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Experimental tests for the seismic response evaluation of cold-formed steel shear walls sheathed with nailed gypsum-based panels

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Abstract

The European project named "Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction" (Project acronym: ELISSA) is devoted to the development and demonstration of cold-formed steel (CFS) modular systems. In particular, these systems are nano-enhanced prefabricated lightweight steel skeleton/dry wall construction with improved thermal, vibration/seismic and fire performance, resulting from the inherent thermal, damping and fire spread prevention properties. The different building performances are studied and improved by means of experimental and numerical activities organized on three scale levels: micro-scale, meso-scale and macro-scale. In particular, the evaluation of the seismic performance is carried out at the University of Naples by means tests on connections (micro), seismic-resistant systems (meso) and full-scale two stories house prototype (macro). From a structural point of view,

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the system is a sheathed-braced CFS solution, in which the seismic resistant elements are made of CFS stud shear walls laterally braced by gypsum-based panels. In the adopted solution, the sheathing panels are attached to the CFS frame by means of ballistic nails, whereas clinching points are used for steel-to-steel connections. The present paper illustrates the results of meso-scale tests performed on four full scale shear walls, in which the influence of the aspect ratio, the type of loading and the effect of finishing was investigated.

Introduction

In recent years, the use cold formed steel (CFS) systems for residential low-rise building (housing) is spreading all over the world. The reason of the growing use of these systems lies on the capability to ensure high structural, technological and environmental performances. In particular, the main advantages are the high quality of products, thanks to the production in controlled environment; the economy in transportation and handling, due to the lightness of systems; and the short execution times (Landolfo, 2011). Therefore, CFS systems represent a suitable and competitive solution to the demand for low-cost high performance houses.

The structural behavior of CFS systems, with particular reference to the seismic actions, is defined by the in-plane response of floors and walls, which can be designed by using two different approaches: “all-steel” and “sheathing-braced”. In the case of the “all-steel” approach, only steel elements are considered as part of the load-bearing structure and the lateral bracing system is usually made with flat straps. In the “sheathing-based” design approach, the bracing contribution is provided by the interaction between the steel frame and the sheathing panels (Fiorino et al., 2012b). In this case, the efficiency of the bracing effect provided by sheathing panels is guaranteed by the connections with the steel frame, which strongly influence the lateral/seismic response of walls.

Currently, the University of Naples is involved in the research project named "Energy Efficient LIghtweight-Sustainable-SAfe-Steel Construction" (Project acronym: ELISSA), which is funded by European Commission under the Seven Framework Programme (www.elissaproject.eu). The project is devoted to the development and demonstration of nano-enhanced prefabricated lightweight CFS skeleton/dry wall constructions with improved thermal, vibration/seismic and fire performance, resulting from the inherent thermal, damping and fire spread prevention properties. The project consortium is composed by several academic and industrial partners, which are: National Technical University of Athens (Greece, Coordinator), STRESS SCARL (Italy), Farbe SPA (Italy), Woelfel Beratende Ingenieure GmbH & Co KG (Germany), Ayerisches

Zentrum fur Angewandteenergieforschung ZAE EV (Germany), Knauf Gips GK (Germany), University of ULSTER (United Kingdom), Haring Nepple AG (Switzerland), University of Naples Federico II (Italy), Knauf of Lothar Knauf SAS (Italy), VA-Q-TEC AG (Germany).

In particular, the University of Naples is directly involved in structural/seismic behavior assessments. From the structural point of view, the research is focused on the seismic response of the walls sheathed with gypsum panels. The peculiarity of the investigated system is the use quick connecting systems. Clinching for connections among profiles and ballistic nails for panel to steel connections were selected, with the aim of optimizing the assembling operations toward a more efficient level of prefabrication.

