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SEISMIC RESPONSE OF INNOVATIVE GLASS PARTITIONS

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Abstract

The condition of undamaged or lightly damaged internal partitions after seismic events is of utmost importance for at least three building performance levels: i) life safety, ii) operational and iii) damage. Indeed, victims may be caused by the weight of falling partitions, the obstruction of the ways out and the dust released by some (e.g. brick) partitions. Cracks and dislocations of internal partitions, which can be also caused by frequent earthquakes, may lead to the downtime of the building hosting the partitions; downtime cannot be accepted in case of strategic buildings and may lead to large losses in case of industrial and commercial buildings. Large economic losses are also related to the damage itself of the partitions. Consequently, modern seismic codes pay attention to the protection of these nonstructural elements: i) imposing their seismic qualification; ii) providing strength verifications, based on accelerations, and displacement verifications, based on story drifts. Their protection also conditions the structural design: seismic codes link the stiffness of the structure to the damage of the partitions and the structural strength distribution to the possible irregular distribution of the partitions.

Contemporaneous architectural choices are leading to a large increase of the use of glass partitions, for both aesthetic and functional reasons: sound and thermic compartmentations should not be also visual barriers. Glass partitions are more and more used in offices, belonging also to strategic buildings. On the other hand, fragility, stiffness and weight of the glass sheets are features increasing the seismic vulnerability of this partition type. Consequently, the development of glass partitions, remaining operational after strong earthquakes, is an urgent need, which cannot be reached without a strong cooperation between research and industry. Indeed, glass partitions are sophisticated industrial products, characterized by a detailed and expensive manufacture of glass and either steel or aluminum.

The paper shows the development of glass partitions which remain operational after very severe earthquakes, i.e. under large accelerations and story drifts, as shown by shake table tests. Four types of partitions are developed, fully glass, glass partition with a glass door, mixed glass and steel and, finally, mixed glass and wood. It is confirmed that, as already known, simple details may largely increase the seismic performance of nonstructural elements

Keywords: Nonstructural element, glass partition, shake table test, seismic performance, earthquake engineering.

1 Introduction

Several recent earthquakes highlighted the huge impact of nonstructural components (NSC) on earthquake loss [1]. The 2010 Darfield earthquake in New Zealand underlined that nonstructural and content damage can be significant [2] even in buildings with low damage to their structural systems. Past earthquake reconnaissance reports underlined the enormous contribution of nonstructural components to the three Damage States (DS):

- dollars: most of the construction cost of a building is related to nonstructural components, up to 92% of the total cost for hospitals [3]. The loss related to the failure of nonstructural components may easily exceed the total cost of the building, if breakdown and loss of inventory are considered [4];
- downtime: nonstructural components generally exhibit damage for low seismic demand levels, which do not cause serious structural damage. The seismic performance of nonstructural components is especially important in frequent, that is, less intense, earthquakes, in which their damage can cause the inoperability of structurally undamaged buildings;
- deaths: nonstructural component damage can also threaten the life safety. Their damage may cause the obstruction of the ways in/out of buildings, which can cause human suffocation. In this sense, it should be noted that 64% of the fatalities caused by the 1995 Great Hanshin Earthquake was due to people’s suffocation [5].

This paper deals with temporary internal partitions, which can be classified as architectural nonstructural components, according to Villaverde [6]. The attention of the research community has moved towards the seismic assessment of nonstructural components over the last decade. Several research studies can be found in the literature concerning the seismic assessment of nonstructural components, for example, [7] - [14] among many others; many research activities focused on the experimental assessment of the seismic performance of NSC; some numerical studies were also developed based on such experimental campaigns.

Some studies dealt with the assessment of the performance of lightweight partition systems (and light office furniture) [15] - [17]. Extensive experimental campaigns were conducted at the State University of New York at Buffalo and at the University of Nevada [11], [18]. However, the lack of previous studies on the seismic performance of temporary (mobile) internal partitions is clearly denoted in literature. This partition typology is worldwide spread particularly in office buildings. Some applications can be found also in airports, hospitals, and shopping centers. Their seismic performance assumes a key role in the earthquake expected annual loss of these buildings, which is characterized by a large cost due to their evacuation. Finally, it should be underlined that these partitions are characterized by a peculiar construction technique; hence, they cannot be studied as other partition typologies.

