buildings

MDPI

Article

Earthquake Response of Cold-Formed Steel-Based Building Systems: An Overview of the Current State of the Art

Gianmaria Di Lorenzo and Attilio De Martino *

Department of Structures for Engineering and Architecture, University of Naples Federico II, Via Forno Vecchio 36, 80134 Naples, Italy; gianmaria.dilorenzo@unina.it
* Correspondence: atdemart@unina.it

Received: 26 July 2019; Accepted: 25 October 2019; Published: 31 October 2019

Abstract: Building systems fabricated with cold-formed steel (CFS) profiles and members made of wood, gypsum, or other materials allow solving a range of issues arising in common constructional elements thanks to their advantages, such as lightness, strength, durability, physical stability, sustainability, and cost-effectiveness. As a result of this inherent competitiveness of CFS based buildings, their use has been gradually increasing in recent years both in the field of structural systems as non-structural architectural components and, above all, in the area of earthquake resistant buildings, where lightness play a key role. After a general introduction, the paper gives an overview of the current codification and ongoing research on CFS non-structural architectural and structural systems. Finally, the main conclusions are summarised, and possible future developments are outlined.

Keywords: cold-formed steel; drywall; lateral force resisting systems; lightweight steel; non-structural architectural elements; seismic behaviour

1. Introduction

The success of a constructional typology usually depends on the capacity to meet the needs of the market, which is increasingly oriented towards solutions characterised by economic efficiency and ecological performance. Building systems made by assembling cold-formed steel (CFS) profiles and panels made of wood, gypsum, or other materials allow solving a range of issues arising in common constructional elements thanks to their advantages, such as lightness, strength, durability, physical stability, sustainability, cost-effectiveness. For this reason, the application of CFS-based building systems has been booming over the years both in the field of structural systems as non-structural architectural components and, above all, in the area of earthquake-resistant buildings [1–4], where lightness play a key role. However, the knowledge on seismic response of CFS building systems is still very limited and not properly diffused among the structural engineering community. In this context, this paper attempts to provide a brief overview of the studies carried out on most commonly used CFS building constructional systems and their response under earthquake actions.

The main CFS structural systems in a building are usually the load-bearing floors and walls. The load resisting walls are comprised of studs, i.e., vertical load-bearing studs spaced at 300 to 600 mm and fastened at each end to wall tracks, which serve the purpose of supporting the studs laterally and distributing loads among them. In a seismic area, the resistance to horizontal in-plane actions can be provided through different systems: X-bracing (Figure 1a), sheathing panels (Figure 1b), mixed solutions obtained by the introduction of both X-bracing and panels. Floors are fabricated with horizontal load-bearing members (joists) and a cladding made of wood or gypsum panels or steel sheets (Figure 2). Joists are located in line with the wall studs, fastened at their ends to a floor track.

Usually, studs and joists are C (lipped channel section) shaped profiles, whereas wall and floor tracks are U (unlipped channel section) shaped profiles.

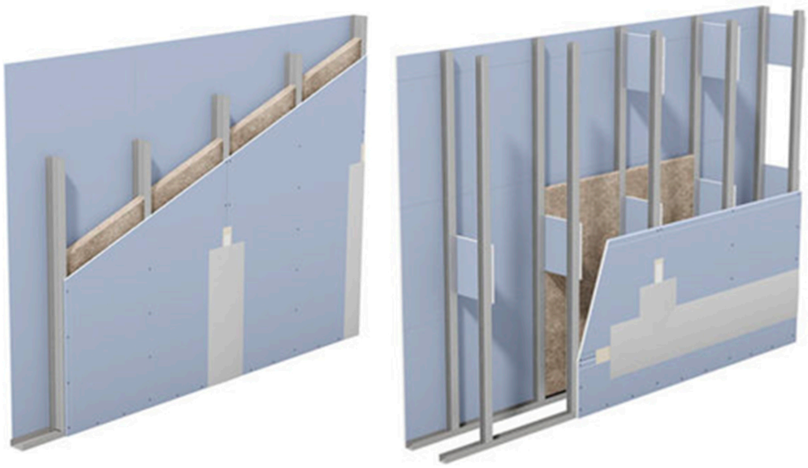
(**a**) (**b**)

Figure 1. Cold-formed steel (CFS) structural systems: walls. (**a**) X-braced wall; (**b**) sheathed-braced wall.

(**a**) (**b**)

Figure 2. CFS structural systems: floors (**a**): Floor sheathing being placed on floor joists; (**b**): Hold-down connection between floors and walls.

Typical applications of CFS systems in the field of non-structural components are drywall systems such as partitions, suspended ceilings, and façade constructions. Drywall partitions are mainly made of C and U shaped CFS profiled stud frames. The tracks are anchored to the floor or ceiling, whereas the studs are typically placed with a distance equal to or half the width of the sheathing panels (usually 600 mm), which typically are gypsum-based boards fastened to the CFS frame (Figure 3) through screws. Partitions made with the assemblage of cold-formed steel (CFS) profiles and panels can reach very high performances, such as the wall heights up to 12 m, acoustic insulations up to 80 dB, and fire resistance up to 120 min (fire resistance). Common solutions for suspended ceilings are usually made of a double profile frame or a flush profile frame or a suspended furring channel (Figure 4). Mostly, U and C shaped CFS members and gypsum panels are the basic products utilised in these types of buildings. CFS drywall systems can also be used for making an envelope of the building. In this case, since the external façades are exposed to moisture, exterior claddings are usually made of waterproof cement panels, and interior claddings are made of gypsum panels (Figure 5). A special thermal insulation material is also used to fill the wall cavity, which guarantees the anticipated energetic performance.