In the last years, several experimental research programs studied similar CFS systems. In particular, Tissel (1993) and Serrette & Nolan (2009) carried out experimental tests on full-scale walls sheathed with OSB and plywood panels connected by means of ballistic nails (steel pins). Monotonic tests on wall sheathed with gypsum board having different aspect ratio were carried out by Pan & Shan (2011). Lange & Naujoks (2006) tested walls sheathed with gypsum fibreboard under vertical and horizontal monotonic loads. Ye et al. (2015) performed cyclic tests on walls sheathed with gypsum board in combination with calcium silicate board or bolivian magnesium board, whereas Wang & Ye (2015) extended this research by considering the effect of RHS stud reinforced with concrete. The interaction of gypsum boards and strap-braced walls was investigated by Moghimi & Ronagh (2009).

On this topic, many research activities were also undertaken at the University of Naples. In particular, experimental tests were performed on full-scale wall prototypes and their components (Landolfo et al. 2006; Iuorio et al. 2014); whereas numerical and theoretical studies were carried out on the prediction of the wall response (Della Corte et al. 2006; Iuorio et al. 2012), the evaluation of behavior factor (Fiorino et al. 2012a) and the definition of design procedures (Fiorino et al. 2009; Fiorino et al. 2012b).

This paper presents the results of the experimental activity on full-scale shear walls. Four different wall tests were carried out, in order to evaluate the influence on the wall response of different parameters, such as the wall aspect ratio, the type of loading protocol and the effect of finishing materials.

The experimental program

The objective of the ELISSA project is to evaluate and enhance the different building performances (seismic, vibration, thermal, hygrometric, fire) of lightweight steel modular systems, mainly conceived for residential housing. To this aim, a case study, consisting of a dwelling named “ELISSA house”, were developed. The dwelling is composed by three rectangular modules (Fig. 1) of plan dimensions 2.5×4.5 m, horizontally and vertically jointed, and it aims to be expression of a real-life solution, which could potentially incorporate in the full testing phase all the facilities required for a residential housing (Fiorino et. al 2015).

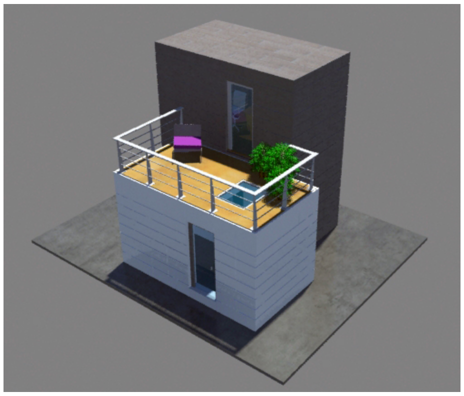

Figure 1. The ELISSA house.

From a structural point of view, the load-bearing structure of ELISSA house is based on the “Transformer” system by COCOON (by Haring Nepple AG), which consists in an industrially prefabricated module composed by floors and walls made with lightweight steel profiles sheathed with gypsum-based boards. The system is already in use and obtained the European Technical Approval for static loads (ETA-11/0105, 2011). Its upgrading to withstand also seismic loads is one of the main objective, in terms of structural performance, of the ELISSA project. In particular, the main lateral resisting system is represented by a sheathed-braced CFS solution (Fiorino et al. 2012b), in which the seismic resistant elements are made of CFS stud shear walls laterally braced by Diamant-X gypsum board by Knauf. Therefore, a comprehensive experimental campaign was planned in order to investigate the response of the seismic resistant systems. In order to improve the seismic response of the structural systems, the components selected for the ELISSA house were investigated by means of the experimental tests organized on three scale levels: micro-scale, meso-scale and macro-scale.

Micro-scale level consisted of monotonic and cyclic tests on main connecting systems, namely clinching steel-to-steel connections and ballistically nailed panel-to-steel connections (Fiorino et al., in press). Meso-scale tests, consisting of monotonic and cyclic tests on full-scale seismic resistant systems (shear walls), were conducted and the obtained results are the topic of this paper. Finally, in order to evaluate the global seismic response of the ELISSA house, shaking table tests on two-storeys module (macro-scale level) will be performed. Meso-scale tests were aimed at investigating the seismic behavior of the shear walls, representative of the seismic resistant system of the ELISSA house. In particular, four tests on full-scale shear walls were performed. The wall configurations are selected in order to consider the influence of the aspect ratio (different wall length), the type of loading (monotonic and cyclic) and the effect of the presence of finishing materials. The test program is summarized in Table 1, in which each tested configuration is illustrated. The series label defines the specimen typology. Namely, the first group of characters indicates the wall typology (WS: only structural wall without finishing; WF: structural wall with finishing); the second group of digits is the wall length expressed in millimeters; the third group represents the loading protocol (M: monotonic, C: CUREE cyclic protocol).