Based on the aforementioned motivations, a shake table test campaign is conducted on temporary internal partitions. Four different specimens, representative of typical European partitions, are selected. These specimens are subjected to both in-plane and out-of-plane interstorey drift and accelerations. Continuous and mixed glass specimens are simultaneously tested in order to allow a direct comparison between their performances. The experimental setup, the input definition, and the instrumentation are discussed in the following section.

2 Experimental facilities, test setup, specimens and testing protocol

The shake table tests are carried out at the laboratory of the Department of Structures for Engineering and Architecture of the University of Naples Federico II. The test setup (Fig. 1) is composed of (a) a shaking table simulator, (b) a 3D steel test frame, and (c) four partitions, one for each bay of the test frame.

The test frame is composed of four columns fixed to the base and hinged at the head of the horizontal beams in both directions. On these beams there is a slab of reinforced concrete whose purpose is to confer a functional mass to simulate the seismic action of a generic floor.

The test frame is designed to dynamically stress the sample, simultaneously subjecting it to in-plane and out-of-plane relative displacements and accelerations [9], [19]. Mass and stiffness were evaluated by a parametric analysis, so that the frame for a typical mass value (1.0t/m^2) and for a seismic acceleration corresponding to a frequent earthquake (return period of 50 years) in an Italian zone with high seismicity, exhibited an interstory drift equal to 0.5%.

A 3x3 m shaking table is used, which is characterized by two degrees of freedom in the two horizontal directions. The maximum payload is 200kN with a frequency range of 0-50Hz, peak acceleration, associated to the maximum payload, equal to 1.0g, peak velocity equal to 1m/s, and total displacement equal to 500mm (250mm). Test setup properties, specimens, shake table input, and instrumentation are discussed in the following paragraphs.

Fig. 1 - Global view of the test setup.

2.1 Test setup and specimens

Four different partition typologies are tested:

- specimen no.1: continuous glass partition;
- specimen no.2: mixed glass-wood partition;
- specimen no.3: mixed glass-steel partition;

- specimen no.4: glass partition with door.

The continuous glass partition system (Fig. 2) is composed of four glass panels, two side by side and two parallel to them with an interspace, and has a total thickness of 86mm. The glass panels are made of float glass laminated either with plastic material or with polyvinyl butyral film (PVB). This allows the wall to have greater elasticity and therefore less vulnerability during seismic shaking. In addition, in case of breakage, the PVB layer intervenes holding together the glass layers that surround it. The thickness of the individual glass panels is 10 mm. The panels are generally high up to 3 m and 1.2 m wide; in the specific case panels with a height of 2.61 m and a width of 1.1 m were mounted. The parallel glass panels are separated longitudinally by an H-shaped aluminum profile, so as to create an adequate acoustic and thermal insulation. A double-sided adhesive tape is placed between the side-by-side glasses, so as to create a single element. The glass wall is positioned inside aluminum profiles mechanically fixed to the structure.

The mixed glass-wood partition (Fig. 3) consists of a blind part made of wood and of another part made of glass. In particular, each face (inside and outside the frame) of the blind part has three panels: two external ones with 226mm width and 2570mm height and a larger central one with 796mm width and 2570mm height. Each panel has a thickness of 18mm. The glazed part is instead composed of two glass panels 453mm wide and 2612mm high, and with a thickness of 10mm. The partition system has a total thickness of 86mm.

The mixed glass-steel partition (Fig. 4) is identical to the previous partition system, but steel, instead of wooden, panels are installed. In particular, steel panels have a thickness of 0.8mm, containing a plasterboard layer 12.5 mm thick plasterboard. The partition system has a total thickness of 86 mm.

The glass partition with door (Fig. 5) has the same total thickness of the other three partitions and consists of a glazed part and of a door. The latter is composed of a steel frame and a glazed door. The door is made of double glass and has the following dimensions: width 996mm, height 2679mm. The glass part consists of two parallel glass panels of 753mm width and 2612 mm height, and a thickness of 10mm.