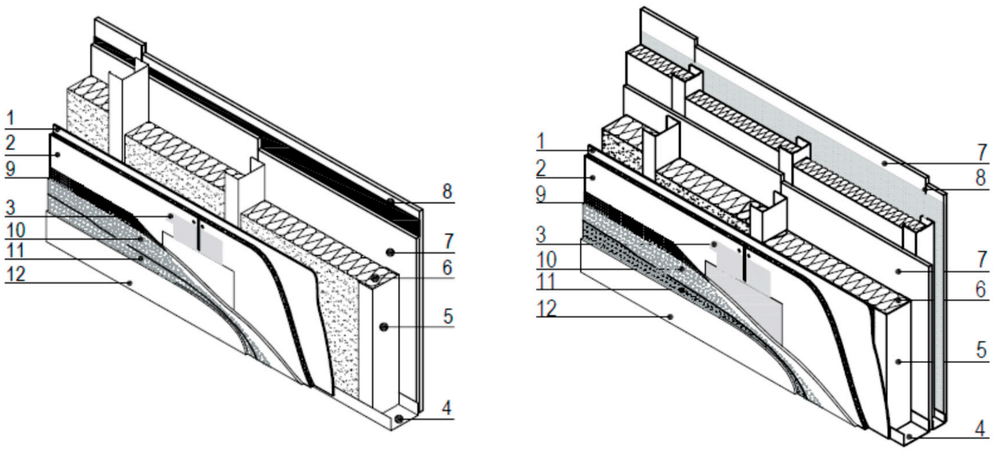


(a) (b)

Figure 3. Drywall non-structural architectural components: partitions. (**a**) Partition with single layer of studs; (**b**) partition with double layer of studs.

(**a**) (**b**)

Figure 4. Drywall non-structural architectural components: suspended ceilings. (**a**) Suspended ceiling without a flush profile frame; (**b**) suspended ceiling with a flush profile frame.



(**a**) (**b**)

Figure 5. (**a**) façades with single layer of studs; (**b**) façades with double layer of studs, Drywall non-structural architectural components: façades; 2 = waterproof cement panels; 4 = track profile; 5 = stud profile; 6 = thermal insulation material; 7 = gypsum panel.

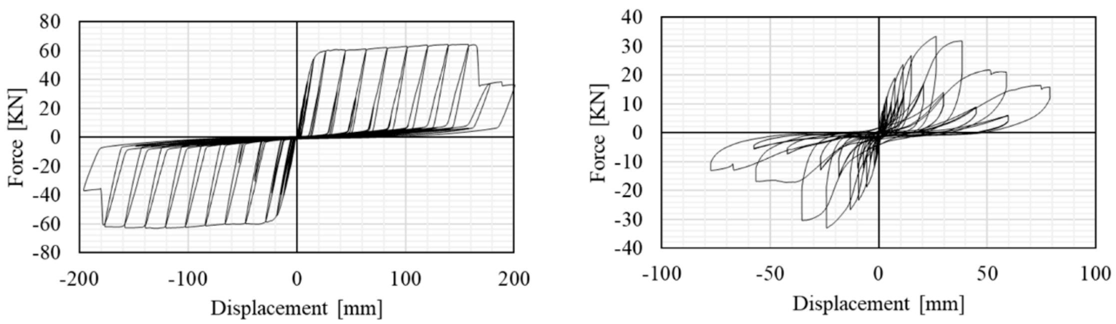
In the next Sections, after a general introduction, an overview of current codification and ongoing research is presented for both CFS structural and non-structural architectural building systems. In particular, since several studies have been carried out on the earthquake response of CFS systems, only a brief summary of some recent research is given here.

2. Seismic Response of Structural Systems

2.1. General Issues

An interesting feature of CFS lateral force resisting systems is the option to carry out the structural design checks according to two distinctive approaches: "strap-braced design" and "sheathing-braced design". When in-plane resistance is computed according to the "strap-braced design", the steel straps are used as diagonal elements in an X configuration to resist in-plane lateral loads. Steel straps are pin connected to the external faces of stud flanges, whereas they are connected to the bottom flanges of joists on the floor. On the other hand, when the "sheathing-braced design" approach is considered, the resistance provided by sheathing the panel-to-steel frame interaction is considered as a dominant source of lateral resistance.

In both strap-braced and sheathing-braced lateral force resisting systems, the seismic response is dominated by the degradation in strength and stiffness along with a significant pinching behaviour (Figure 6). CFS strap-braced walls rely on thin steel strap braces placed in an X configuration to dissipate the energy through the tensile yielding of the strap, while CFS sheathing braced shear walls rely on tilting or bearing at the sheathing connections between panels and CFS frame to dissipate energy. In addition, strap-braced systems exhibit an initial linear lateral response, whereas sheathing-braced systems have a strong non-linear behaviour. However, despite their weak hysteretic response in terms of energy dissipation in comparison to traditional steel structures, CFS constructions could be a competing alternative for mid-rise buildings, mainly due to their lightweight nature, which allows them to meet reasonable structural performances in earthquake prone regions.



