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OUT-OF-PLANE SEISMIC PERFORMANCE OF PLASTERBOARD PARTITION WALLS VIA QUASI-STATIC TESTS

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ABSTRACT

Internal partitions, as many nonstructural components, should be subjected to a careful and rational seismic design, as is done for structural elements. A quasi-static test campaign aimed at the evaluation of the out-of-plane seismic performance of Siniat plasterboard internal partitions with steel studs was conducted according to FEMA 461 testing protocol. Four tall, i.e. 5 m high, specimens were selected from the range of internal partitions developed in Europe by Siniat, a leading supplier of plasterboard components in Europe.

Under the specified testing protocol, a significant nonlinear pinched behaviour of the tested specimen was observed. The pinched behaviour was caused by the damage in the screwed connections, whose cyclic behaviour was strongly degrading. Both stiffness and strength of the specimens are significantly influenced by the board typology and the amount of screwed connections. Finally, it was concluded that Eurocodes significantly underestimate the resisting bending moment of the tested specimens.

INTRODUCTION

The seismic performance of nonstructural components is nowadays recognized to be a key issue in the framework of Performance-Based Earthquake Engineering (PBEE). Indeed, PBEE explicitly defines different accepted damage levels for non-structural components and contents at different levels of seismic excitations [1], according to a multi-level seismic design approach. Four main issues motivate research studies on this topic.

- Nonstructural components generally exhibit damage for low seismic demand levels. The seismic performance of nonstructural components is crucial in frequent and less intense earthquakes, where their damage can cause the inoperability of several buildings. For instance, damage in partition walls and infill walls caused the evacuation, and the consequent downtime, of several lightly damaged reinforced concrete structures after the 2009 L'Aquila earthquake.
- The cost of nonstructural components represents the largest portion of the building's construction cost. Indeed, Taghavi and Miranda [2] showed that the structural cost only corresponds to 18%, 13% and 8% of the construction cost for offices, hotels and hospitals, respectively.
- The failure of nonstructural components can also cause injuries or deaths; the threatening to the life safety due to nonstructural components increases if it is considered that suffocation is the most common cause of death due to an earthquake. 64% of the fatalities caused by the 1995 Great Hanshin Earthquake were due to the suffocation of the human body due to compression or obstruction [3]. Such a phenomenon could be caused by the damage to nonstructural components, which may limit the accessibility of an egress route.
- Nonstructural components may participate in the lateral system of the primary structure at often unknown levels, i.e. varying the lateral strength and stiffness of the structural system. However, the behaviour in the out-of-plane direction of internal partitions, which is the focus of this paper, gives a negligible contribution to the global behaviour of the primary structure.

The following research study deals with "tall", i.e. 5 m high, plasterboard internal partitions for industrial and commercial buildings. Plasterboard internal partitions with steel studs are classified as architectural nonstructural components according to Villaverde [4]. They, as many nonstructural components, should be subjected to a careful and rational seismic design, as for the structural elements, given the above mentioned motivations.

Several research studies on the seismic assessment of plasterboard internal partitions characterized by cold-formed steel studs can be found in the literature, e.g. [5-9]. Fifty tests on cold-formed steel stud internal partitions were conducted at the University at Buffalo as part of the NEES Nonstructural Grand Challenge project. Thirty-six internal partition walls were tested in-plane under quasi-static [10] and dynamic loading protocols, whereas fourteen wall specimens were dynamically tested in the out-of-plane direction [11] by means of the University at Buffalo Nonstructural Component Simulator (UB-NCS). The influence given by the presence of a bookshelf and/or return walls on the global behaviour of the specimen was investigated. However, the tested components did not reflect the typical partitions used in European countries, being representative of US construction market.

Bidirectional shake table tests on innovative drywall internal partitions are described in Magliulo *et al.* [12]. This test campaign aimed at the evaluation of the seismic performance of an innovative partition system considering in-plane and out-of-plane interaction. A steel test frame was designed in order

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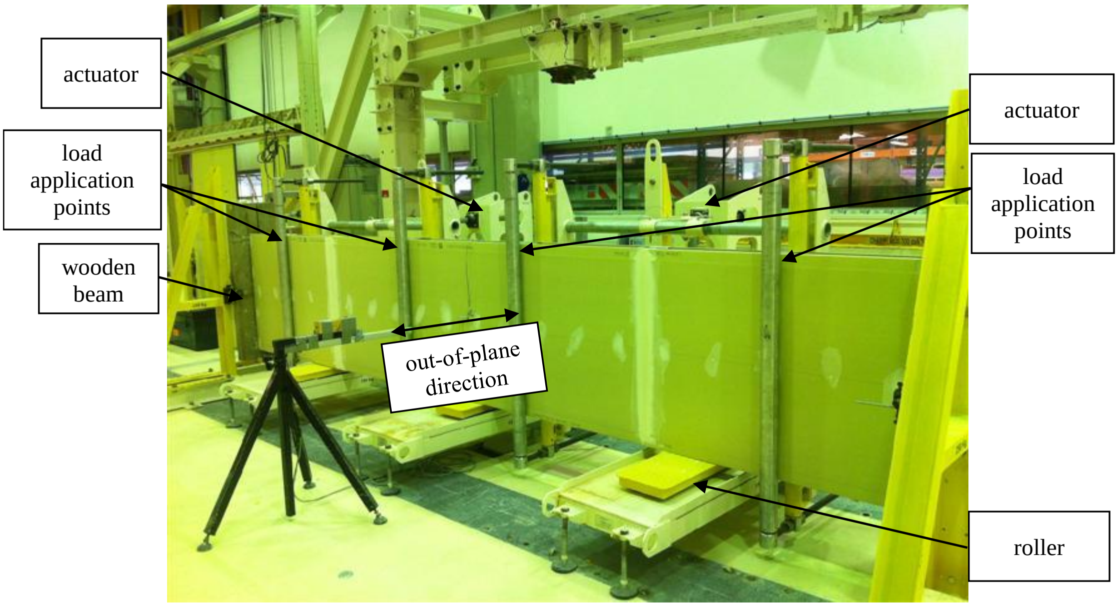

Figure 1: Global view of the test setup for specimen no. 1.

Figure 2: Details of the actuator and the load application points (specimen no. 2).

to simulate the seismic effects at a generic building storey. The AC 156 [13] testing protocol was adopted.

According to current building codes, e.g. Eurocode 8 [14], partition systems are nonstructural components, which must be designed in order to withstand a predefined seismic action. Their seismic design was performed by comparing the seismic demand on the component with the capacity of the partition system. The assessment was performed in the out-of-plane direction since internal partitions are acceleration-sensitive components in such a direction. While the seismic demand can be assessed by means of code formulae, the seismic capacity should be evaluated through either experimental tests or reliable analytical/numerical models. Dynamic tests should be preferred in the assessment of the capacity through experimental tests. However, in this study quasi-static tests were considered, as detailed in the following Sections.

In the available literature there is very limited evidence of out-of-plane quasi-static tests on plasterboard partitions, aimed at the evaluation of their seismic performance in terms of strength, stiffness and ductility. However, some similar studies are available concerning structural walls made of steel studs [15], which significantly differ from the internal partitions both in terms of applied loads and in terms of components. Moreover, tests in the out-of-plane direction are typically performed by private companies according to ASTM E-72 standard [16], but they are not publicly accessible.

In this research study, quasi-static tests were performed on 5 m tall plasterboard internal partitions built with Siniat products, aimed at evaluating their seismic performance in terms of strength, stiffness and ductility. This partition typology is commercialized in Europe by Siniat, a leading supplier of plasterboard components, for industrial and commercial buildings. A test setup was designed in order to perform quasi-static tests on such components. Four different specimens were subjected to the quasi-static test protocol provided by FEMA 461 [17]. The typical damage typologies are shown as well as the recorded force-displacement envelopes. Finally, a critical comparison with the current European building code is discussed.

Table 1: Components adopted for the different specimens.

Specimen no.	Siniat stud	Siniat plasterboard	Siniat guide
1	50-100-50 mm section with 6 mm lips, 0.6 mm thick, 900 mm spacing	1 layer of BA18S boards 18 mm thick, 900 mm wide	30-100-30mm "U" section, 0.6mm thick
2	50-150-50 mm section with 6 mm lips, 0.6 mm thick, 600 mm spacing	2 layers of BA13 boards 12.5 mm thick, 1200 mm wide	50-150-50mm "U" section, 0.6mm thick
3	50-150-50 mm section with 6 mm lips, back to back, 0.6 mm thick, 600 mm spacing	2 layers of BA13 boards 12.5 mm thick, 1200 mm wide	50-150-50mm "U" section, 0.6mm thick
4	50-100-50 mm section with 6 mm lips, back to back, 0.6mm thick, 400 mm spacing	2 layers of BA18 boards 18 mm thick, 1200 mm wide	30-100-30mm "U" section, 0.6mm thick

EXPERIMENTAL FACILITIES, TEST SETUP, SPECIMENS AND TEST PROTOCOL

A quasi-static test campaign was conducted in the Laboratory of the Technical Development Centre of Siniat International Company in Avignon, France (Figure 1 and Figure 2). The tests were aimed at assessing the out-of-plane seismic behaviour of internal plasterboard partitions installed in industrial and commercial buildings, which are typically characterized by large interstorey height.