Table 1: Test matrix for the monotonic and cyclic tests on shear walls

Typology	Label	Geometry (length x height)	Finishing	Loading protocol	No. tests
1	WS_2400_M	2.4 m x 2.3 m	NO	Monotonic	1
2	WS_2400_C	2.4 m x 2.3 m	NO	Cyclic CUREE	1
3	WS_4100_C	4.1 m x 2.3 m	NO	Cyclic CUREE	1
4	WF_2400_C	2.4 m x 2.3 m	YES	Cyclic CUREE	1
			Total number of tests		4

Wall specimens

For all the wall specimens, the steel frame was made with studs having C147/50/1.5 mm (outside-to-outside web depth/flange size/thickness) lipped channel sections fabricated by COCOON mainly spaced at 625 mm on the center. The studs were connected at the ends to U150/40/1.5 section wall tracks by COCOON. All the steel members were fabricated by S320GD+Z steel (characteristic yield strength: 320 MPa, characteristic ultimate tensile strength: 390 MPa). The connections among the steel profiles were made by 8 mm diameter clinching points. The steel frame was sheathed with 15.0 mm thick Knauf Diamant-X panels (impact resistant special gypsum board) on both sides. Sheathing panels were attached to steel frame by 2.2 mm diameter ballistic nails spaced at 150 mm both at field and at the perimeter of the panels. In order to withstand the axial force due to overturning phenomena, back-to-back coupled studs and HTT5 hold-down devices by Simpson strong tie were placed at the wall ends. The hold-down devices were connected to studs by 26 SX5/8-L12 screws (5.5 mm diameter self-drilling screws) and to the base beam by one M16 bolt (8.8 steel grade; characteristic yield strength: 640 MPa, characteristic ultimate tensile strength: 800 MPa). The shear connection between tracks and top and bottom beam was made by M8 bolts (8.8 steel grade) spaced at 300 mm.

The steel framing of wall with length of 2400 mm (WS_2400_M; WS_2400_C; WF_2400_C) and 4100 mm (WS_4100_C) are provided in Fig. 2 and 3, respectively. In the case of the specimen WF_2400_C, the wall was completed with finishing and insulating materials. In particular, insulation mineral wool was inserted among the steel stud and wall linings were realized on both faces of the structural wall. The different layers used for WF_2400_C specimen are shown in Fig. 4.

It is important to note that, in the case of the WS_4100 specimen, some connections between gypsum panels and steel framing presented imperfections. In particular, the connections between the panel edges and the internal studs were realized with an edge distance lower than 15 mm and some nails excessively penetrated the panel.