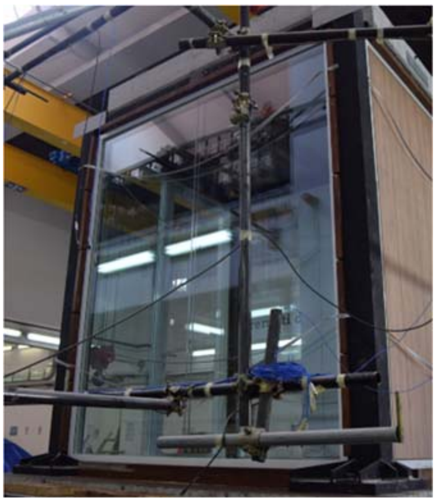


Fig. 2 - Continuous glass partition

Fig. 3 - Mixed glass-wood partition


Fig. 4 - Mixed glass-steel partition


Fig. 5 - Glass partition with door

2.2 Input and testing protocol

The input to the shaking table consists of two horizontal 30-s time histories, generated in accordance with the international seismic certification protocol for nonstructural components AC156 [20]; they act simultaneously along the two horizontal directions. The time histories are artificially defined so as their response spectra match a target response spectrum derived from the American Society of Civil Engineers (ASCE) 7–10 [21] force formulation for nonstructural components:

$$F_p = \frac{0.4\, a_p S_{DS} W_p}{R_p/I_p}\left(1+2\frac{z}{h}\right) \leq 1.6 W_p I_p S_{DS} \tag{1}$$

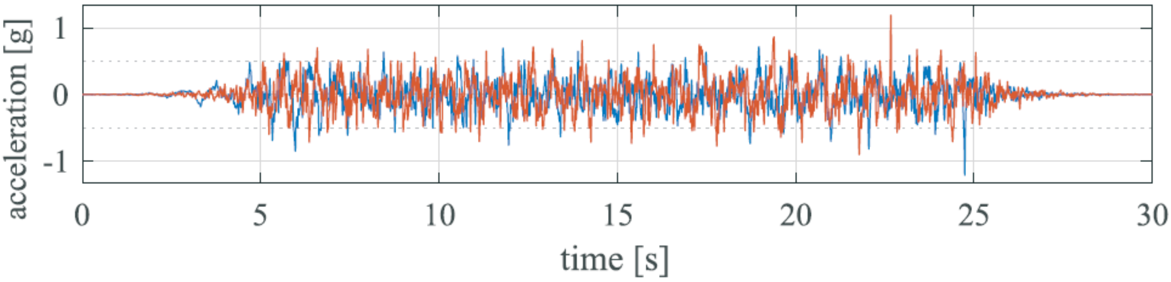
where a_p is the floor-to-component amplification factor, S_{DS} is the design spectral acceleration at short periods, W_p is the weight of the component, R_p is the component force reduction factor, I_p is the importance factor, and z/h is the relative height ratio where the component is installed. The required response spectrum is defined by two spectral accelerations, A_{FLX} and A_{RIG}, which assume a component amplification factor a_p equal to 2.5 and 1, respectively, and R_p and I_p equal to 1:

$$A_{FLX} = S_{DS} * \left(1+2\frac{z}{h}\right) \leq 1.6 S_{DS} \tag{2}$$

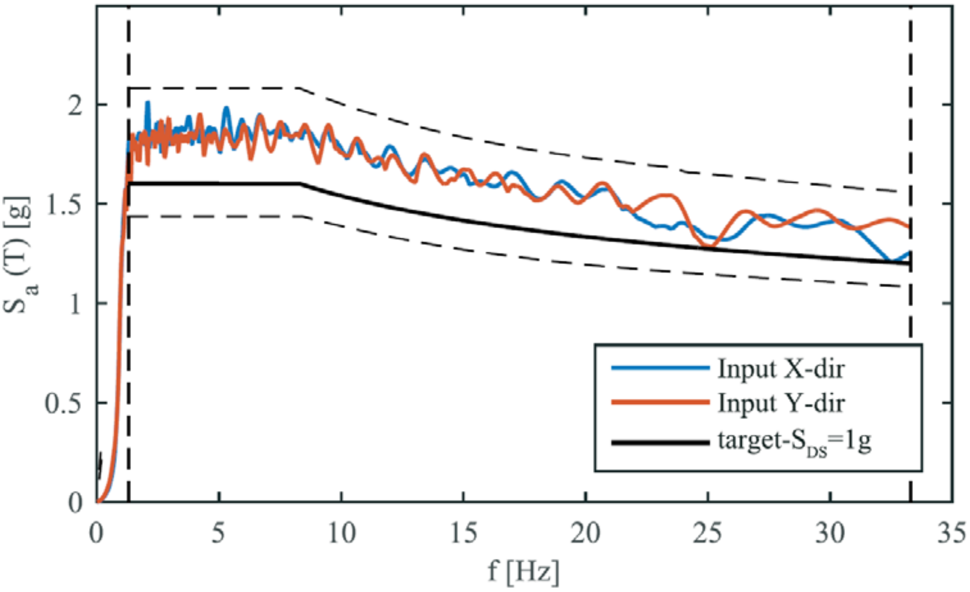
$$A_{RIG} = 0.4 * S_{DS} * \left(1+2\frac{z}{h}\right) \tag{3}$$