The specimens are representative of Siniat plasterboard partitions with steel studs. In particular, four different 5 m high plasterboard partitions were tested. Their selection, performed by an industrial partner committee, reflects the typical high partition configurations for industrial buildings that are commercialized by Siniat in European countries. They were also selected since in-plane quasi-static tests were performed on these specimens, as detailed in Petrone *et al.* [18]. Quasi-static tests were preferred to dynamic tests since the available facilities did not allow dynamic investigation of the tall partitions considered in this study.

Test Setup

A single vertical "strip" of each partition was tested in this test campaign, characterized by the width of a single vertical plasterboard. It is implicitly assumed that the partition was wide enough in order to neglect the contribution of the adjacent boards in the horizontal direction. The specimen was placed horizontally (Figure 1) in order to accommodate the features of the available facility. The test was based on the six point bending scheme shown in Figure 3. The test setup provided two actuators placed symmetrically with respect to the centre of the specimen; each actuator was characterized by two application points (Figure 2). The total force applied to the partition was therefore divided into four different forces, which were characterized by the same magnitude. The four forces were positioned in order to reproduce a bending moment diagram similar to the one that would occur for an uniformly distributed load acting in the out-of-plane direction.

The external restraints were given by two wooden beams, which were fixed at the base by steel elements. These beams were made of wood in order to facilitate the installation of the steel guides.

Specimens

Specimen no. 1 was 5000 mm high and 900 mm wide. Its cross-section is depicted in Figure 4a and it is composed of the following components:

- Two horizontal (vertical in the test setup) Siniat U-shaped guides made of 0.6 mm thick galvanized steel; they were screwed into wooden beams (Figure 1) which were positioned at the top and at the base of the partition;
- A single vertical (horizontal in the test setup) Siniat C-shaped stud made of 0.6 mm thick galvanized steel, called M100-50, because it was characterized by 50 mm wide flanges and by a 100 mm wide web;
- A 18 mm thick Siniat plasterboard layer on each side of the partition. The plasterboards were connected both to the stud and to the horizontal guides by 250 mm spaced screws; even though all types of boards were 2600 mm high, three boards were adjacently installed in order to reach the 5000 mm height according to the construction practice (Figure 1). The horizontal joints were sealed with paper and Siniat joint compound.

Specimen no. 1 was representative of a partition with 900 mm spaced studs. Specimen no. 2 was characterized by two layers of 1200 mm wide and 12.5 mm thick plasterboards for each side (Figure 4b). The plasterboards were screwed to two M150-50 studs, which were 600 mm spaced; inner plasterboards were connected to the studs with a 600 mm spaced screwed connections, whereas the outer plasterboards were characterized by 300 mm spacing. Specimen no. 3 was characterized by two layers of 1200 mm wide and 12.5 mm thick plasterboard for each side, which were screwed to two back-to-back M150-50 studs with a 600 mm spacing (Figure 4c). Specimen no. 4 was characterized by two layers of 1200

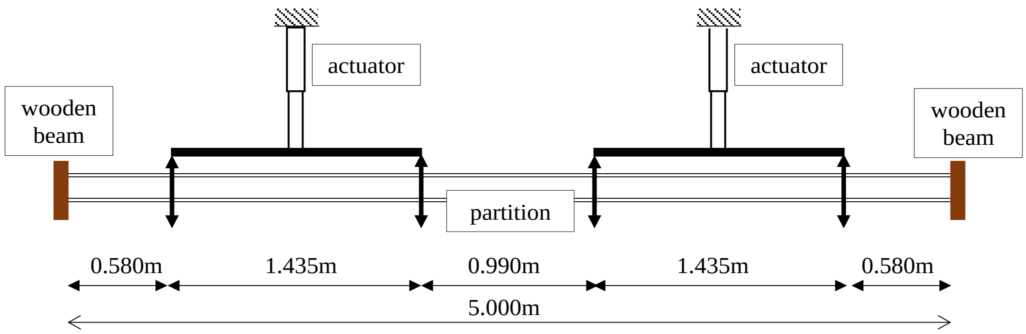

Figure 3: Top view on the specimen: six point bending scheme adopted for the test campaign.

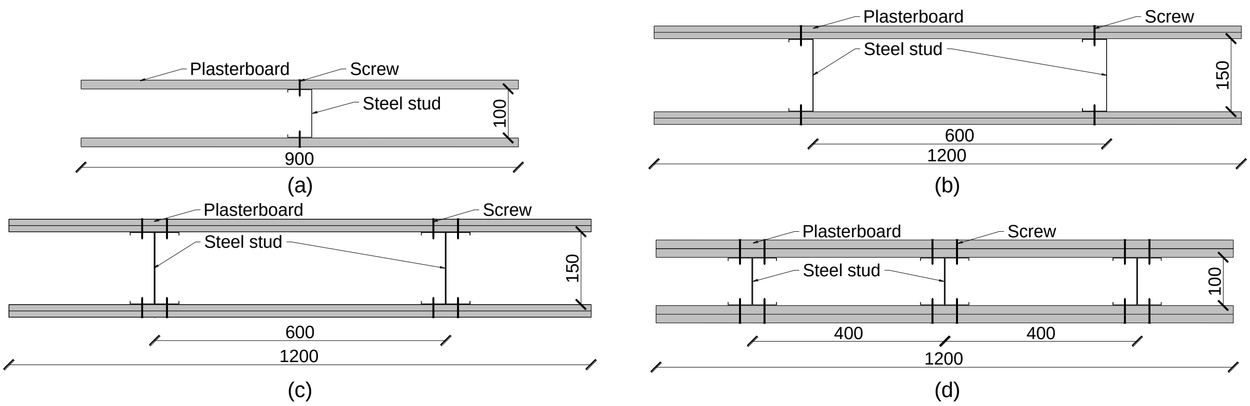

Figure 4: Test specimen cross-sections: (a) specimens no. 1, (b) specimen no. 2, (c) specimen no. 3 and (d) specimen no. 4.