(**a**) (**b**)

Figure 6. Hysteretic response of typical CFS lateral force resisting systems. (**a**) CFS strap-braced walls [5]; (**b**) CFS gypsum sheathed shear walls [6].

The hysteretic responses shown in Figure 6 are obtained by subjecting the complete wall specimens (Figure 7) to the in-plane quasi-static cyclic load defined using the displacement control loading protocols [7]. The test does not involve the application of any gravity loads during the test except the self-weights of walls and test setup itself. All of the out-of-plane displacement in the tests were also avoided during the test. The tested walls were assembled with C or U shaped CFS profiles with 1.5 mm thickness.

(**a**) (**b**)

Figure 7. Pictures of the tested specimens. (**a**) CFS strap-braced walls [5]; (**b**) CFS gypsum sheathed shear walls [6].

2.2. Current Codifications

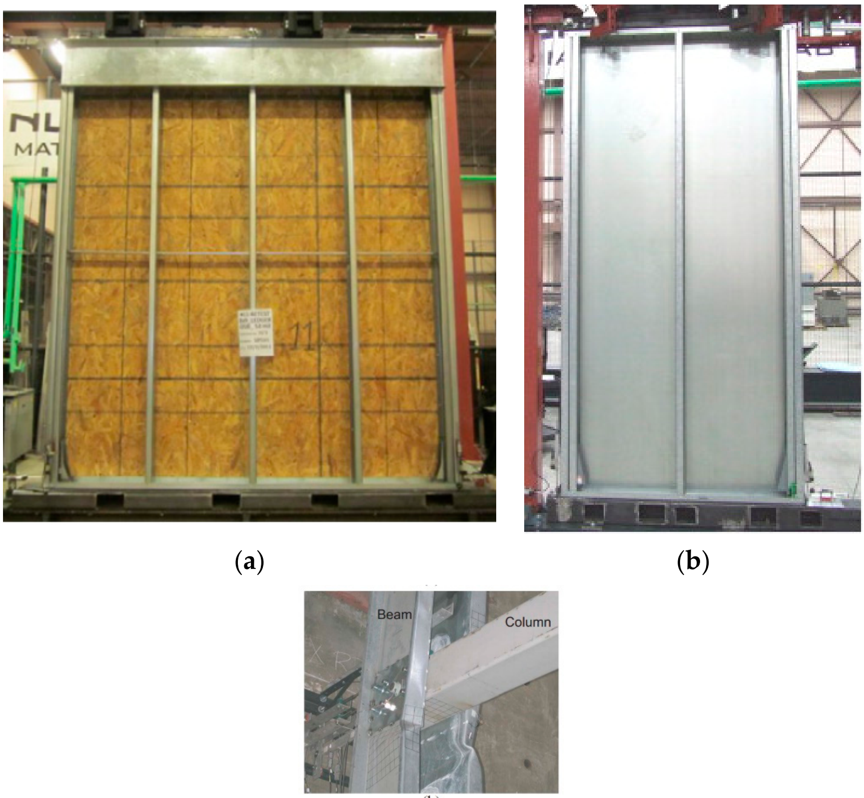
Nowadays, very advanced design codes for CFS structures are available in some countries [8–10]. Though, only North American Codes: AISI S400 [11], ASCE 7 [12], and NBCC [13] cover the design of these structures in earthquake prone areas.

In the European code for seismic design EN 1998-1 [14], there is not a specific section for CFS structures, therefore, according to the current framework of the code, the design of diagonal strap-braced walls and walls braced with steel sheets could be only made by assuming them as a hot rolled traditional steel structures fabricated with Class 4 cross-sections and classifying them as a Low Ductility Class. As a result, the use of strap-braced walls and steel sheathed shear walls is merely limited to low seismicity regions, which must have a reference design peak ground acceleration not greater than 0.08 g, and their seismic design can be carried out only by using a behaviour factor equal to 1.5 or less. However, the design of walls sheathed with panels made of materials different from steel is not possible by using the current EN-1998-1 [14].

North American standard AISI S400 [11] represents the most developed reference for the design of CFS structures under seismic actions. In particular, AISI S400 covers the following lateral force resisting systems: (1) CFS light-frame shear walls sheathed with wood structural panels (Figure 8a); (2) CFS light-frame shear walls sheathed with steel sheet sheathing (Figure 8b); (3) CFS light-frame strap-braced wall systems (Figure 7a); (4) CFS special bolted moment frames (Figure 8c); (5) CFS light-frame shear walls with a wood-based structural panel sheathed with wood panels on one side and gypsum panels on the other (similar to Figure 7b); (6) CFS light-frame shear walls sheathed with gypsum board or fibreboard panel sheathing (Figure 7b); (7) conventional construction CFS light-frame strap braced wall systems (Figure 7a).

All lateral force resisting systems covered be the AISI S400 are energy-dissipating structures, with the exception of CFS light-frame strap braced wall systems intended for conventional construction, which represents a non-designated energy-dissipating structure.