A_{FLX} is the spectral acceleration acting on flexible components, characterized by a natural frequency ranging from 1.3 to 8.3 Hz, whereas A_{RIG} is the spectral acceleration of very rigid components, with natural frequency larger than 33.3 Hz. The defined response spectra envelop the target spectrum in the frequency range 1.3-33.3 Hz and assume a damping value equal to 5% of the critical damping. In this range, they do not exceed the target spectrum more than 30%. Furthermore, in cases where it can be shown that no resonance response phenomena exist below 5 Hz, the input spectrum is required to envelop the target spectrum only down to 3.5 Hz. When resonance phenomena exist below 5 Hz, the input spectrum is required to envelop target spectrum only down to 75% of the lowest frequency of resonance. Lastly, the peak shake table acceleration shall be larger than 90% of A_{RIG}. The time histories are artificially defined according to the procedure included in [22]. The obtained time histories are then filtered with a 0.70Hz high-pass filter in order not to exceed the displacement and velocity limitations of the earthquake simulator. Results are shown in Fig. 6. The procedure has been executed for $S_{DS} = 1.00g$; the accelerograms are then scaled to reach several shaking intensities.

The test frame is designed for a bidirectional input motion characterized by a 2.0g spectral acceleration, which corresponds to 1.0% interstory drift ratio. In case unidirectional input motion is employed, larger acceleration and interstory drift can be obtained without damaging the test setup. An additional couple of time histories have therefore been generated to be used for unidirectional tests (Fig. 7). This couple of accelerograms is filtered with a 1.32Hz high-pass filter in order to not exceed displacement limitations of the adopted instrumentation. The corresponding couple of spectra still satisfy the prescriptions on spectrum matching, considering the expected natural frequency of the tested components.



(a)



(b)

Fig. 6 - Input time histories and spectra for S_{DS} equal to 1.00g: (a) acceleration time-history – X direction (blue) and Y direction (red) and (b) input accelerogram spectra and matching frequency range (vertical dashed line).

