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EFFECT OF CONSTRUCTION DETAILS ON THE IN-PLANE SEISMIC RESPONSE OF DRYWALL FAÇADES

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Abstract

In the last years, after many seismic event, a great attention focused on seismic behaviour of architectural non-structural components in a building. In particular, for lightweight steel (LWS) constructions, drywall façade is one of the most widely used architectural non-structural components. In this perspective the Department of Structures for Engineering and Architecture of University of Naples "Federico II" started a collaboration with Knauf Group to investigate the effect of various construction details on the seismic response of facades. To this aim in-plane quasi-static reserved cyclic tests were carried out on 14 different full-scale façades made with LWS framing. The investigated parameters include single or double frame walls, type of sheathing panels, presence of finishing, variation in surrounding constructional elements, absence of track members, type of connection to the surrounding constructional elements, and presence of protrusion. The paper reports the effect of the construction parameters on the lateral response of the façades examined in terms of strength, stiffness, force–displacement hysteretic response, and damage mechanisms. Therefore, the damage phenomena observed during the tests were employed for the definition of seismic vulnerability, and the fragility curves for different façade typologies. In the end, based on the fragility data, the evaluation of seismic performance according to interstory drift limits for non-structural components given by Eurocode 8 is also presented.

Keywords: Lightweight steel, Drywall façade, Architectural nonstructural components, Seismic behaviour, Cyclic tests.

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1 INTRODUCTION

During last seismic events non-structural-elements, including façades, partitions, and ceilings, showed severe damages, limiting building's functionality and causing significant economic losses. Since the non-structural element collapse can have disastrous consequences, as structural element collapse, the study of the seismic response of non-structural systems has received less attention in the past, resulting in a lack of specified design guidelines for non-structural systems. In fact, during the last decades the University of Naples was really active in the study of seismic response of traditional and lightweight steel structures [1-28] and, only recently started many research projects [29-32] aimed to identify the seismic response of non-structural systems and give some prescriptions for the codification.

In this perspective, an experimental campaign has been just concluded at the University of Naples Federico II to estimate the in-plane seismic response of façade walls (also known as external walls) made of lightweight steel (LWS) drywall systems, and the results are described in this study.

Façade walls are principally different from other non-load bearing external building elements like curtain walls and claddings because are usually infilled or partially infilled in the building frame and are always supported by a bottom structural element: a beam or floor slab. Façade walls made of LWS framing are quite similar to the commonly used LWS internal partition walls, except for the type of panels being used in façades on the exterior face, which are usually cement-based panels. This detail can ensure better outdoor performance due to being waterproof and impact resistant. Façades are also usually made thicker to achieve better insulation properties. The larger thickness is achieved by constructing facades with dual steel frames instead of one. The two frames of the façade walls are separated by the cavity for better insulation performance.

2 EXPERIMENTAL PROGRAM

A wide experimental campaign was conducted at Laboratory of Department of Structures for Engineering and Architecture, which included 14 tests on 2400 mm x 2700 mm (length x height) full-scale infilled façade wall specimens. The complete experimental program is shown in Table 1. The walls were built according to the construction practice currently used for metal stud non-structural walls and different types of panels, connections, finishing, and steel profiles were used. The 14 walls can be classified as follows: (1) Three walls with double frames (W-01, W-02, W-03), i.e., made of an "External" frame representative of frames facing the exterior of the building and an "Internal" frame representative of frames facing the interior of the building; (2) nine walls with single "External" frame (W-04, W-06, W-07, W-11, W-12, W-14, W-15, W-18, W-20); (3) two walls with single "Internal" frame (W-05, W-10). More details are given in [29]. The effect of different construction parameters on the seismic response was investigated, comparing selected walls and Table 2 summarizes the main parameters under investigation and the selected walls compared for each of them.

A specific 2D hinged steel frame was adopted as a test set-up. The instrumentation included one potentiometer for measuring the wall top horizontal displacement (i.e. lateral drift); four linear variable differential transducers (LVDTs) for measuring the relative horizontal displacements between the exterior face of the external sheathing panels and surrounding elements and four LVDTs for measuring the relative vertical displacements between the exterior face of the external sheathing panels and surrounding elements. A load cell was used to measure the applied loads.

Tests were performed by subjecting the wall specimens to the loading protocol given by FEMA 461 [33].