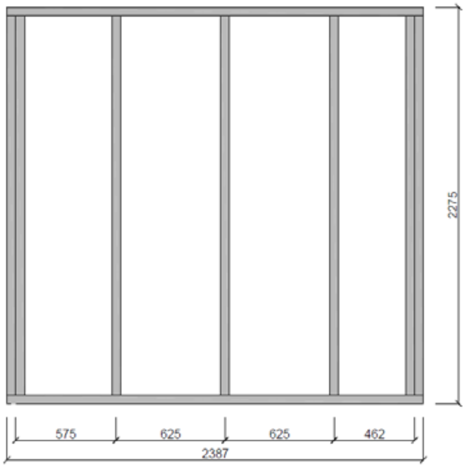

Figure 2: Steel frame for WS_2400_M, WS_2400_C and WF_2400_C specimens

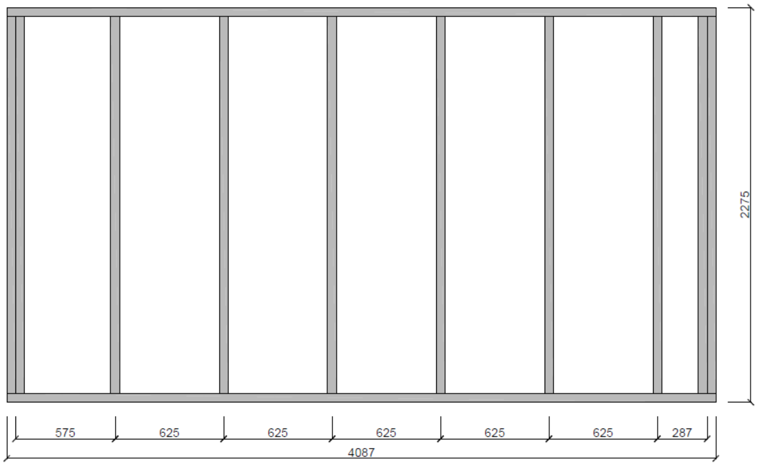

Figure 3: Steel frame for WS_4100_C specimen

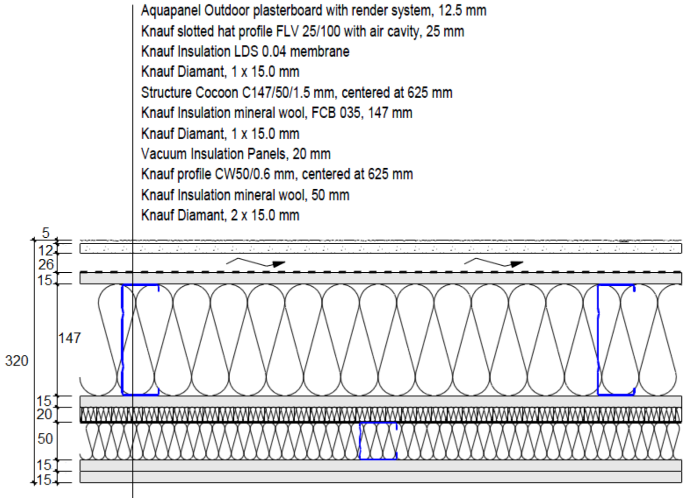

Figure 4: Section of WF_2400_C wall

Test set-up and loading protocols

Tests on full-scale wall specimens were carried out by using a specifically designed testing frame for in-plane horizontal loading. Horizontal loads were transmitted to the upper wall track by means of a 200x120x10 mm (width x height x thickness) steel beam with rectangular hollow section. The wall prototype was constrained to the laboratory strong floor by the bottom beam of testing frame. The out-of-plane displacements of the wall were avoided by two lateral supports realized with HEB 140 columns and equipped with roller wheels. The tests were performed by using a hydraulic actuator having 500 mm stroke displacement and 500 kN load capacity. A sliding-hinge was placed between the actuator and the loading top beam in order to avoid the transmission of any vertical load on the specimen.

Six instruments were used to measure the specimens displacements, as shown in Figure 5. In particular, two wire potentiometers (W1, W2) were used to record the horizontal displacements of the loading beam and at wall top, whereas four LVDTs measured vertical (L1, L3) and horizontal (L2, L4) displacements at bottom wall corners in correspondence of hold-down devices. A load cell was used to measure the applied loads.