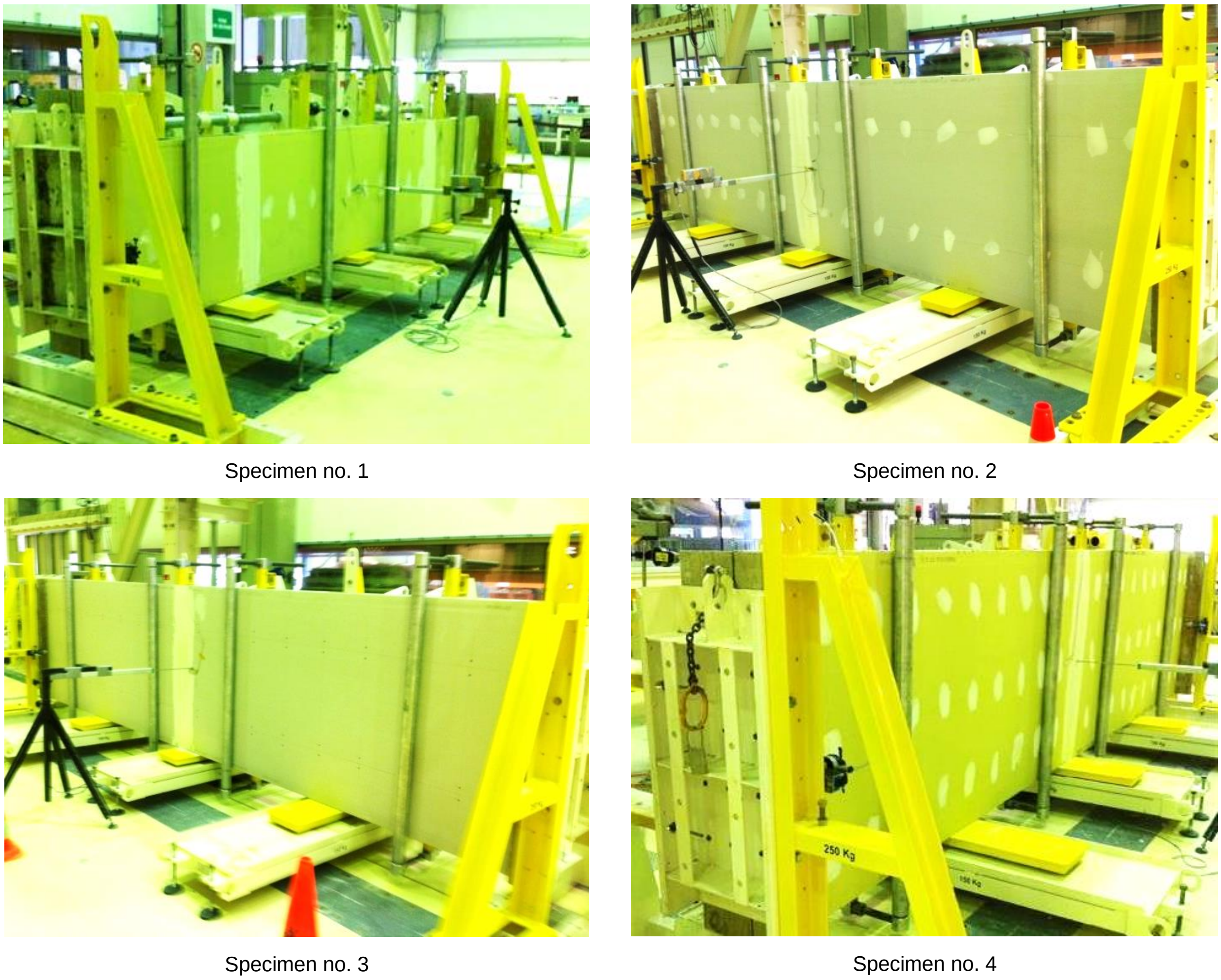

Figure 5: Global view on the four tested specimens.

mm wide and 18 mm thick plasterboards for each side, screwed to three back-to-back studs M100-50 with a 400 mm spacing (Figure 4d); inner plasterboards were connected to the stud with a 600 mm spaced screwed connections, whereas the outer plasterboards were characterized by 300 mm spacing. The main features of the tested specimens are summarized in Table 1.

Steel studs were characterized by 300 N/mm^2 tensile strength and 210,000 N/mm^2 elastic modulus resulting from tensile tests on stud specimens. BA13 board was characterized by a 3.31 N/mm^2 compressive strength and 1.84 N/mm^2 tensile strength; BA18 board exhibited a 5.50 N/mm^2 compressive strength and 1.57 N/mm^2 tensile strength, whereas BA18S board exhibited a 8.16 N/mm^2 compressive strength and a 1.43 N/mm^2 tensile strength. The elastic modulus range was 2410-5240 N/mm^2. The self-drilling screws adopted for the different specimens were characterized by a 3.5 mm diameter, 35 mm length and with a flat head. Finally, a global picture of the four tested specimens is reported in Figure 5.

Test Protocol

The protocol of the quasi-static test was defined according to FEMA 461 “Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components” [17]. FEMA 461 proposes the loading history as a numeric succession of two consecutive steps with amplitude a_i and a_{i+1}, respectively, according to the following relationship:

$$a_{i+1} = c \cdot a_i \tag{1}$$

Two cycles at the same displacement amplitude a_i were provided for each step. Equation (1) is calibrated in order to be representative of the response of SDOF systems subjected to a set of ground motions in ordinary conditions recorded in the US region. The suggested value of the parameter c was 1.4.

Based on the research study included in Petrone *et al.* [18], which is based on earthquakes recorded in Europe, the parameter c was slightly modified to 1.39. A 100 mm target displacement Δ_m at the 15th step of the loading protocol was defined, which w representative of the collapse displacement of the partition. In case the collapse of the partitions was not exhibited at the target displacement value, the loading history was continued by using further increments of amplitude of 0.3 times Δ_m, i.e. 30 mm, according to FEMA 461. The displacement loading protocol is depicted in Figure 6, assuming a total number of steps equal to 20.

Instrumentation

Several instruments were selected in order to monitor the response of the specimens when subjected to the predefined loading protocol. A Linear Variable Displacement Transducer (LVDT) was placed at the centroid of the partition in order to record the mid-span out-of-plane displacement of the partition (Figure 7a). Several strain gauges were placed at different points of the specimen:

- Four strain gauges were placed on the inner and on the external faces of the boards at the centroid of the partition, i.e. strain gauges A, B, C and D in Figure 7b;
- Three strain gauges were positioned on three different cross-sections of a steel stud, according to the arrangement provided in Figure 7b, i.e. strain gauges E, F and G. The three selected cross-sections corresponded to: (a) the force application point closest to the external support, (b) the centroid of the partition and (c) the horizontal joint between the plasterboard panels.

Two LVDTs were also installed in order to monitor relative displacements in the out-of-plane direction between the external wooden beam and the partition, both at the base and at the top of the partition. Finally, two LVDTs were installed to measure the absolute displacement of the external wooden beams in the out-of-plane direction, in order to verify the effectiveness of their restraining effect.

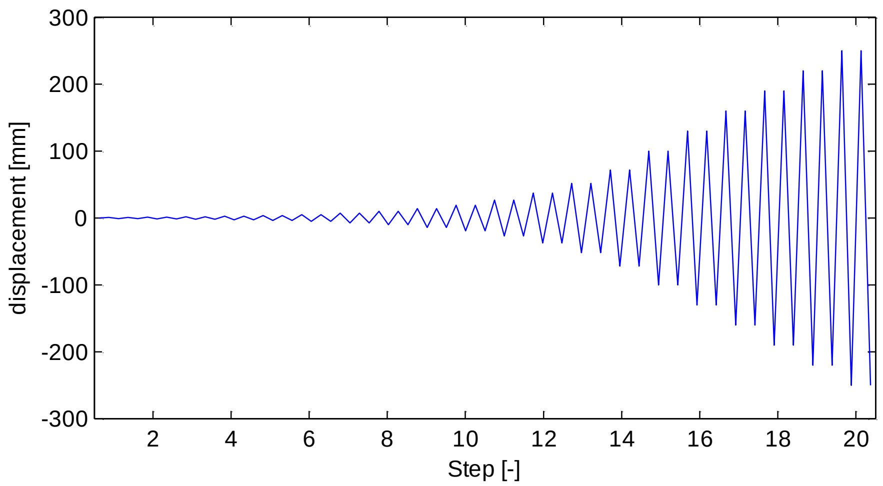

Figure 6: Adopted displacement loading protocol.

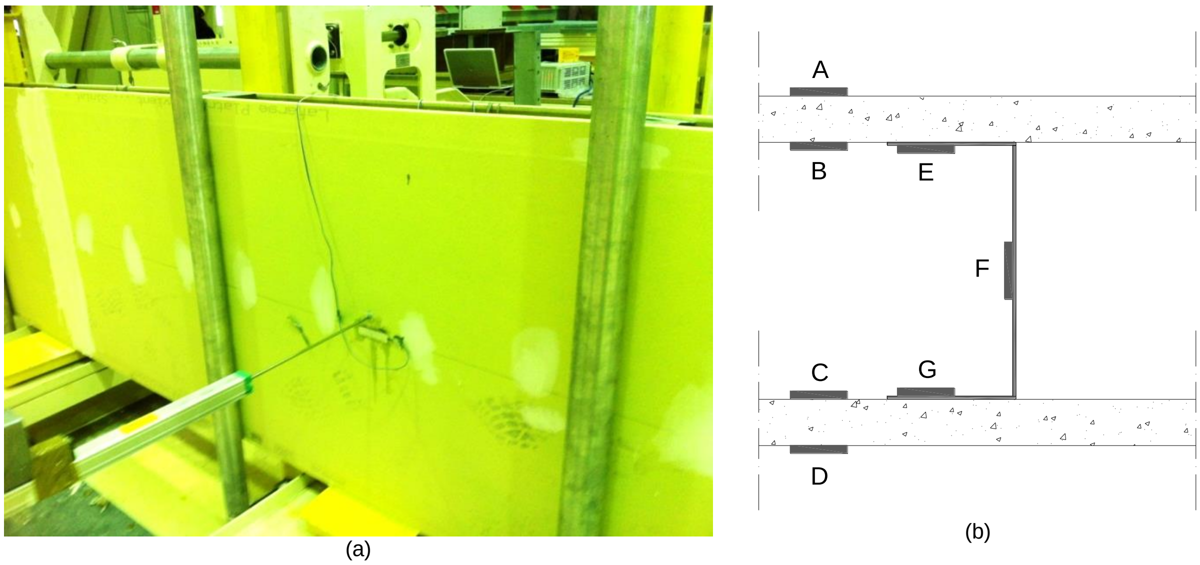

Figure 7: (a) LVDT used to record the mid-span out-of-plane displacement; (b) strain gauges arrangement in the partition cross-section corresponding to the centroid of the specimen.

