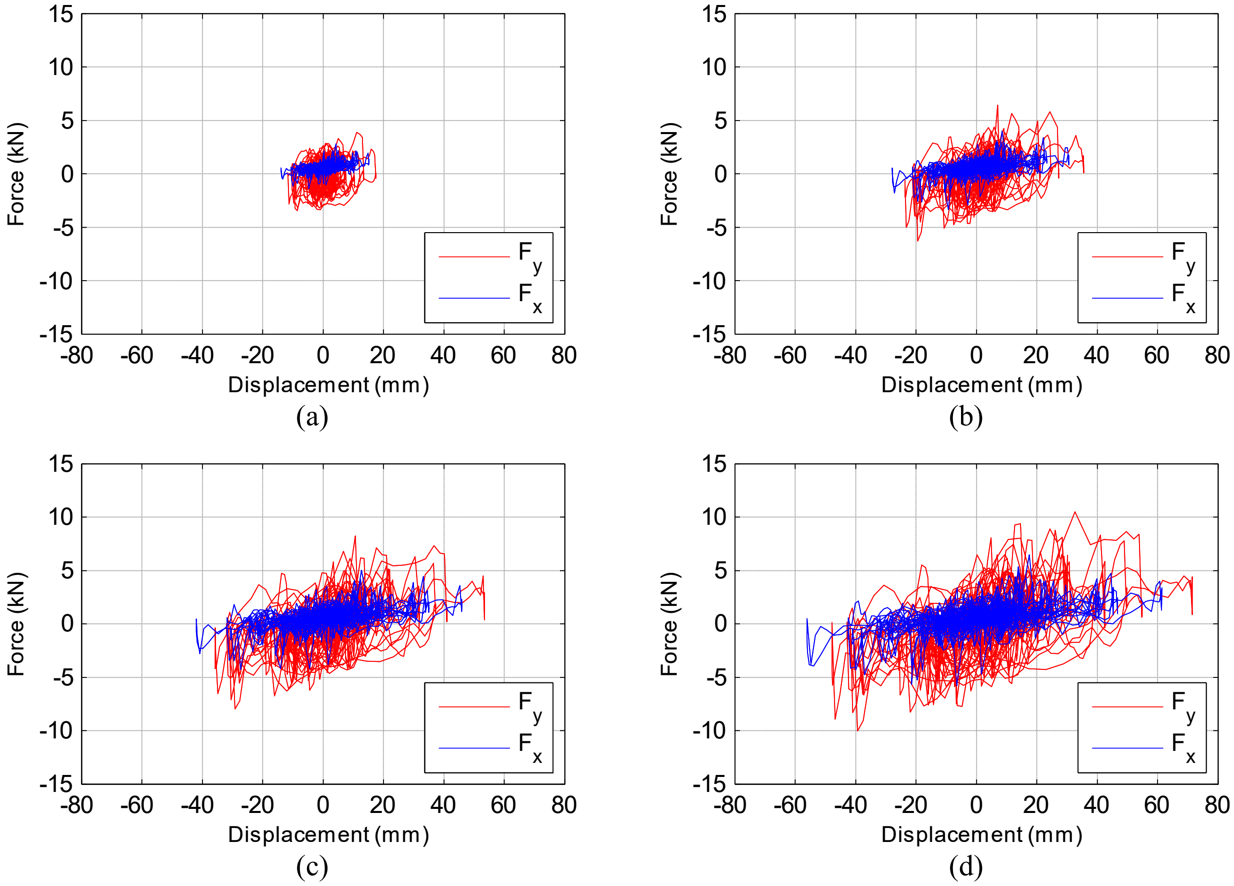

Fig. 12 - Force-displacement curves in x (blu) and y (red) directions for dynamic tests according to AC156: input displacement amplitude equal to (a) 0.25, (b) 0.5, (c) 0.75 and (d) 1 of the maximum amplitude.

Also in dynamic conditions the system allows large displacements (up to 70 mm in in-plane direction) of the external part (panels) with respect the innermost one (uprights connected to infill). However It should be highlighted that at the end of the tests the uprights position with respect the horizontal elements is no longer the original one, evidencing re-centering problems (Fig. 13)

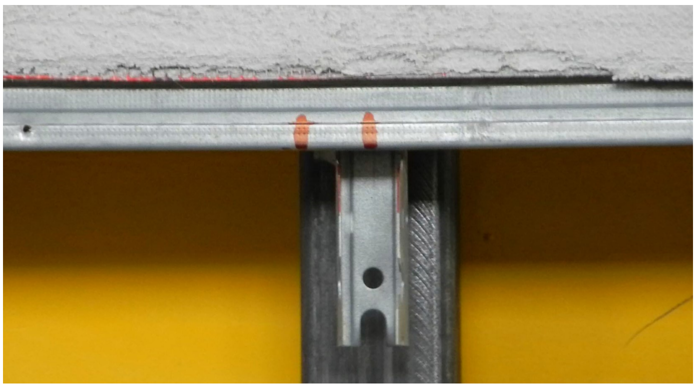

Fig. 13 – Position of the upright with respect the horizontal elements at the end of the dynamic tests.

5. Conclusions

The work herein presented deals with the seismic assessment of an innovative composite cladding system. The system, designed to enhance both thermal and acoustic performances of existing façades, is subjected to seismic test in order to evaluate its suitability in earthquake-prone areas. A 2.8m wide and 3.2m high specimen is subjected to an in-plane quasi-static cyclic test performed according to FEMA 461, and to bi-directional dynamic test performed according to AC156 procedure.

The results of the full scale tests evidenced that the system does not show any damage, also for very high values of in-plane displacement (64 mm corresponding to 2% inter-story drift) both in quasi-static and dynamic conditions. This is due to the special design of the system providing horizontal C-shaped elements able to slide into the vertical U-shaped uprights.

At the end of the dynamic tests re-centering problems are evidenced. The issue should be properly addressed. Further investigations are also required in order to study the behavior of the system in the corner of the building where panels of the cladding system meet orthogonally.

6. Acknowledgements

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