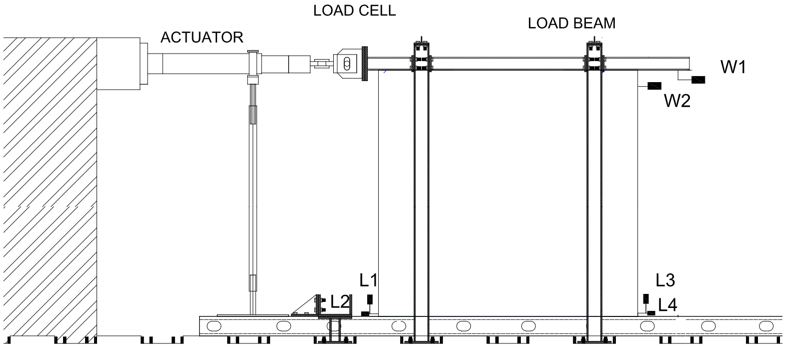

Figure 5. Test set-up and instrumentation

Tests on wall prototypes were conducted under displacement control in quasi-static monotonic and reversed cyclic regime. Under monotonic loading history, specimens were subjected to progressive displacements up to failure. This testing protocol involved displacements at a rate of 0.15 mm/s and the data were recorded with a sampling frequency equal to 25 Hz.

The CUREE protocol was used for cyclic tests. This loading procedure is a reversed cyclic protocol, developed for wood-frame structures by Krawinkler et al. (2001). The displacement amplitudes of each cycle were defined starting from a reference displacement $\Delta = \gamma\ \Delta_m$, where the values of Δ_m was calculated on the basis of monotonic test results, as the displacement corresponding to a load equal to 80% of the maximum load on the post-peak branch of the response curve (conventional ultimate displacement), and γ was assumed equal to 0.60. From the result of monotonic test, Δ is set equal to 39.0 mm. The considered displacement rate involved displacements at a constant rate of 0.50 mm/s up to cycle 28 (maximum applied displacement equal to 9.0 mm) and 2.00 mm/s for cycle 29 and higher. The CUREE cyclic protocol with the indication of stepwise increasing deformation cycles is shown in Figure 6.

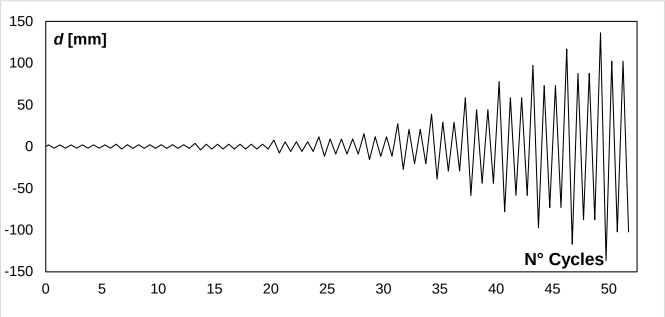

Figure 6. CUREE cyclic protocol

Tests results

The results of tests on wall protoypes are shown in Table 2, in which the parameters used to describe the experimental behavior are: H_p wall resistance corresponding to the maximum recorded load; d_p displacement corresponding to H_p; H_e conventional elastic limit load equal to 40% of the maximum load (H_p); d_e displacement corresponding to H_e; d_u ultimate displacement corresponding to a load equal to $0.80 \cdot H_p$ on the post-peak branch of the response curve; k_e conventional elastic stiffness assumed equal to H_e / d_e, μ ductility defined equal to d_u/d_e; E_m monotonic dissipated energy defined as the area under the response curve (backbone curve for cyclic tests) for displacements not more than the conventional ultimate displacement (d_u); E_c cyclic dissipated energy defined as the sum of area inside each cycle evaluated for displacements not more than the conventional ultimate displacement. These parameters were evaluated on the load (H) vs. top wall displacement (d) curves. In the case of cyclic tests, the values of parameters are obtained on both positive (pushing) and negative (pulling) envelopes, the average values are also provided.

The test results revealed that, for all specimens, the wall collapse was mainly governed by the sheathing-to-frame connections with the tilting and pull-out of the nails, as shown in Figure 7. At global level, the steel frame deformed as a parallelogram with a consequent rigid rotation of the sheathing panels, as shown in Figure 8.