RESULTS AND DISCUSSION

Damage Description

The different specimens showed similar damage typologies. The main damage typologies were:

- Cracking of the horizontal joints between adjacent panels (Figure 8a);
- Damage of the stud-to-panel screwed connections; it started at the connections close to the external restraints (Figure 8b) and then affected the ones closest to the centre of the partition;
- Local buckling of either the web or the flange or both the web and the flange of the steel stud, clearly denoted by the waves in the stud (Figure 8c);
- Pull out of the boards and/or of the studs from the base or top horizontal guide due to the excessive local plastic deformation in the stud; this damage type was the typical cause of the collapse of the whole specimen (Figure 8d).

It should be noted that the recorded damage points out that the plasterboards were typically not damaged at the end of the test. Hence, the "weak" part of the tested specimen was either the stud or the horizontal guide or the panel-to-stud screwed connections. Moreover, the recorded damage typologies can be also found in previous experimental studies on plasterboard partition walls, e.g. [7, 11].

Global Behaviour: Results Summary

Recorded forces in the two actuators are similar to one another: the static scheme, i.e. the six point bending scheme, was well reproduced during the tests. The total force applied in the out-of-plane direction is plotted versus the centroid out-of-plane displacement in Figure 9 for the four tested specimens. Recorded displacements agreed well with the predefined input protocol. A nonlinear behaviour of the tested partitions, which occurred after an initial linear trend, is clearly observed. Moreover, their response was unsymmetrical, as highlighted by the different negative and positive strengths of the specimens. The occurrence of different damage typologies was also highlighted in the hysteresis loops. The main damage typologies can be summarized in local buckling failure in the studs and joint cracking; the final collapse corresponded for all cases to the

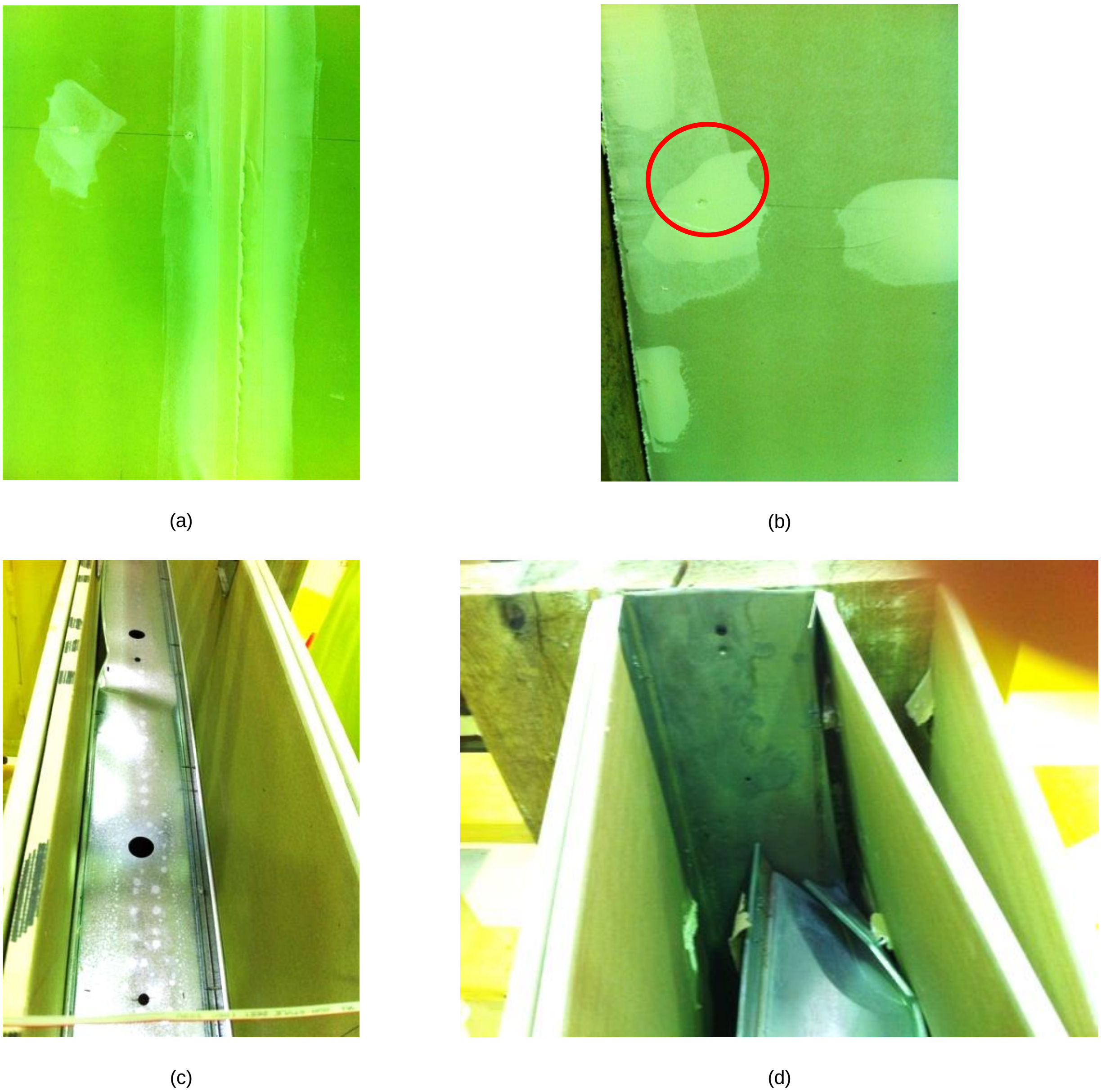

Figure 8: Main recorded damage typologies: (a) paper cracking in the horizontal joints; (b) damage in the panel-to-stud screwed connections; (c) local buckling in the studs; (d) pull out of the stud from the horizontal guide.

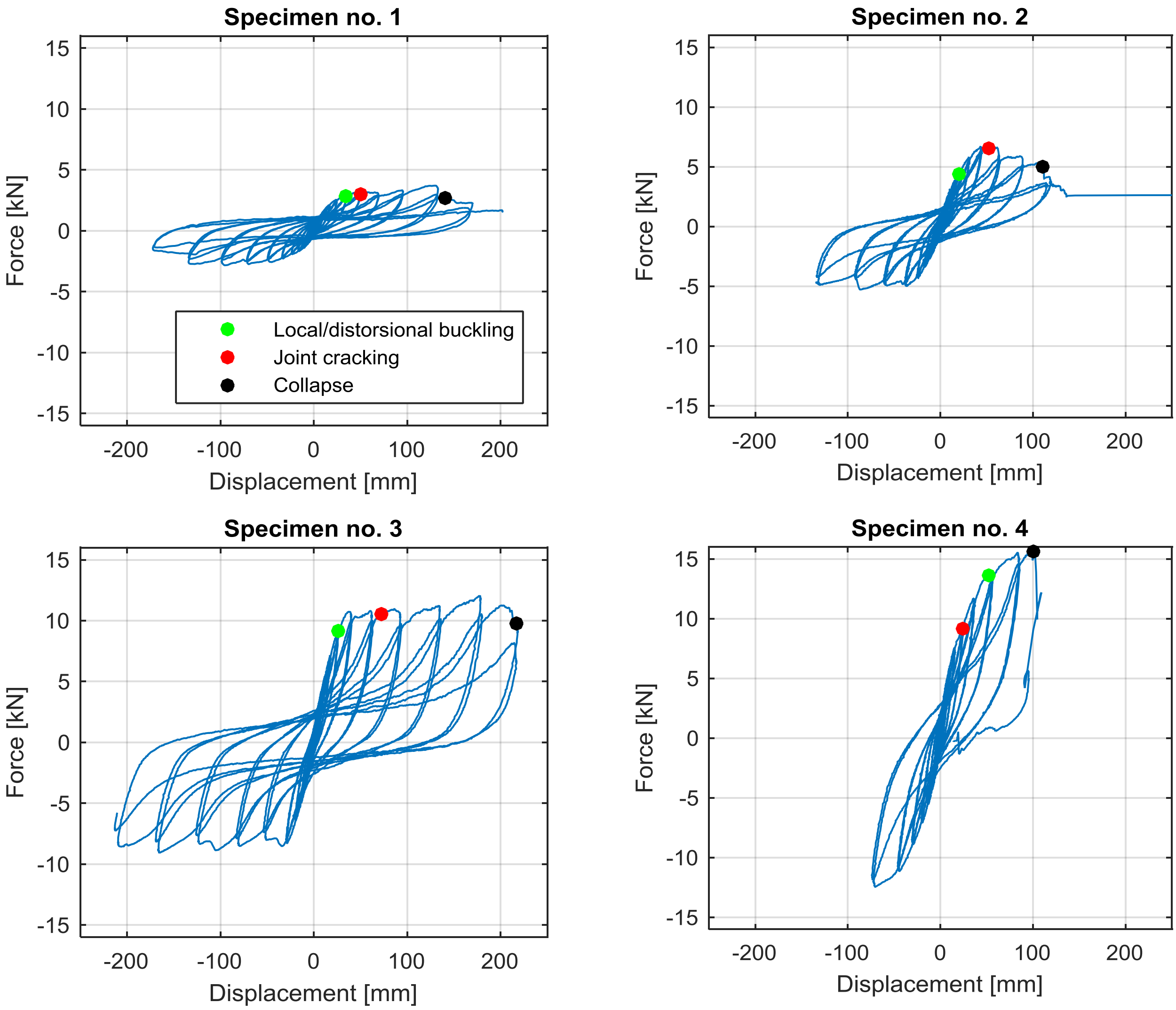

Figure 9: Hysteresis loops for specimens no. 1 - no. 4.

pull off of boards and/or of studs from the horizontal guides due to local plastic deformation of the guide or failure of the board.