	Surrounding constructional elements			External Frame		Panels				
Label	**Type of top connection**	**Protrusion / offset (mm)**	**Material**	**Studs**	**Tracks / Brackets**	**External frame Interior face**	**External frame Exterior face**	**Internal frame Exterior face**	**Additional Cladding**	**Additional Finishing**
W-01	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Aquapanel	2 x Diamant	No	No
W-02	Fixed	No	Concrete blocks	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Aquapanel	2 x Diamant	No	No
W-03	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Aquapanel	2 x Diamant	No	Yes
W-04	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Aquapanel		No	No
W-05	Fixed	No	Steel box profiles					2 x Diamant	No	No
W-06	Sliding	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x GKB	1 x Aquapanel		No	No
W-07	Fixed	No	Steel box profiles	Slotted KAW C 150x45x1.0 @ 600	1.0 mm thick. slotted L-brackets	1 x GKB	1 x Aquapanel		Yes	No
W-10	Fixed	No	Steel box profiles					2 x GKB	No	No
W-11	Fixed	Yes / 38	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Aquapanel		No	No
W-12	Fixed	No	Steel box profiles	Slotted U 75x50x2.0 @ 600	2.0 mm thick. slotted L-brackets	1 x Diamant	1 x Aquapanel		No	No
W-14	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Guardex		No	No
W-15	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x Diamant	1 x Vidiwall		No	No
W-18	Fixed	No	Steel box profiles	Slotted KAW C 150x45x1.0 @ 600	1.0 mm thick. slotted L-brackets	1 x GKB	1 x Aquapanel		No	No
W-20	Fixed	No	Steel box profiles	C 75x50x0.6 @ 600	U 75x40x0.6	1 x GKB	1 x Aquapanel		No	No

Internal frame: Studs C 50x50x0.6 @ 600, Tracks U 50x40x0,6

Table 1: Experimental program.

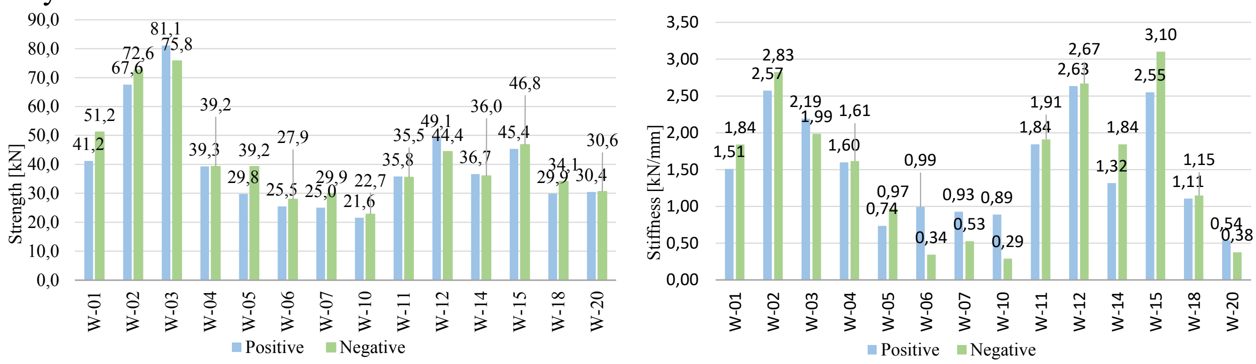
Constructional parameter	Walls to be compared
Interaction between external and internal frame	W-01/W-04, W-01/W-05
Type of surrounding constructional elements	W-01/W-02
Presence of additional finishing	W-01/W-03
Type of sheathing panels	W-05/W-10, W-04/W-14, W-04/W-15, W-14/W-15, W-04/W-20
Presence of a protrusion	W-04/W-11
Type of external frame	W-04/W-12, W-18//W-20
Presence of additional cladding on the exterior face	W-07/W-18
Type of connections between wall and surrounding constructional elements	W-06/W-20

Table 2: Summary of constructional parameters under investigation.

3 EFFECT OF THE COSTRUCTION DETAILS ON THE SEISMIC RESPONSE OF FAÇADES

The experimental results are presented in terms of peak strength and stiffness for each test and damage states. In this way it is quite easy to individuate the main differences among selected tests and evaluate the effect of the construction details on the seismic response of the facades. Globally, walls were characterized by a lateral response fully nonlinear, pinched in nature of hysteretic cycles, and with degradation of strength and stiffness with increasing amplitudes of displacements. Specimens suffer different types of damage during the tests, which occur at different IDR values.