For each system, the specification defines the requirements for seismic design, as well as geometrical and material limitations, prescriptions for dissipative elements, and capacity design rules governing strength in the non-dissipative elements. For the definition of the seismic force reduction factor (R), AISI S400 refers to ASCE 7-10 [12] for the USA and Mexico, and NBCC [13] for Canada (Table 1).



(**a**) (**b**)

(**c**)

Figure 8. (**a**) CFS light-frame shear walls sheathed with wood structural panels [15]; (**b**) CFS light-frame shear walls with steel sheet sheathing [16]; (**c**) beam-column joint in a CFS special bolted moment frame [17].

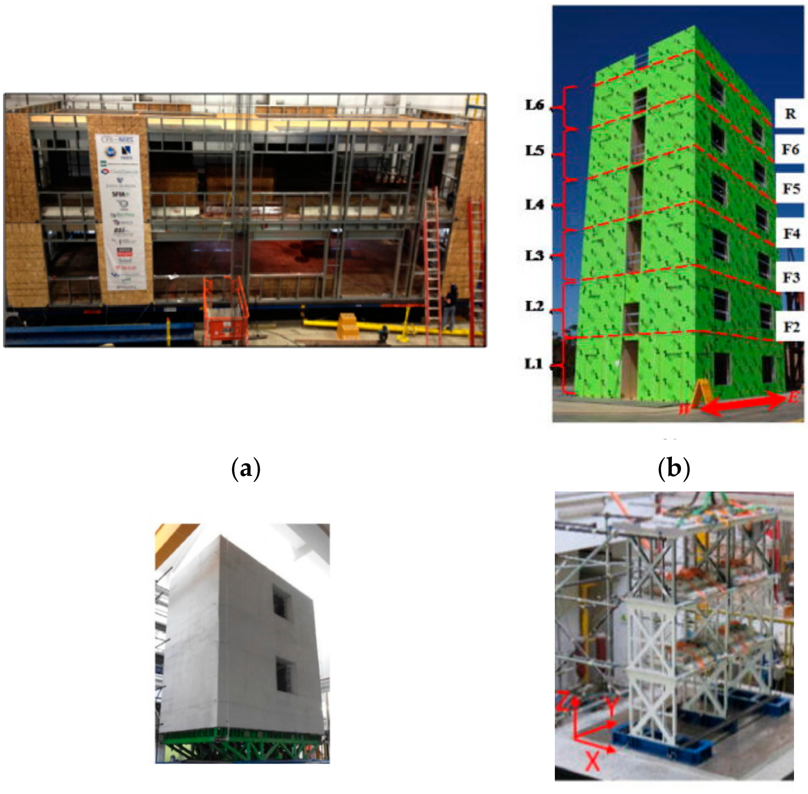
Table 1. Force reduction factor (R) given by ASCE 7 and NBCC Codes for lateral force resisting systems defined by AISI 400.

Lateral Force Resisting System	ASCE 7	NBCC
CFS light-frame shear walls sheathed with wood structural panels	6.5 to 7.0	4.25
CFS light-frame shear walls with steel sheet sheathing	6.5 to 7.0	2.6
CFS light-frame strap braced wall systems	4.0	2.47
CFS special bolted moment resisting frames;	3.5	-
CFS light-frame shear walls with gypsum sheathing on one side and wood-based sheathing on the other side	-	2.55
CFS light-frame shear walls with fiberboard or gypsum sheathing.	2.0 to 2.5	-
Conventional construction CFS light-frame strap braced wall systems	-	1.56

2.3. Ongoing Research

Experimental activity dealing with seismic behaviour of CFS walls started in the 90s with Adham et al. [18], which evaluated the lateral hysteretic characteristics of CFS steel stud/gypsum wallboard panel combinations subjected to lateral cyclic loads.

Shake-table tests have been commonly used in North America and Europe in previous years, although the first experiment was in Australia [19]. In particular, the bigger North American research studies involving shake table tests are the "CFS-NEES" projects [20], with tests of a two-storey full-scale commercial building (Figure 9a) having floors and walls sheathed with wood structural panels, and the research carried out on the outdoor shake table at University of California, with tests on a six-storey CFS building (Figure 9b) having shear walls sheathed on one side with steel sheets glued to gypsum panels [21]. The results indicated that the load-bearing gravity systems in the specimen caused an increase of four times while the addition of non-structural elements to the specimen increased additional 4.5 times the lateral stiffness of the building [21]. In Europe, studies involving shake table tests on a full-scale double-storey building (Figure 9c) having floors and walls sheathed with gypsum-based panels have been carried out in Italy within the "ELISSA" European project [22]. The main findings of this experimental activity showed that the characteristics of the building were significantly altered by the non-structural systems, with a decrease of the fundamental period of about 20%, corresponding to an increase of the lateral stiffness equal to about four times, and the specimen showed box building behaviour. The seismic response of low dissipative CFS strap-braced structures was evaluated through shake-table tests on two triple storey reduced-scale specimens (Figure 9d) within the "LAMIEREDIL" project [23]. Results showed that the global response was almost linear for both specimens for all scaling factors of the used earthquake record, and the observed damages were strap yielding and bolt loosening. It is also important to note that the buildings tested within North American studies and the "ELISSA" project also included non-structural architectural systems. Shake-table testing of the whole building, which includes both structural and non-structural systems, demonstrates that the current seismic methodologies are conservative in the prevision of the real response under earthquake actions.