Table 2: Results of shear wall tests

Label		H_e [kN]	d_e [mm]	k [kN/m]	H_{max} [kN]	d_{max} [mm]	d_u [mm]	μ	E_m [kNmm]	E_c [kNmm]
WS_2400_M	-	16.54	4.16	3.98	41.36	43.60	64.91	16	2527	-
WS_2400_C	Pos. Env.	13.36	4.38	3.05	33.41	27.16	44.77	10	2368	5768
	Neg. Env.	13.22	4.46	2.96	33.05	27.24	44.47	10	2284	6575
	Av.	13.29	4.42	3.01	33.23	27.20	44.62	10	2326	6171
WS_4100_C	Pos. Env.	18.80	4.52	4.16	46.99	37.73	62.99	14	3786	8961
	Neg. Env.	17.15	3.64	4.71	42.87	27.17	62.43	17	3624	8582
	Av.	17.98	4.08	4.44	44.93	32.95	62.71	16	3705	8771
WF_2400_C	Pos. Env.	20.21	5.19	3.90	50.54	38.78	61.66	12	3025	7198
	Neg. Env.	19.05	4.28	4.45	47.62	27.17	31.12	7	1914	5856
	Av.	19.63	4.74	4.17	49.08	32.98	46.39	9	2470	6527

Figure 7. Failure of nailed sheathing-to-frame connections

Figures 9 through 12 show the experimental response in terms of acting load (*H*) vs. top displacement curve (*d*) for each performed test. As far as the cyclic tests are concerned, the experimental curves showed a substantially symmetrical response in the two loading directions with the only exception of finished specimen WF_2400_C. In this case, the area inside the part of the cycles of the pushing phase was larger than the pulling phase (Fig. 12). This evidence was also demonstrated by the marked difference of dissipated energy in the two phases. In addition, an unexpected contact between the loading beam and the external wall finishing, which influenced the post-peak branch, was observed in the pushing phase. The results in terms of wall strength showed that values recorded in pushing phase were higher with respect to the pulling phase, with quite small differences ranging from 1% to 9%. In the case of conventional elastic stiffness, the differences between pushing and pulling phase ranged from 3% to 12%.

Figure 8. Wall deformed shape

In order to evaluate the influence of the cyclic loads, the results of the WS_2400_M and WS_2400_C specimens were compared. In particular, the experimental results showed that, in the cases of cyclic loads, the wall strength decreased of 20% in average with respect to the monotonic results, whereas the values of the wall stiffness in cyclic test showed a reduction of 32% with respect to monotonic one.

The comparison between WS_2400_C and WS_4100_C provided the influence on the wall response of the wall aspect ratio and, in particular, of the wall length. It has to be noted that WS_4100_C specimen (wall length: 4100 mm; aspect ratio: 2) exhibited values of the wall strength and stiffness higher than WS_2400_C (wall length: 2400 mm; aspect ratio: 1), with difference of 35% and 48%, respectively. It also has to be noted that, by comparing the experimental results per unit length, the WS_2400_C showed a higher unit strength (13.9 kN/m) than WS_4100_C specimen (11.0 kN/m) with a difference of 26%. Also in the case of unit stiffness, WS_2400_C (1.26 kN/mm/m) results are higher than those of WS_4100_C specimen (1.08 kN/mm/m). This evidence was related to the presence of imperfect connections between the panel edges and the internal studs of the specimen WS_4100_C.

The effect of non-structural parts and finishing on the lateral response of the wall can be evaluated by comparing the results of WF_2400_C and WS_2400_C. In particular, the presence of the finishing entailed an increase in average of 48% for the wall strength, whereas the difference in terms of stiffness was of 39%.