For each test peak load and peak strength are given in Fig. 1 for both positive and negative cycles.



a) Stiffness b) Strength

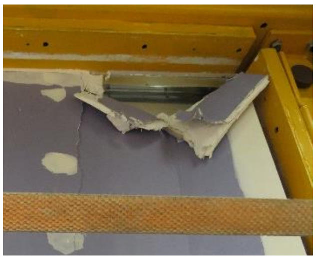
Figure 1. Stiffness and strength for all test specimens.

The evaluation of the damages suffered by the walls during the tests was carried out through visual observation of the specimens. In particular, the main damage phenomena observed during the execution of the tests are shown in Fig. 2. The observation of damages was associated with three Damage States (DSs) defined according to the damage level in terms of required repair action and safety. In particular, DS1, is characterized by superficial damage to the wall and no risk for life safety, the wall can be repaired with plaster, tape, and paint; DS2, is characterized by local damage, mainly finishing, sheathing panels and panel fixings, and/or limited damage in steel frame profiles and moderate risk for life safety. It requires the removal and replacement of sheathing panels, panel fixings (screws), and/or local repair of steel frame profiles; DS3, is characterized by severe damage to walls and a high risk for life safety and it requires the replacement of a part or a whole wall.

For each specimen, the IDR value for which the single damage phenomenon occurred was noted. Table 3 shows the minimum value, for which a defined DS is triggered for each specimen.

1a) Rupture, crushing or spalling of panel portions (limited)

1b) Rupture, crushing or spalling of panel portions (intermediate)



1c) Rupture, crushing or spalling of panel portions (severe)

2) Crack in panel

3) Out-of-plane collapse of panels without falling down of panels

4) Falling down of panels

5) Detachment of joint cover / crack in joint finishing

6) Screw tilting

7) Screw breaking on panel edge

8) Screw pull out/trough

9) Plastic deformation of studs/tracks

10) Stud-to-track fixing failure

11) Residual detachment between the wall and surrounding elements

12) Wall-to-surrounding element connections failure

Figure 2: Damages observed during the tests

DS	Damage phenomenon	IDR triggering damage phenomenon/DS for each specimen													
		W-01	**W-02**	**W-03**	**W-04**	**W-05**	**W-06**	**W-07**	**W-10**	**W-11**	**W-12**	**W-14**	**W-15**	**W-18**	**W-20**
1	1a. Rupture, crushing or spalling of panel portions (limited)	0.78	1.09	0.78	0.78	1.09	1.09	0.56	0.78	0.56	0.78	0.56	0.78	0.56	1.09
	5. Detachment of joint cover / crack in joint finishing	-	1.53	0.78	0.40	-	0.78	1.53	-	-	0.78	1.09	0.78	0.56	0.56
	6. Screw tilting > 10%	0.40	0.78	0.78	0.40	-	0.40	0.40	0.40	0.78	0.78	0.78	0.78	0.40	0.40
	10. Residual detachment between wall and surrounding elements between 1 and 5 mm	0.56	0.40	0.40	0.40	0.40	0.56	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	Minimum for DS1	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
2	1b. Rupture, crushing or spalling of panel portions (intermediate)	1.09	1.53	-	1.09	1.53	1.53	0.78	1.09	1.09	1.53	0.78	1.53	0.78	2.14
	2. Crack in panel > 10 cm	1.09	-	2.14	1.53	1.53	1.09	-	0.78	0.78	0.78	0.78	0.78	1.53	-
	3. Out-of-plane collapse of panels without falling down of panels >10%	2.14	3.00	1.53	2.14	3.00	3.00	3.00	-	1.09	1.53	2.14	2.14	2.14	4.79
	7. Screw breaking on panel edge or screw pull out/trough > 10%	1.09	1.53	1.53	1.53	1.09	1.53	1.53	1.53	1.53	1.53	1.53	1.09	1.09	0.56
	Minimum for DS2	**1.09**	**1.53**	**1.53**	**1.09**	**1.09**	**1.09**	**0.78**	**0.78**	**0.78**	**0.78**	**0.78**	**0.78**	**0.78**	**0.56**
3	1c. Rupture, crushing or spalling of panel portions (severe)	-	-	-	3.00	3.89	-	-	4.79	2.14	1.53	3.00	2.14	2.14	-
	4. Falling down of panels	5.69	-	-	-	-	-	4.79	-	-	2.14	-	-	3.89	-
	8. Plastic deformation of studs/tracks	3.89	3.89	4.79	3.00	2.14	2.14	1.53	2.14	1.09	-	2.14	2.14	-	4.79
	9. Stud-to-track fixing failure > 10%	3.00	4.79	-	3.00	2.14	2.14	-	2.14	4.79	-	-	-	-	2.14
	11. Wall-to-surrounding element connections failure > 10%	-	3.00	-	-	-	-	-	-	-	-	-	-	-	-
	Minimum for DS3	**3.00**	**3.00**	**4.79**	**3.00**	**2.14**	**2.14**	**1.53**	**2.14**	**1.09**	**1.53**	**2.14**	**2.14**	**2.14**	**2.14**