(a) (b) (c) (d)

Figure 9. CFS building specimens tested on shaking table. (**a**) CFS building with wood sheathed shear walls [20]; (**b**) CFS building with combined gypsum-steel panel sheathed shear walls [21]; (**c**) CFS building with gypsum sheathed shear walls [22]; (**d**) scaled CFS building with strap-braced walls [23].

Experimental activity dealing with the seismic in-plane response of structural walls are very numerous worldwide. Researchers from the US and Canada were very active in last few years, with studies of Yu [16] on steel sheathed shear walls; Peck et al. [24] on gypsum sheathed shear walls; Schafer et al. [20] on wood sheathed shear walls with gypsum panels on the interior faces of walls and ledger in some cases; Velchev et al. [25] and Mirzaei et al. [26] on strap-braced walls. In Europe, Mohebi et al. [27] studied steel sheathed shear walls with layers of either gypsum or fibre cement board panels on the interior side; Accorti et al. [28] tested walls having a combination of strap braces inside and cement sheathing panels on the outside; Macillo et al. [6] tested shear walls sheathed with gypsum panels having different aspect rations by including the influence of non-structural finishing; Fiorino et al. [29,30] studied the experimental cyclic behaviour of low dissipative strap-braced walls. Even in Asia and Australia, some research teams have been very active on this task, with the walls sheathed with various combinations of board panels tested by Ye et al. [31,32], steel sheathed walls studied by Esmaeili Niari [33], and strap-braced walls having different positions of bracings tested by Moghimi and Ronagh [34]. Starting from the large amount of available results, it is possible to identify the basic factors affecting the seismic response of structural walls. The seismic response of walls is characterised by strength and stiffness degradation and pronounced pinching behaviour and, in the case of sheathing-braced walls, strong nonlinearity. The effect of construction techniques and frame and anchorage details is crucial, e.g., the correct design of chord studs (e.g., by using double studs) and corner foundation anchorages (e.g., by using hold-down devices) can help to resist the significant rocking actions.

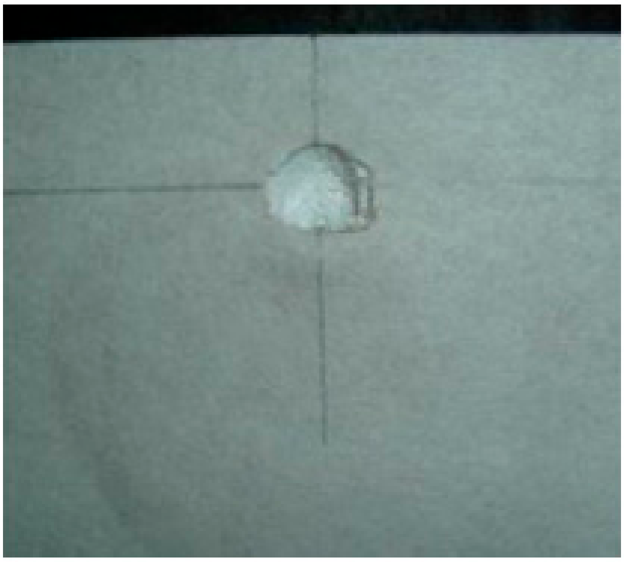
Certainly, fewer experimental studies are specifically dedicated to the horizontal diaphragms made of CFS profiles, as witnessed by few research carried out in Canada on wood-sheathed diaphragms (Figure 10a) with different constructional details and the presence of finishing layers in Canada [35,36] and wood-sheathed diaphragms and diaphragms made of steel deck (Figure 10b) in Italy [37]. Experimental results of the tests conducted on CFS diaphragms sheathed with wood panels underlined the dependency of the lateral response on construction technique and detail (e.g., the presence of panel edge blocking), screw spacing, and screw size. The effect of non-structural components, such as gypsum ceiling and flooring finishing, was also demonstrated.

(**a**) (**b**)

Figure 10. (**a**) Wood-sheathed diaphragm specimen [36]; (**b**) steel deck diaphragm specimen [37].

A very active field of research is the response of CFS connections, which can be grouped in steel-to-steel connections and sheathing panel-to-steel connections. The experimental characterisation of panel-to-steel connections is crucial for sheathing-braced systems, where these connections have a great influence on the global seismic response. Note that the experimental characterisation of the earthquake response of connections used in CFS components is a subject that cuts across both non-structural and structural systems. Recent studies have been particularly concentrated on connections between CFS profiles and sheathing panels, as represented by research carried out in the US by Vieira and Schafer [38] and Peterman et al. [39] on wood and gypsum-based sheathing connections, and by Swensen at al. [40] on gypsum sheathing connections; tests performed on different typologies of boards in China [41], i.e., wood, gypsum, magnesium, and calcium silicate boards; studies on gypsum-based sheathing connections carried out in Italy [42,43]. The main results of available studies on sheathing panel-to-steel connections demonstrate that the type of sheathing had a significant effect on the shear response of connections: pull-through is dominant for wood-based sheathing connections (Figure 11a), which show a comparatively larger strength and energy dissipation capacity; whereas, bearing is dominant for gypsum-based sheathing connections (Figure 11b), which show a relatively larger stiffness and ductility.