The comparison of the backbone curves (Figure 10a), evaluated as the envelope of the hysteresis loops up to the failure of the specimen, allowed evaluation of the influence of several parameters:

- Specimen no. 3 exhibited a larger strength than specimen no. 2; the introduction of back-to-back studs, which also doubled the amount of screws in the specimen, significantly increased the seismic performance in the out-of-plane direction; indeed, the collapse displacement also increased with the introduction of back-to-back studs;
- Specimen no.4 showed the largest strength among the tested specimens, even though specimens no. 3 and no. 2 were characterized by a deeper stud. Hence, the contributions to the strength of the specimen of both the thicker boards, i.e. 18 mm thick boards vs 12.5 mm thick boards, and the larger number of studs, i.e. six M100-50 vs four M150-50, were therefore significant. Finally, it should be noted that specimen no. 4 was also characterized by a low collapse displacement.

The different specimens exhibited similar secant stiffness trends (Figure 10b), which degrade as the specimens get damaged. The secant stiffness was evaluated both for positive and negative displacements. The following features can be noted observing the trend of the curves:

- Specimen no. 4 showed the largest secant stiffness among the tested specimens, even though it was characterized by a 100 mm deep stud; the presence of six studs and the double layer of 18 mm boards per side gave a strong contribution to the stiffness of the partition;
- The doubled number of both the studs and consequently the screwed connections in specimen no. 3 compared to the specimen no.2 significantly increased the stiffness of the partition in the out-of-plane direction. Hence, secant stiffness was significantly influenced by the amount of screwed connections.

The hysteresis loops of each single step of the test protocol are isolated in order to underline their shape change during the test. Indeed, in the first steps the force-displacement relationship is almost linear and friction mechanisms are noted; in the last steps a pinching phenomenon is clearly visible in the force-displacement relationships. The pinched behaviour is caused by the damage in the screwed connections, whose cyclic behaviour was strongly degrading at large displacement levels. The comparison between steps no. 9 and no. 16 for specimen no. 1 (Figure 11) clearly highlighted the change in the hysteresis loop shape. The sensitivity of the tested specimen to the selected protocol was therefore demonstrated; it should be underlined that the FEMA

461 protocol might be significantly different from the seismic action experienced by a partition during a real earthquake.

The dissipated energy in test no. 1 for each negative and positive semicycle of the given protocol is shown in Figure 12. The degrading behaviour of the specimen is clearly highlighted. Indeed, the test protocol provided two consecutive cycles at the same displacement; the energy dissipated in the second cycle of the step was smaller than the energy dissipated in the first cycle of the same step. In particular, the energy reduction among two cycles at the same imposed displacement in specimen no. 1 is 6.2% at step no. 8, where it showed an almost linear trend up to steps no. 16 and 17, where the energy reduction was about 25% (Figure 13a). The same conclusions can be drawn from the dissipated energy trends of the tests no. 2 to no. 4, which showed a similar dissipated energy decay among two cycles at the same imposed displacement (Figure 13a).

The energy dissipated in the negative semi-cycle was similar to the energy dissipated in the preceding positive semi-cycle for specimen no. 1, even if the negative force was typically smaller than the positive one, i.e. discrepancies up to 12%. Instead, larger discrepancies among positive and negative dissipated energies were found in specimens no.2 to no. 4 (Figure 13b), which confirmed the unsymmetrical behaviour of the tested partition systems.

It should be emphasised that the tests were performed in a quasi-static regime. Such a test typology allows evaluation of

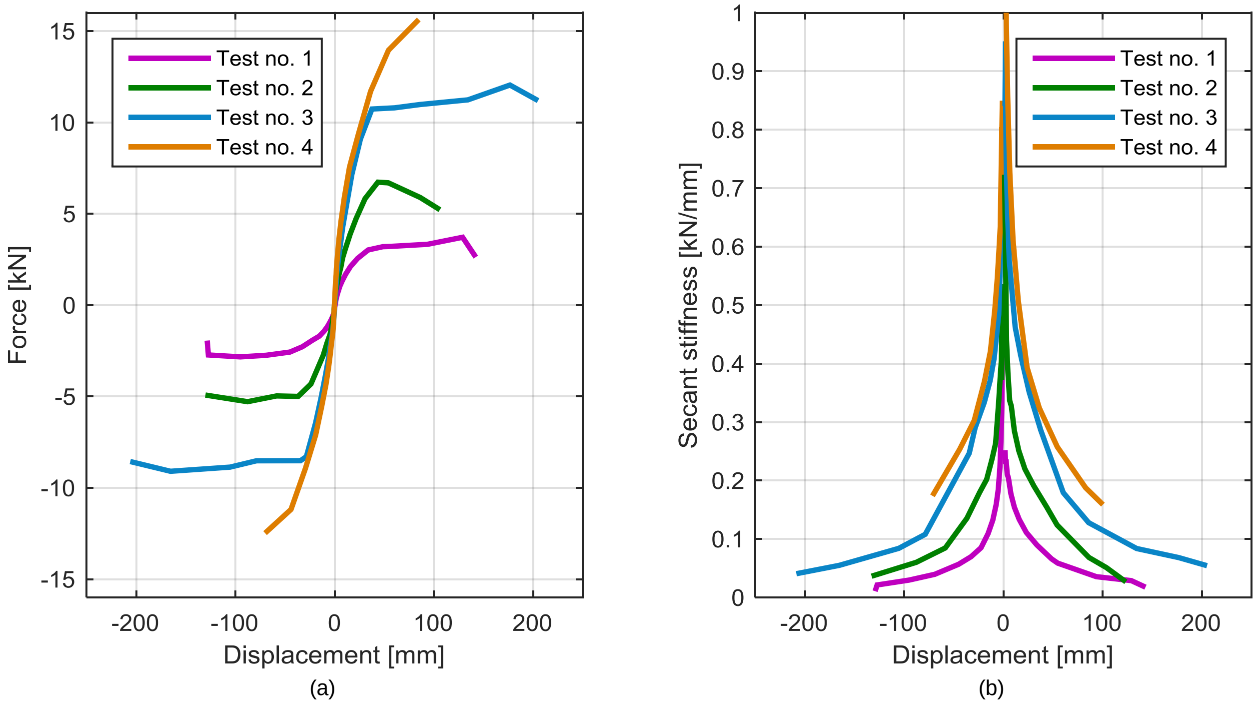

Figure 10: Comparison among the different tested specimens in terms of (a) backbones curves and (b) secant stiffness.

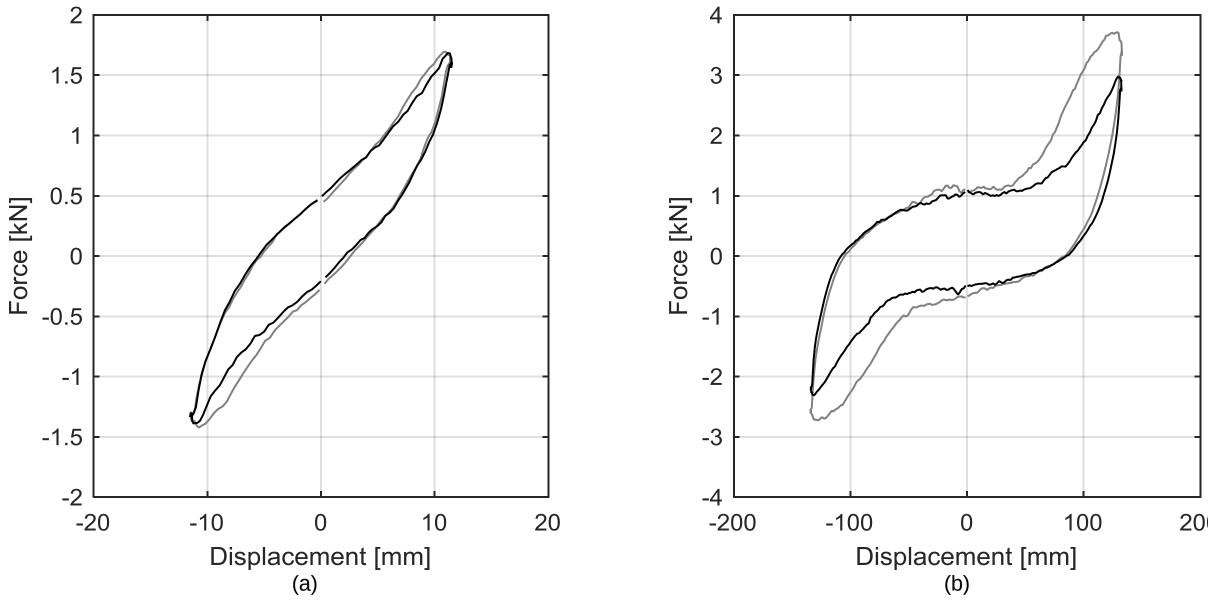

Figure 11: Force-displacement relationship for (a) step no. 9 and (b) step no. 16 of the defined loading test protocol in specimen no. 1; the first of the two cycles of the step is in gray, whereas the latter cycle is in black.