Table 3: Correlation between observed damage phenomena/DSs and IDRs.

To evaluate the influence of constructive parameters on the seismic response of the tested walls, the comparison of the damage between two nominally identical specimens, except for a given constructive parameter, has been performed. In particular, for a selected constructive parameter, the minimum values of IDRs for which the DSs were triggered have been compared by considering a couple of identical walls (e.g., wall i-th and wall j-th), except for the selected constructive parameter and, if the all the ratios $IDR_{DS1,i}/IDR_{DS1,j}$, $IDRD_{S2,i}/IDR_{DS2,j}$, and $IDR_{DS3,i}/IDR_{DS3,j}$ were within the range 0.7 to 1.4, then the influence of the selected constructive parameter has been assumed as “non-sensitive”, otherwise the influence has been assumed as “sensitive”. $IDR_{DSX,i}$ and $IDR_{DSX,j}$ are the minimum values of IDR for which the DSX, with X=1, 2 or 3, was triggered for the wall i-th and wall j-th, respectively. From the results, it can be noticed that the behaviour of tested walls in terms of damage sensibility was particularly affected only by some constructive parameters, i.e., presence of additional finishing, presence of Diamant boards (only in case of external frame), protrusion of the wall with respect to surrounding elements, presence of slotted U-shaped studs and slotted L-brackets, “sliding” connection between the top side of the wall and surrounding elements, whereas all other design variation did not have a significant effect of the evaluation of the damage. Table 4 summarizes the results.

Constructive parameter		Comparable walls	IDRDS1,i / IDRDS1,j	IDRDS2,i / IDRDS2,j	IDRDS3,i / IDRDS3,j	Influence of constructive parameter
Interaction between external and internal frame	Double frame vs. single external frame	W-01/W-04	1.00	1.00	1.00	non-sensitive
	Double frame vs. single internal frame	W-01/W-05	1.00	1.00	1.40	non-sensitive
Type of surrounding constructional element materials	Steel vs. concrete	W-01/W-02	1.00	0.70	1.00	non-sensitive
Presence of additional finishing	**Without vs with additional finishing**	**W-01/W-03**	1.00	0.70	**0.60**	**sensitive**
Type of sheathing panels	Diamant vs. GKB (1)	W-05/W-10	1.00	1.40	1.00	non-sensitive
	Aquapanel vs. Guardex	W-04/W-14	1.00	1.40	1.40	non-sensitive
	Aquapanel vs. Vidiwall	W-04/W-15	1.00	1.40	1.40	non-sensitive
	Guardex vs. Vidiwall	W-14/W-15	1.00	1.00	1.00	non-sensitive
	Diamant vs. GKB (2)	**W-04/W-20**	1.00	**1.96**	1.40	**sensitive**
Presence of a protrusion	**Without vs with protrusion**	**W-04/W-11**	1.00	1.40	**2.75**	**sensitive**
Type of external frame	**Studs and tracks vs. slotted U-shaped studs and slotted L-brackets**	**W-04/W-12**	1.00	1.40	**1.96**	**sensitive**
	Slotted KAW C-shaped studs and slotted L-brackets vs. studs and tracks	W-18/W-20	1.00	1.40	1.00	non-sensitive
Presence of additional cladding on the exterior face	With vs. without additional cladding	W-07/W-18	1.00	1.00	0.70	non-sensitive
Type of connections between wall and surrounding elements	**Sliding vs. fixed**	**W-06/W-20**	1.00	**1.96**	1.00	**sensitive**
(1) Internal frame walls (2) External frame walls						

Tabel 4: Influence of constructive parameters on the seismic response.