(**a**)



(**b**)

Figure 11. (**a**) Pull through failure of a wood sheathing connection to frame [44]; (**b**) bearing failure of a gypsum sheathing connection to frame.

In addition to the very extensive experimental activity, many studies have been dedicated to the development of numerical models to predict the seismic response of CFS systems. They can be grouped in: (1) equivalent truss finite element models (Figure 12a); equivalent shell finite element models (Figure 12b); and detailed finite element models (Figure 12c). In particular. An equivalent truss model [44–49] uses equivalent nonlinear truss elements or linear truss elements combined with nonlinear springs to predict the behaviour of both strap-braced walls and sheathing-braced walls by allowing relatively simple models that can also be used for whole building structures [50,51]. A shell model [52] utilises shell elements with equivalent mechanical and physical properties that represent the nonlinear behaviour of the entire wall. Detailed models [31,52–56] follow a more realistic approach by predicting the nonlinear behaviour of the whole wall through modelling the main structural elements, including studs, tracks, connections, anchors, and panels (in the case of sheathing-braced walls). Even with available numerical models, it is possible to capture with an acceptable prevision of the real response of a building under seismic actions, especially when the structural response is known at a component level, significant efforts remain to transfer the findings to practice.

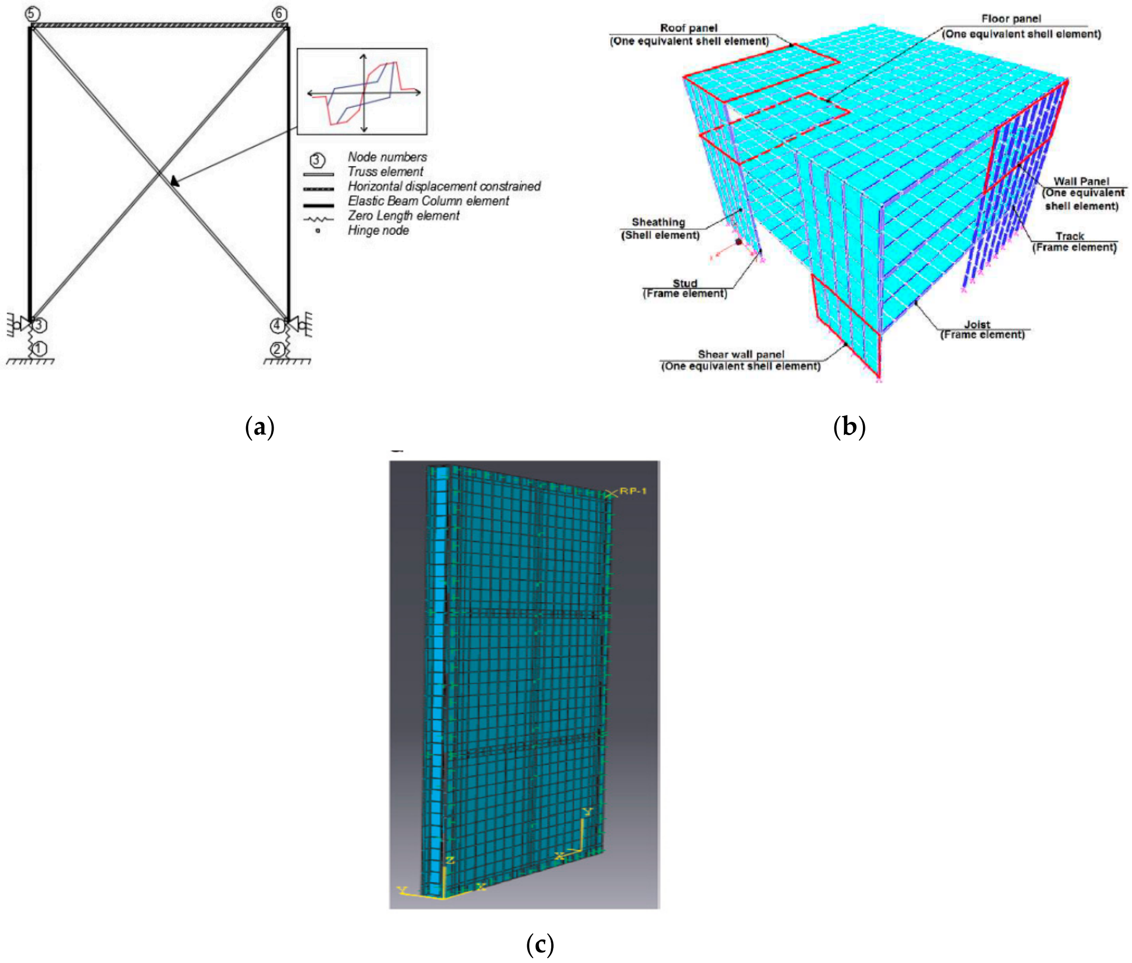


Figure 12. (**a**) Equivalent truss finite element model [49]; (**b**) equivalent shell finite element models [52]; (**c**) detailed finite element model [31].