the capacity of the component to compare it with the seismic demand. However, a dynamic test might show different modes of failure, besides taking into account the inertia loads and the dynamic behaviour of the component. For instance, the delamination of the board from the studs could not be observed in the performed quasi-static tests, given the adopted test setup. Such a mode of failure could be particularly observed in the case of a bookcase fixed to the wall.

Local Behaviour: Contribution of the Boards to the Resisting Bending Moment

This section shows the contribution of both Siniat boards and screwed connections to both the strength and the stiffness of the partition. In order to highlight their influence on the global behaviour of the partition in the out-of-plane direction, the strain gauge recordings were investigated. In Figure 14 the strain recordings on Siniat boards of the specimen no. 1 are shown: the green line shows the deformations recorded on the internal side of the board, whereas the blue line shows the strain recorded on the external side.

The strains on the internal and external sides were almost coincident during the first cycles of the test; after some cycles they tended to become opposite. This issue suggests that the board-to-stud cross-section behaved as a composite cross-section; two different components, i.e. plasterboards and steel studs, were connected by steel screwed connections in this cross-section.

Initially the stud and the boards behaved as a unique cross-section (Figure 15a); as the screwed connections started failing, a relative slip between studs and boards was recorded and the components did not act as a unique cross-section anymore; they tended to act as three different cross-sections in parallel (Figure 15b). This behaviour was confirmed by the trend shown in Figure 16, where the strains recorded at the same cross-section location both on the steel stud and on the board are compared for test no. 1. During the first cycles, the

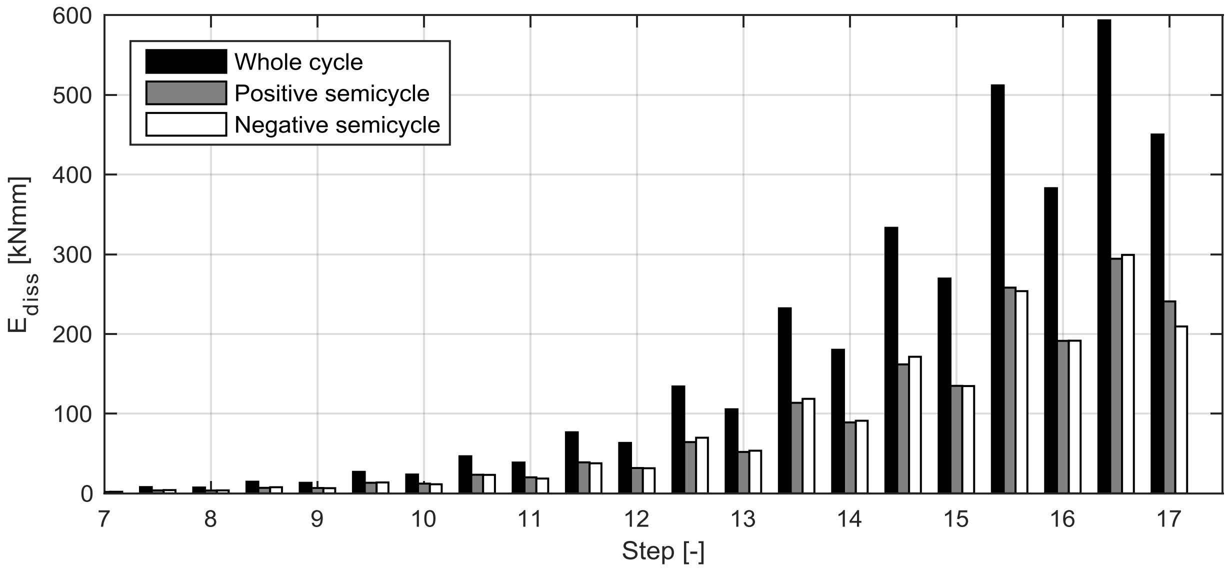

Figure 12: Energy dissipated for each cycle during the test no. 1.

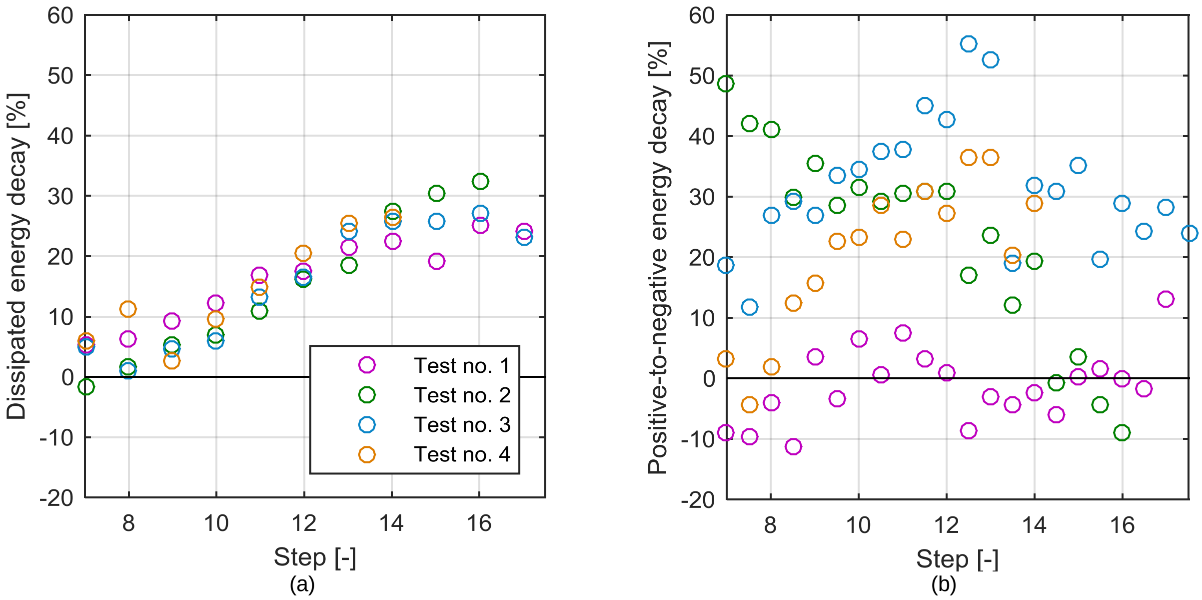

Figure 13: (a) Dissipated energy decay among two consecutive cycles at the same imposed displacement; (b) dissipated energy decay among positive and negative semicycles.

steel and plasterboard strains were almost coincident. At large displacement levels, the strain compatibility rule, i.e. plane cross-sections remain plane, was not valid anymore and furthermore, the strains become opposite in sign, as expected according to Figure 15b. Moreover, secant stiffness values attained at the first steps were in line with the stiffness of the composite element, whereas the secant stiffness, evaluated after the connections are fully damaged, is close to the "non-composite" stiffness. As a consequence, the inertia, i.e. the out-of-plane stiffness of the partition, significantly reduced at large displacement levels; this phenomenon might justify the nonlinear stiffness trend exhibited by the partitions (Figure 10b). Hence, the nonlinear behaviour exhibited by the different specimens might have been attributed both to the local buckling of the studs and, particularly, to the board-to-stud screwed connection damage. Finally it should be noted that this behaviour was also exhibited by the other three tested specimens.