4 FRAGILITY CURVES

The fragility curves of tested facade walls were developed, taking into account the presence of additional finishing, Diamant boards (only in the case of external frame), protrusion of the wall with respect to surrounding elements, presence of slotted U-shaped studs and slotted L-brackets, and "sliding" connection between the top side of the wall and surrounding elements, whereas all other design variations were ignored. Fragility data were collected in three groups: (1) Group I, double frame or external frame walls with common tracks and studs, Diamant boards, fixed upper connections, and without protrusion and additional finishing (W-01, W-02, W-04, W-14, W-15); Group II, external frame walls with GKB sheathing boards, fixed upper connections, and without protrusion (W-07, W-18, W-20); (3) Group III, internal frame walls with fixed upper connections and without protrusion (W-05, W-10). As a result of the criterion adopted to group the walls with similar behaviour, walls W-03 (with additional finishing), W-06 (with sliding upper connections), and W-11 (with slotted U-shaped studs and slotted L-brackets) were not included in above-defined groups. Fragility curves and parameters are shown in Figure 3, in which the IDR limits (0.5, 0.75, 1.0%) for ductile non-structural elements given by Eurocode 8 EN 1998-1 [34] are also marked.

From the analysis of the obtained curves, it is evident that each group shows the same behavior for the first limit states (DS1), with the average values of the log-normal distribution equal to 0.40%. For DS2 the average value of the log-normal distribution is from 0.70% to

1.02%, for Group II and Group I, respectively; whereas for DS3 the average value of the log-normal distribution is from 1.91% to 2.62%, for Group II and Group I, respectively.

Fragility curves can be used in order to assess seismic performance by considering the IDR limits for ductile non-structural elements given by Eurocode 8 EN 1998-1 [34]; the probabilities obtained for each DS, defined Group of walls, and IDR limits given by Eurocode 8 are provided in Table 5.