3. Seismic Response of Non-Structural Architectural Components

3.1. General Issues

Earthquakes often showed significant damage to partitions, facades, and ceilings, with very important impacts in terms of economic costs and, in some cases, human lives safeguard. For this reason, the interest in the seismic response of these non-structural systems has greatly increased over recent years.

Based on the response under an earthquake, non-structural components can be grouped into two main categories: (1) deformation-sensitive components, which take damage mainly due to deformation of the structure; and (2) acceleration-sensitive components, which suffer damage mainly due to inertial seismic forces. Then there is also the case of non-structural elements, which are both deformation and acceleration-sensitive components. Some examples of this classification are listed in Table 2.

The seismic behaviour of non-structural architectural components depends on several factors: characteristics of the earthquake ground motion; dynamic characteristics of a building structure; location of the non-structural elements within the building structure (non-structural components located on upper storeys are subjected to higher accelerations than those at the building base); dynamic characteristics of the non-structural component; weight of the non-structural component; attachment type to the building structure, i.e., anchorage or bracing; interaction with other structural or non-structural components.

Table 2. Examples of classification of non-structural components based on the sensitive to the seismic actions.

Non-Structural Components	Category
Drywall partitions and façades (in-plane response) Suspended discontinuous ceilings	(1) deformation-sensitive
Drywall partitions and façades (out-of-plane response) Suspended continuous drywall ceilings	(2) acceleration-sensitive

3.2. Current Codifications

In current seismic codes, the space devoted to non-structural systems is very limited compared with that dedicated to structural systems. With respect to European and US codes, the design of non-structural components against earthquakes is covered by EN 1998-1 [14] in Europe and ASCE 7 [12] and ASCE 41 [57] in the US for new and existing buildings, respectively.

EN 1998-1 defines the seismic design requirements for non-structural components and systems. EN 1998-1 specifies the procedures for evaluating the seismic hazard demand on acceleration-sensitive components through an equivalent static design force method in its Section 4.3.5. In particular, non-structural components of normal importance that can cause risk to human life or have an effect on the performance of the main structures or services of critical facilities should be verified to resist the horizontal equivalent static design force acting at the component's centroid in the most unfavourable direction. The European seismic code provides the design criteria to define the relative displacement demand for deformation-sensitive components by imposing inter-storey drift limits on the main structural system in its Section 4.4.3. In particular, it requires that an inter-storey drift ratio, defined as the ratio (dr v/h) between the design inter-storey drift (dr) adjusted with a reduction factor (v, that ranges between 0.4 and 0.5 and depends on the importance class of the building) and the storey height (h), should be limited to: 0.5% for buildings that have brittle non-structural components attached to the structure; 0.75% for buildings that have ductile non-structural components; or 1.0% for the buildings that have ductile non-structural components fixed in a way so that they do not interfere with structural deformations.

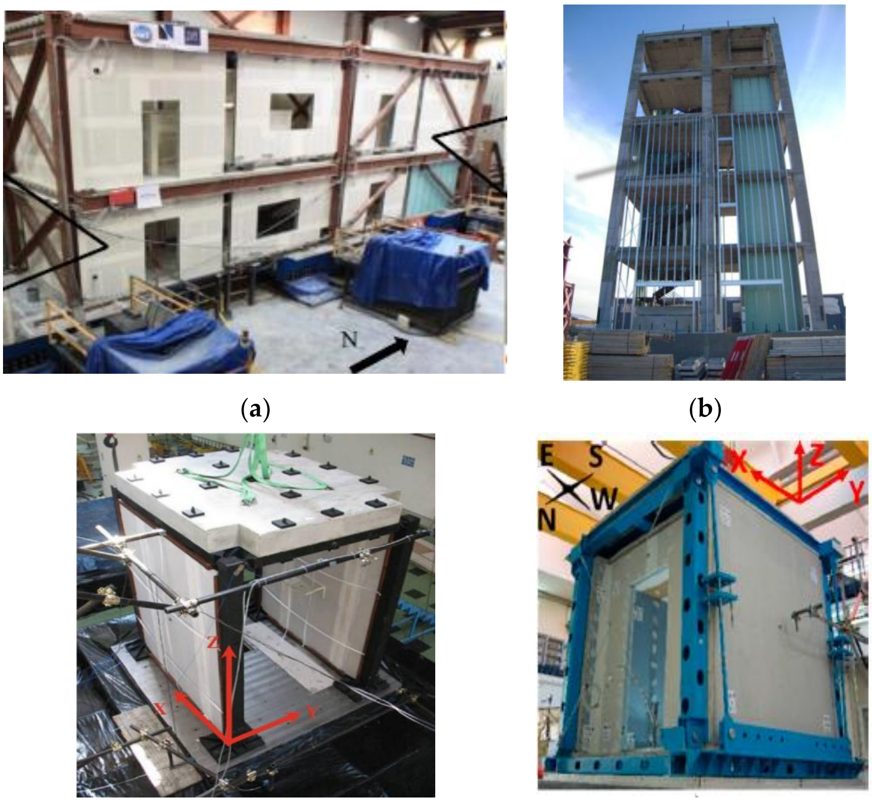
ASCE 7 dedicates its Chapter 13 to the non-structural components, which are permanently attached to structures, their supports, and the attachments. In particular, the code gives the general design requirements in its Section 13.2, the procedure to evaluate the design seismic force demand and the relative seismic displacement demand in its Section 13.3, the requirements for attachments in its Section 13.4, and the requirements for architectural components in its Section 13.5. Non-structural components should be verified with specific designs, which should be submitted for approval to the authority or should be accompanied by seismic qualification certificates produced by the manufacturer. Moreover, ASCE 7 uses the equivalent static design force method for evaluation of the earthquake load demand on the acceleration-sensitive components and a relative displacement demand on the deformation-sensitive components, though the relationships given by the US Code are different from those provided by EN 1998-1.