Assessment of the Tested Partitions: Eurocode vs Experiments

According to Eurocode 8 [14], partition walls are nonstructural components, which must be designed according to a seismic demand corresponding to a design seismic intensity level; such an intensity level is the same level considered during the design of the primary structure [19, 20]. The force-based seismic design of internal partitions is conducted in a straightforward way by comparing the seismic demand on the component with its capacity. Since internal partitions are acceleration-sensitive components in the out-of-plane direction, their assessment is performed in this direction. The assessment of the tested partitions is included in this Section according to Eurocode, which is based on a Load Resistance Factor Design (LFRD). In particular, evaluation of seismic demand and assessment of capacity are discussed in the next two Sections. Thereafter, Eurocode approach to both the capacity assessment and the global assessment of the tested partitions was compared to the experimental outcomes.

Seismic Demand Evaluation

According to Section 4.3.5 of Eurocode 8, the seismic demand is determined by applying to the nonstructural element a horizontal force F_a in the out-of-plane direction, which is defined as follows:

$$F_a = \frac{S_a \cdot W_a \cdot \gamma_a}{q_a} \tag{2}$$

where:

- F_a is the horizontal seismic force, acting at the centre of mass of the nonstructural element in the considered direction;
- S_a is the seismic coefficient applicable to nonstructural elements, evaluated according to Equation (3);
- W_a is the weight of the element;
- γ_a is the importance factor of the element, equal to 1 in ordinary conditions;
- q_a is the behaviour factor of the element, equal to 2 for internal partitions.

The seismic coefficient S_a may be calculated using the following expression:

$$S_a = \alpha \cdot S \cdot \left[\frac{3 \cdot \left(1 + \frac{z}{H}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - 0.5 \right] \tag{3}$$

where:

- α is the ratio between the design peak ground acceleration on stiff soil, ag, and the acceleration of gravity g;
- S is the soil factor, assumed equal to 1 in this simplified calculation;
- T_a is the fundamental vibration period of the nonstructural element;
- T_1 is the fundamental vibration period of the building in

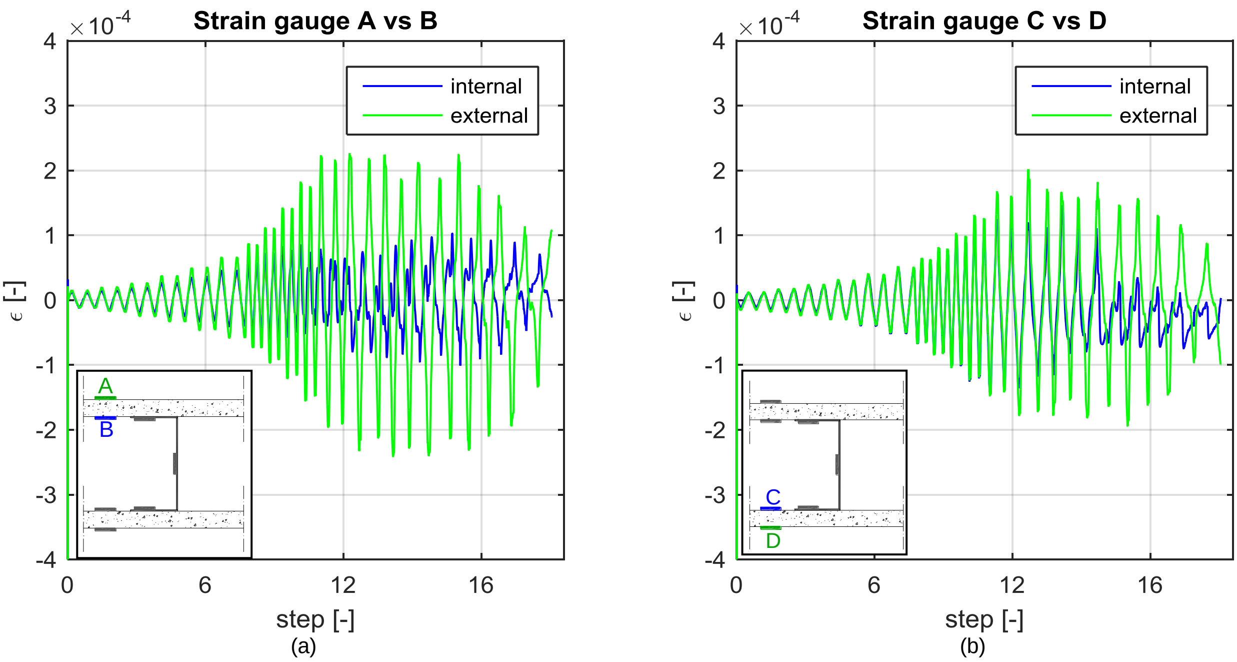

Figure 14: Strain gauge recording in both the sides of the two plasterboards installed in specimen no. 1.

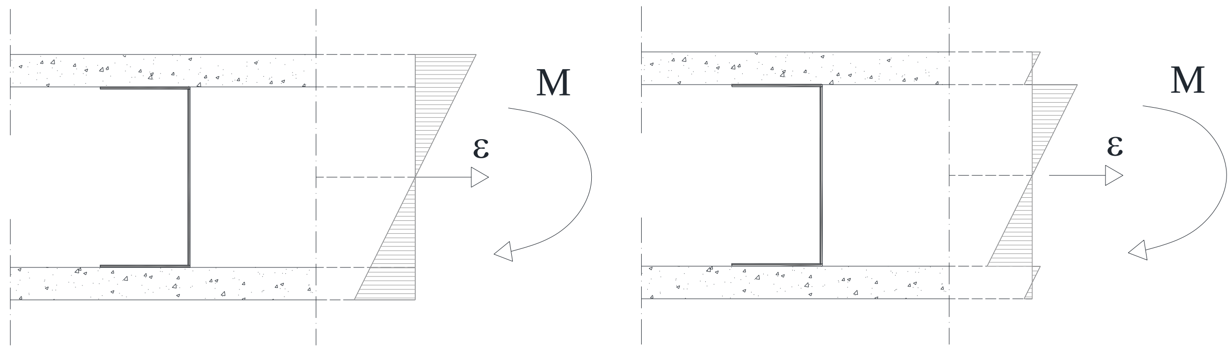

Figure 15: Plasterboard partition cross-section behaviour in terms of recorded strain (a) as a unique composite section and (b) as three different components acting in parallel.

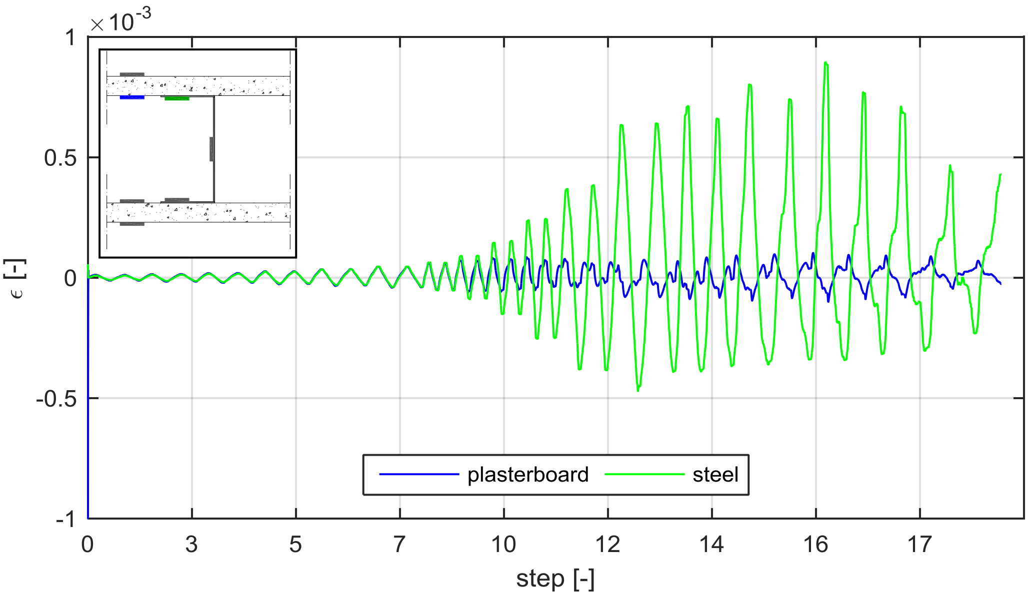

Figure 16: Strain recorded on both steel and plasterboard at the same cross-section position in test no. 1.

the relevant direction;

- z is the height of the nonstructural element from the foundation or from the top of a rigid basement;
- H is the building height measured from the foundation or from the top of a rigid basement.