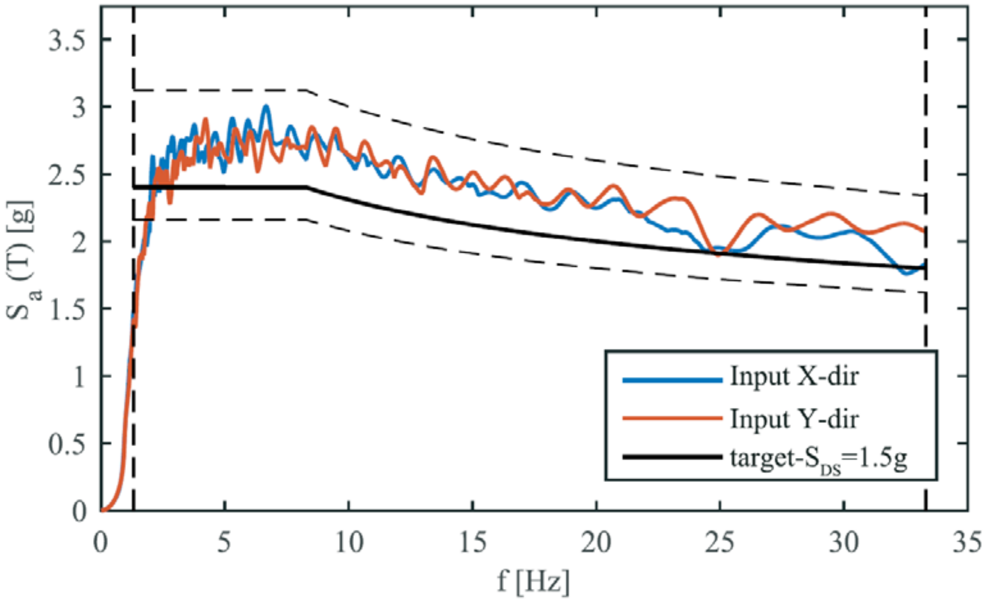


Fig. 7 - Input accelerogram spectra, target spectrum and its limits (dashed line) for S_{DS} equal to 1.50g.

The input levels range from $S_{DS} = 0.05g$ to $S_{DS} = 1.30g$ in order to generalize the execution of the test, being representative of a large range of earthquake intensities. As already mentioned, unidirectional tests are performed in case interstory drifts larger than 1.0% are expected, in order to ensure the integrity of the test frame; therefore, shakings with S_{DS} greater than 0.9g are performed unidirectionally. The test campaign provides fourteen shakings, with steps of 0.10g increasing intensity. A low-intensity random vibration is performed after each test, in order to monitor the dynamic properties of the test setup. Table 1 shows the input protocol of the tests on continuous and mixed glass partitions (G&M).

Shake table testing is necessary for the complete seismic qualification of internal partitions, because they are sensitive to both in-plane and out-of-plane accelerations and displacements [9]

Table 1 - Test protocol for G&M partitions.

	ID PROVA	Tipologia	Tipo Provino	Input	PFA - SDS [g]	Direzione	CODICE
1	1000	Random	G&M	RND	0.10	x	MNG_G&M_RND_x_@010
2	2000	Random	G&M	RND	0.10	y	MNG_G&M_RND_y_@010
3	**101**	**Timehistory**	**G&M**	**AC1**	**0.05**	**x&y**	**MNG_G&M_AC1_x&y_@05**
4	**102**	**Timehistory**	**G&M**	**AC1**	**0.10**	**x&y**	**MNG_G&M_AC1_x&y_@010**
5	**103**	**Timehistory**	**G&M**	**AC1**	**0.20**	**x&y**	**MNG_G&M_AC1_x&y_@020**
6	1004	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
7	2004	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
8	**104**	**Timehistory**	**G&M**	**AC1**	**0.30**	**x&y**	**MNG_G&M_AC1_x&y_@030**
9	1005	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
10	2005	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
11	**105**	**Timehistory**	**G&M**	**AC1**	**0.40**	**x&y**	**MNG_G&M_AC1_x&y_@040**
12	1006	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
13	2006	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
14	**106**	**Timehistory**	**G&M**	**AC1**	**0.50**	**x&y**	**MNG_G&M_AC1_x&y_@050**
15	1007	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
16	2007	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
17	**107**	**Timehistory**	**G&M**	**AC1**	**0.60**	**x&y**	**MNG_G&M_AC1_x&y_@060**
18	1008	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
19	2008	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
20	**108**	**Timehistory**	**G&M**	**AC1**	**0.70**	**x&y**	**MNG_G&M_AC1_x&y_@070**
21	1009	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
22	2009	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
23	**109**	**Timehistory**	**G&M**	**AC1**	**0.80**	**x&y**	**MNG_G&M_AC1_x&y_@080**
24	1010	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
25	2010	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
26	**110**	**Timehistory**	**G&M**	**AC1**	**0.90**	**x&y**	**MNG_G&M_AC1_x&y_@090**
27	1011	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
28	2011	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
29	**111**	**Timehistory**	**G&M**	**AC1**	**1.00**	**x**	**MNG_G&M_AC1_x_@0100**
30	**211**	**Timehistory**	**G&M**	**AC1**	**1.00**	**y**	**MNG_G&M_AC1_y_@0100**
31	1012	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
32	2012	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
33	**112**	**Timehistory**	**G&M**	**AC2**	**1.10**	**x**	**MNG_G&M_AC2_x_@0110**
34	**212**	**Timehistory**	**G&M**	**AC2**	**1.10**	**y**	**MNG_G&M_AC2_y_@0110**
35	1013	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
36	2013	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
37	**113**	**Timehistory**	**G&M**	**AC2**	**1.20**	**x**	**MNG_G&M_AC2_x_@0120**
38	**213**	**Timehistory**	**G&M**	**AC2**	**1.20**	**y**	**MNG_G&M_AC2_y_@0120**
39	1014	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
40	2014	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
41	**114**	**Timehistory**	**G&M**	**AC2**	**1.30**	**x**	**MNG_G&M_AC2_x_@0130**
42	**214**	**Timehistory**	**G&M**	**AC2**	**1.30**	**y**	**MNG_G&M_AC2_y_@0130**
43	**214bis**	**Timehistory**	**G&M**	**AC2**	**1.30**	**y**	**MNG_G&M_AC2_y_@0130**
44	1015	Random	G&M	RND	0.20	x	MNG_G&M_RND_x_@020
45	2015	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020
46	2015bis	Random	G&M	RND	0.20	y	MNG_G&M_RND_y_@020