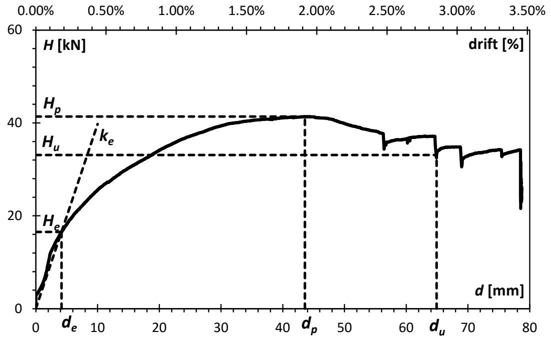

Figure 9. *H-d* curve for WS_2400_M

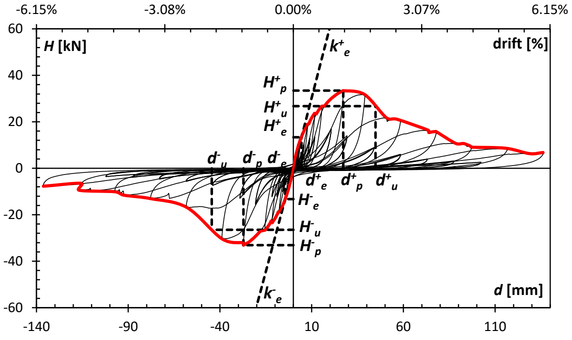

Figure 10. *H-d* curve for WS_2400_C

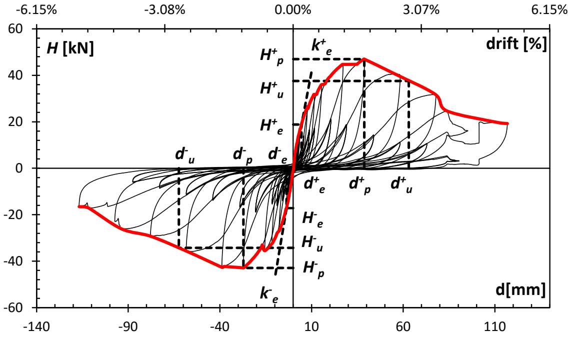

Figure 11. *H-d* curve for WS_4100_C

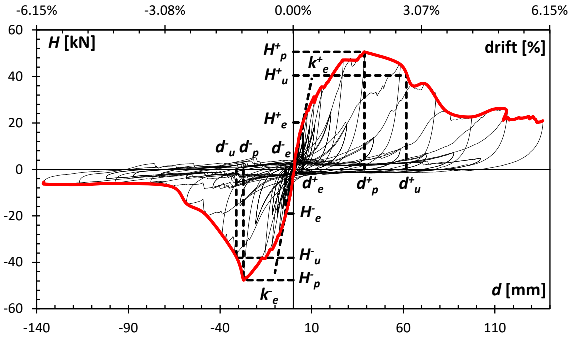

Figure 12. *H-d* curve for WF_2400_C

Conclusions

The paper presents the results of an experimental campaign on seismic resistant systems adopted in the ELISSA house prototype. In particular, monotonic and cyclic tests on different configurations of shear walls laterally braced by gypsum boards connected to the CFS frame by ballistic nails were carried out. In particular, four full-scale walls were tested and the wall configurations were selected in order to investigate the effect of the type of loading, aspect ratio and finishing on lateral/seismic wall response. The experimental results mainly allowed to characterize the shear walls response in terms of strength and stiffness, which are key parameters for the seismic design of CFS structures. The tests showed that the wall collapse always occurred for the failure of sheathing-to-frame nailed connections. The experimental results revealed that the cyclic loads gave a reduction of wall lateral strength of 20%, whereas the increase of the aspect ratio from 1 m to 2 m resulted in an increase of strength of 35%. The presence of finishing material showed an increasing of strength of about 50%.

Acknowledgments

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Appendix. – Notation

d	applied displacement;
d_e	displacement corresponding to H_e;
d_p	displacement corresponding to H_p;
d_u	ultimate displacement corresponding to a load equal to $0.80 \cdot H_p$ on the post-peak branch of the response curve;
E_c	cyclic dissipated energy;
E_m	monotonic dissipated energy;
H	horizontal force acting on wall;
H_e	conventional elastic limit load equal to 40% of the maximum load (H_p);
H_p	wall resistance corresponding to the maximum recorded load;
k_e	conventional elastic stiffness assumed equal to H_e / d_e,
γ	coefficient assumed equal to 0.60
Δ	reference displacement CUREE protocol
Δ_m	displacement corresponding to a load equal to 80% of the maximum load on the post-peak branch of the response curve
μ	ductility defined equal to d_u/d_e;