The value of the seismic coefficient S_a should not be taken less than $\alpha \cdot S$. For internal partitions, it can be assumed that they are installed at the top storey of the structure; moreover, on the safe-side, it is supposed that the fundamental period of the component in the out-of-plane direction is equal to the period of the structure, i.e. T_a/T_1 is set equal to 1. Finally, the maximum bending moment M_{max}, acting at the centroid of the partition, according to a pinned-pinned static scheme is equal to $F_a \cdot h/4$, where h is the interstorey height, equal to 5 m for the tested specimens. It should be noted that the assumption of the static scheme is on the safe side compared to a fixed-fixed boundary condition. The maximum axial force acting in the partition is the weight of the partition, whereas the maximum shear force is $F_a/2$. However, as expected, both the axial and the shear forces were negligible compared to the corresponding capacities of the considered partitions. For this reason, the verification was conducted only in terms of bending moment.

Seismic Capacity Evaluation

The resisting bending moment of the tested partition is evaluated in this paragraph. Unfortunately, formulations that allow taking into account the contribution of the boards to the steel studs are not available in the current building codes, e.g. Eurocode 3 part 1-3 [21]. Hence, the resisting bending moment of a plasterboard partition can be evaluated as the capacity of the steel studs included in the considered partition; the presence of the plasterboards implies that the seismic demand is equally distributed among the different studs of a partition. According to Eurocode 3 part 1-3 [21], which is related to cold-formed steel elements, the resisting bending moment of a partition can be evaluated as follows:

$$M_{b,Rd} = \chi_{LT} \cdot W_{z,eff} \cdot \frac{f_{yb}}{\gamma_{M1}} \cdot n_{studs} \tag{4}$$

where χ_{LT} is the reduction factor due to the lateral-torsional buckling, which takes into account several geometrical and mechanical features of the studs, $W_{z,eff}$ is the effective section modulus, f_{yb} is the nominal steel yield strength, γ_{M1} is the partial safety factor and n_{studs} is the total number of studs in the given partition. In the specific case, nominal steel yield strength was set equal to *300 N/mm²* and partial safety factor was set equal to 1.0, i.e. a safety factor was not considered.

It should be noted that the effective section modulus was evaluated according to a reduced "effective" section, where some portions of the cross-section were not considered; this reduction was due to both local and distortional instabilities, as clearly described in Eurocode 3 part 1-3 [21]. Since the cross-section of the stud is not symmetric with respect to the neutral axis, the section modulus is taken as the minimum between the positive and negative ones.

Assessment of the Tested Partitions: Eurocode vs Experimental Tests

In Figure 17a the resisting bending moments evaluated according to Eurocode 3 are plotted in black for each partition. These values are compared to the strength exhibited by the tested specimens (in white), which was simply evaluated from the maximum force recorded during each test. Such a maximum force was equal to the peak negative force, given the unsymmetrical behaviour of the tested specimens (Figure 10a). The Eurocode approach shows a strong underestimation of the resistance of the tested specimens. This underestimation suggests that the contribution of Siniat boards to the resisting bending moment, which is neglected in Eurocode 3, was significant. Such a contribution was significant also due to the presence of the screws, which allowed the plasterboards to carry a significant amount of bending moment. Indeed, the bending moment absorbed by Siniat plasterboards in the configuration in Figure 15a, where the screwed connections were effective, was much larger than in the configuration in Figure 15b, which was representative of a cross-section without screwed connections.

The performance check of the tested partitions was then assessed by comparing the demand with the capacity in terms of bending moment. In particular, the seismic demand can be evaluated in terms of maximum bending moment according to the assumptions stated earlier. In order to generalize the problem, the design peak ground acceleration on stiff soil a_g, required for the seismic demand to equal the seismic capacity (Figure 17a), was evaluated and plotted in Figure 17b. The a_g values evaluated according to Eurocode strength were much lower than typical a_g values in moderate-to-high European seismic zones, which are larger than *0.30g*. In other words, according to Eurocode-based strength assessment, these partitions could not be used in these zones: a larger number of studs would be needed. Instead, considering the experimental strength, the tested Siniat partitions could be used in almost the whole European territory.

The large discrepancy between the Eurocode and the experimental results obtained on Siniat partitions shows the urgent need to define a formulation that would include the contribution of the plasterboards, through the screws, to the resisting bending moment. However, caution should be taken in generalizing the results since a limited amount of tests were performed, i.e. only one specimen for each partition typology.

CONCLUSIONS

A quasi-static test campaign aimed at the evaluation of the seismic performance of plasterboard internal partitions with steel studs was presented in the paper. The research study dealt with the out-of-plane behaviour of such a nonstructural component. Four tall, i.e. 5 m high, specimens were selected; they are typical Siniat plasterboard internal partitions installed in Europe. FEMA 461 test protocol was adopted.

The specimens showed similar damage typologies at different displacement demand intensities: minor damage states, such as (a) paper cracking in the horizontal joints between adjacent panels, (b) damage of the stud-to-panel screwed connections, (c) local buckling of the steel studs, at low displacement demand; major damage states, such as pulling out of the boards and/or of the studs from the base or top horizontal guide, at larger displacement demand. A significant nonlinear pinched behaviour of the tested specimen was observed. The pinched behaviour was caused by the damage in the screwed connections, whose cyclic behaviour is strongly degrading. The comparison of the backbone curves allowed evaluating the influence of some parameters:

- The use of back-to-back studs, which doubles the amount of screws in the specimens, significantly increased the seismic performance in the out-of-plane direction;
- Both the stiffness and the strength of the specimens were significantly influenced by the adopted board typology and the amount of screwed connections.

Steel and plasterboard strains at the same cross-section location were equal for low displacement demand, suggesting

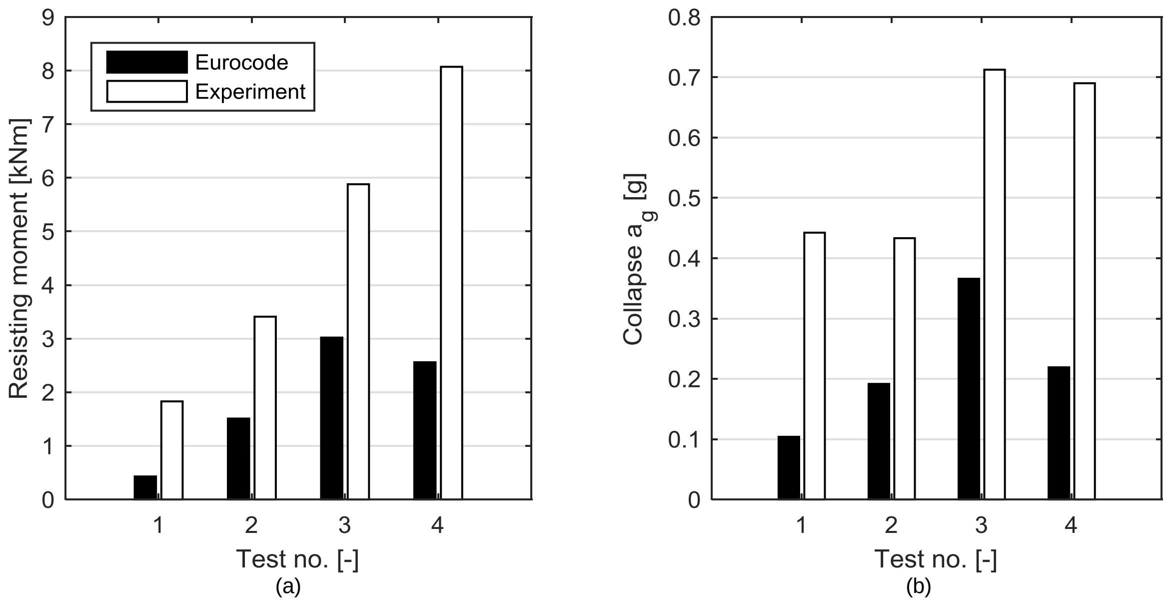

Figure 17: Comparison between (a) resisting bending moments and (b) collapse ground accelerations evaluated both according to Eurocode and from the experimental tests.

that the tested components behaved as a composite board-stud-board component. The strain compatibility rule, i.e. plane cross-sections remain plane, was then violated as damage in the screwed connections started occurring. The stud and the two plasterboards behaved as three distinct components acting in parallel at that stage. The damage in the screws also caused a reduction of the inertia of the whole cross-section, which might justify the nonlinear stiffness trend exhibited by the tested partitions. Hence, the nonlinear behaviour exhibited by the different specimens may be attributed to the board-to-stud screwed connection damage. Finally, the resisting bending moment of the Siniat partitions was evaluated according to Eurocodes and compared to the experimental results. A substantial disagreement between the code and the experimental assessment was shown.

It should be underlined that the tests were performed in a quasi-static regime. Dynamic tests might show different modes of failure which were not exhibited in this research study, due to the nature of the applied load. Future studies will deal with the influence of several parameters that were not considered in this study, such as the environmental conditions and the interaction with sprinkler systems. Moreover, a wide set of partitions, e.g. multiple specimens for each partition typology, is required in order to generalize the results in a design building code.

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