2.3 Instrumentation

Tri-axial accelerometers and displacement laser sensors are used to monitor the response of both the test frame and the specimens. One accelerometer, placed inside the shake table, measures the input accelerations in both directions. Eleven accelerometers are also arranged in order to monitor the acceleration at different locations of the setup, as shown in Fig. 8. Two accelerometers are installed on two orthogonal beams; another one is arranged on the concrete slab above the test frame; eight accelerometers are installed on the partitions, in order to investigate their out-of-plane behavior. In detail, five accelerometers are placed on the South wall: one accelerometer is placed at the center of the wall, while the other four ones are installed along the vertical and the horizontal direction, in order to evaluate the acceleration distribution of the partition along two orthogonal directions. Other three accelerometers are installed: the first one at the center of the East wall, the second one at the center of the North wall and the third at the center of the West wall.

Displacement laser sensors are also employed (Fig. 9); in particular, six short-range laser sensors (denoted with "Weng" in Fig. 9) and three long-range laser sensors (denoted with "Luch" in Fig. 9) are used. Sensors are installed in order to evaluate the absolute and relative displacements of the partitions in both the horizontal directions.

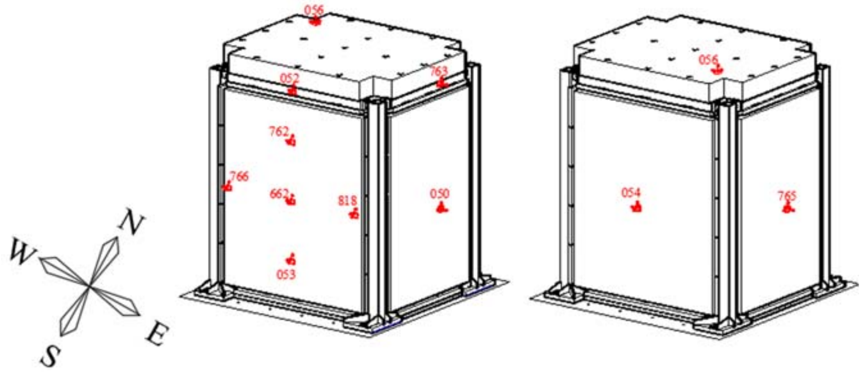


Fig. 8 - Accelerometer positions on both the steel test frame and the specimens.

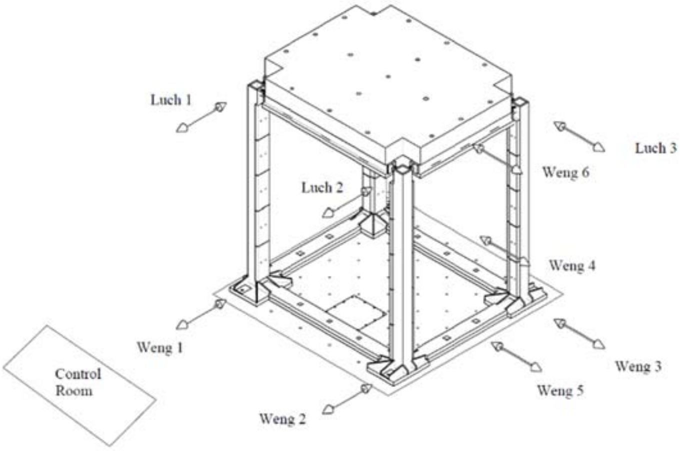


Fig. 9 - Laser positions.