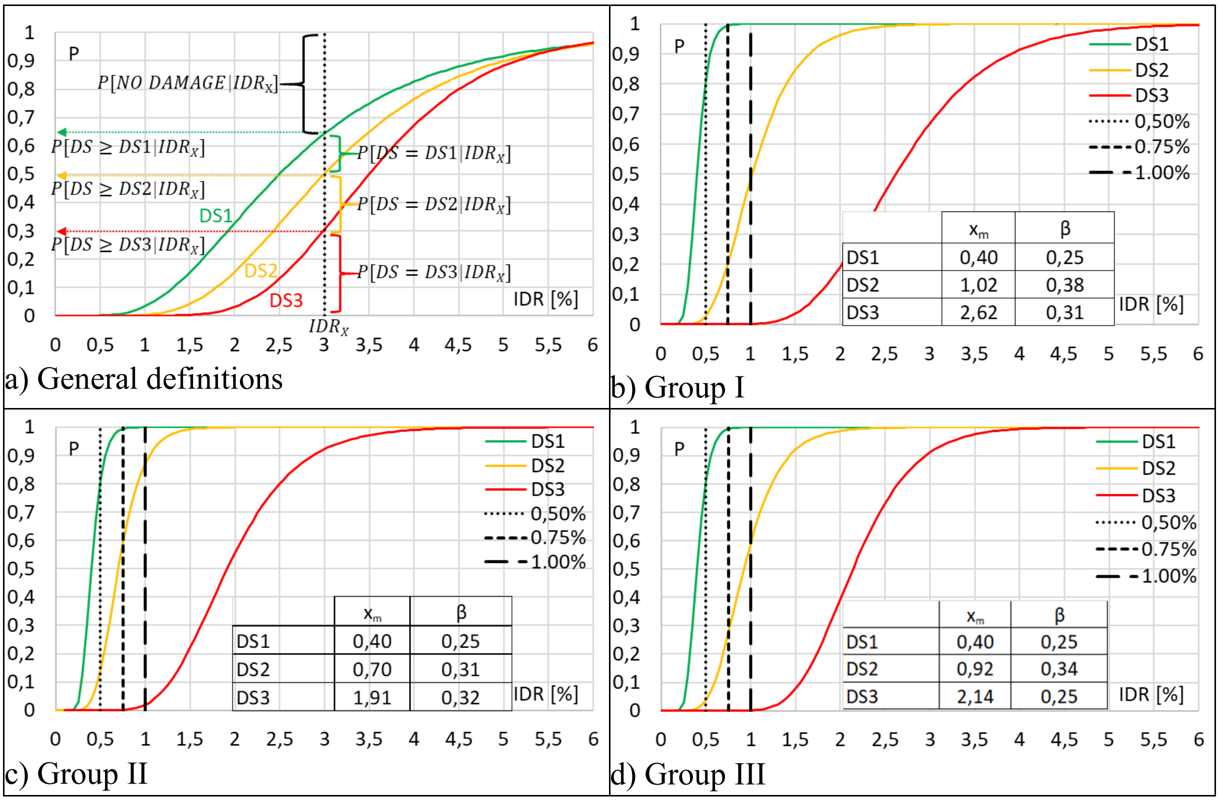


Figure 3: Fragility curves.

	Probability of exceed-ance IDR=0.50%			Probability IDR=0.50%				Probability of exceed-ance IDR=0.75%			Probability IDR=0.75%				Probability of exceed-ance IDR=1,00%			Probability IDR=1,00%			
Group	DS1	DS2	DS3	NO DAM	DS1	DS2	DS3	DS1	DS2	DS3	NO DAM	DS1	DS2	DS3	DS1	DS2	DS3	NO DAM	DS1	DS2	DS3
I	0,81	0,03	0,00	0,19	0,78	0,03	0,00	0,99	0,21	0,00	0,01	0,78	0,21	0,00	1,00	0,48	0,00	0,00	0,52	0,48	0,00
II	0,81	0,14	0,00	0,19	0,67	0,14	0,00	0,99	0,59	0,00	0,01	0,40	0,59	0,00	1,00	0,87	0,02	0,00	0,13	0,85	0,02
III	0,81	0,04	0,00	0,19	0,77	0,04	0,00	0,99	0,27	0,00	0,01	0,72	0,27	0,00	1,00	0,59	0,00	0,00	0,41	0,59	0,00

Table 5: Probabilities of damage for IDR limits given by Eurocode 8.

5 CONCLUSIONS

The experimental results of in plane quasi-static cyclic tests and fragility curves of several typology of façade walls made of lightweight steel (LWS) drywall systems are presented in this paper. The fourteen different wall specimens were selected to study the effect of several constructional parameters including single or double frame walls, type of sheathing panels, presence of finishes, variation in surrounding constructional structural elements, absence of track members, type of connection to the surrounding constructional elements, and presence of protrusion. The influence of constructive parameters on the seismic response affects only the triggering of Damage State DS2 and DS3, whereas the Damage State DS1 was triggered always for the same value of the IDR=0.40%. Regarding the behaviour in terms of triggering of DS2 and DS3, results revealed that Diamant sheathing boards showed better damage tolerance, the presence of a protrusion of the wall with respect to surrounding elements or the presence of an external frame made with U-shaped slotted studs and slotted L-brackets caused a premature triggering of damages, whereas a "sliding" connection between the top side of the wall and surrounding elements as well as additional finishing improved the damage tolerance. The other constructive parameters under investigation did not significantly affect the evolution of damages during the tests. For the fragility curves, three groups of homogeneous walls have been defined (I) Double frame or external frame walls with tracks and studs, Diamant sheathing boards, fixed upper connections and without protrusion and additional finishing; (II) External frame walls with GKB sheathing boards, fixed upper connections, and without protrusion; (III) Internal frame walls with fixed upper connections and without protrusion. The evaluation of fragility shows that the better behaviour was obtained for Group I (x_m=1.02, IDR 0.78% to 1.53% for DS2 and x_m=2.62, IDR from 2.14% to 3.00% for DS3,) and the worst result for Group II (x_m=0.70, IDR 0.56% to 0.78% for DS2 and x_m=1.91, IDR from 1.53% to 2.14% for DS3). Lastly, the probabilities of exceeding the defined DSs for the IDR limits given by Eurocode 8 Part 1 were evaluated: 99%, from 21% to 59%, and 0% for DS1, DS2, and DS3, respectively, for the IDR limit of 0.75%; 100%, from 48% to 87%, and from 0% to 2% for DS1, DS2, and DS3, respectively, for the IDR limit of 1.00%.

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