2.4 Damage description

In this study, three damage states (DS) are considered for the seismic assessment of the partitions: i) minor damage state DS1, ii) moderate damage state DS2, and iii) major damage state DS3. Minor DS achievement implies the need to slightly repair the specimen, in order to restore its original condition. Moderate DS achievement, instead, implies that the nonstructural component is damaged so that it should be partially replaced. Major DS implies that the damage level is such that either the partition needs to be totally replaced or the life safety is not ensured. The DS definitions and their consequences are included in Table 2; they are based on the definition given by Taghavi and Miranda 2003 [3]. In particular, the correlation between each DS and the loss is given in terms of the three Ds [23]: (a) human casualties (Deaths), (b) direct economic loss due to the repair or replacement of the nonstructural component (Dollars), and (c) occupancy or service loss (Downtime).

After each shaking level, damage is observed by inspecting the physical conditions of the components, and an appropriate damage table is compiled. In particular, the damage level required to reach a given DS is indicated in the table for each component of the partition; obviously, the DS is the maximum between the different DS recorded in each component. It should be noted that some damage typologies can be observed only at the end of the test campaign, after dismantling the specimens.

Table 2 - Damage scheme for the correlation between the recorded damage in each component of the partition and the attained damage state.

	DS 1	DS 2	DS 3
Damage type		Need to repair or replace a percentage of specimens larger than	
Dollars	10%	30%	50%
Downtime	-	Moderate (1-2 days)	Significant (≥3 days)
Death	-	Limited	Significant
Component of the system	DS 1	DS 2	DS 3
Wood panels	Slight rotation out of the plane or in the plane of the panel	Out-of-plane consisting rotation of the panels, appearance of cracks concentrated or minor, local plastic deformations of the anchoring system to the studs (misalignment of panels), breakage of 30% of the hooks	Overturning of the panels, diffuse or serious cracks, breakage of 50% of the hooks
Steel panels	Slight rotation out of the plane or in the plane of the panel	Out-of-plane consisting rotation of the panels, appearance of cracks concentrated or minor, local plastic deformations of the anchoring system to the studs (misalignment of panels), breakage of 30% of the hooks	Overturning of the panels, diffuse or serious cracks, breakage of 50% of the hooks
Glass panels	Slight rotations out of the top or in the top of the panel, out of the panel from the side guides, leakage or damage to the seals	Out-of-plane consisting rotation of the panels, appearance of cracks concentrated or minor	Overturning of the panels, diffuse or serious cracks
Glass panel connection system	Localized detachment of the adhesive strip	Widespread detachment of the adhesive strip	Permanent displacements
Screws	Unscrewing 10% of the screws	Unscrewing 30% of the screws	Unscrewing 50% of the screws
Tracks, studs and beams	-	Localized plastic deformations of the flanges	Widespread plastic deformations, collapse due to wing or flange instability
Glass panel locking profiles	Partial detachment	Residual plastic deformations, total detachment and overturning	-
Door	(Opening DS 0), damage to the lock	Locking	Overturning

3 Conclusions

This article provides a preliminary description of the shake table tests performed at the laboratory of the Department of Structures for Engineering and Architecture of the University of Naples Federico II. In particular, experimental facilities, test setup, specimens and testing protocol are described in detail. Specimens are glass, wood and glass, and steel and glass office internal partitions. A glass partition with a door is also tested. Before testing, a couple-of-year research study was performed in order to develop the details of those partitions, to let them be operational under very strong earthquakes: the tested partition systems are now patented.

The article also reports the damage table which was filled during the shake table tests, which correlate the observed damage to three different limit states, defined according to the well-known principles of the performance based seismic engineering.

The aim of the presented test campaign is also to provide the dynamic identification of the specimens, i.e. fundamental period, stiffness, damping and component amplification factor. The urgent need to dynamically identify the nonstructural elements is claimed, in order to perform reliable verifications, computing a reliable demand to be compared to a reliable capacity.

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