ASCE 41 provides, in Chapter 13, the seismic requirements for the retrofit of existing non-structural components, whereas for new components installed in existing buildings, the use of both ASCE 41 and ASCE 7 standards is allowed.

3.3. Ongoing Research

As well as for structural systems, for non-structural systems, the studies involving experimental activity is predominant. Shake-table tests, devoted to evaluate the dynamic properties of non-structural components and identify various damages associated to different levels of earthquakes, are carried out on a two-storey steel braced building with partition walls and ceiling systems (Figure 13a) [58] and on a five-story reinforced concrete building with facades and partition walls (Figure 13b) [59].

Shake-table tests are also used to test a single storey single-bay structure equipped with partition walls (Figure 13c) [60,61], facade walls (Figure 13d) [61], suspended ceilings [62], and their combinations [61] subjected to an earthquake.



(**a**) (**b**)

(**c**) (**d**)

Figure 13. Shake-table tests conducted on the non-structural components: (**a**) two-storey steel braced building having partition walls and ceiling systems [63]; (**b**) five-storey reinforced concrete building equipped with partition and façade walls [59]; (**c**) single storey single-bay structure equipped with partition walls [60]; (**d**) single storey single-bay structure equipped with partition walls, facade walls, suspended ceilings, and their combinations [61].

Since shake-table testing could be limited by their cost, the seismic response of non-structural systems can also investigate with relatively less complex experimental activity, carried out on single non-structural component. In this context, the most common approach is to investigate the lateral response of partition walls through in-plane tests [40,64–68], but the out-of-plane response can also be explored [69]. In these studies, different solutions of non-structural components have been tested to evaluate the effect of construction details and boundary conditions.

The main objectives of available studies have been the definition of the damage ability using different thresholds and the development of fragility curves. Also, the estimation of repair costs caught researchers' attention in many studies.

4. Conclusions and Future Developments

Starting from the main results of past studies, the following shared key conclusions can be drawn.

The seismic behaviour of CFS seismic resistant systems (walls) is marked by strength and stiffness degradation and a pronounced pinching and, also, with strong nonlinearity in the case of sheathing-braced walls. The whole building seismic response is significantly affected by gravity structural systems [20], non-structural architectural components, and box-building behaviour [22], which can produce a significant increase of the lateral stiffness and over-strength. As a result, shake table tests showed that buildings could survive earthquakes stronger than that considered in the design and with small damage.

Drywall (CFS/panels-based) non-structural architectural systems represent an alternative to traditional (masonry-based) architectural systems for applications in earthquake prone areas, thanks to their very good seismic behaviour, characterised by a very high damage tolerance. However, if the solution is not designed and built well, drywall non-structural architectural components can also fail ruinously under an earthquake.

Regarding future developments, it will be necessary to bridge the gap between the current North America and European seismic prescriptions on CFS seismic resistant systems. In fact, in EN 1998-1 [14], specific recommendations on this structural typology are missing, whereas AISI S400 [11], together with ASCE 7 [12] and NBCC [13], appear updated with respect to the results of current research. Also, studies and code prescriptions specifically addressed to the seismic response and design of CFS non-structural systems still have a lot of ground to make up. In particular, in this context, both the behaviour of non-structural components and their impact on the seismic response of structural systems play a key role, with the big challenge represented by the very wide variety of available constructional solutions, usually made of materials having an unknown mechanical response.

Author Contributions: G.D.L. was responsible for writing the paper while A.D.M. did review and editing.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Montuori, R.; Gabbianelli, G.; Nastri, E.; Simoncelli, M. Rigid plastic analysis for the seismic performance evaluation of steel storage racks. *Steel Compos. Struct.* **2019**, *32*, 1–19.
2. Piluso, V.; Pisapia, A.; Nastri, E.; Montuori, R. Ultimate resistance and rotation capacity of low yielding high hardening aluminium alloy beams under non-uniform bending. *Thin Walled Struct.* **2019**, *135*, 123–136. [CrossRef]
3. Castaldo, P.; Nastri, E.; Piluso, V. Ultimate behaviour of RHS temper T6 aluminium alloy beams subjected to non-uniform bending: Parametric analysis. *Thin Walled Struct.* **2017**, *115*, 129–141. [CrossRef]
4. Castaldo, P.; Nastri, E.; Piluso, V. FEM simulations and rotation capacity evaluation for RHS temper T4 aluminium alloy beams. *Compos. Part B Eng.* **2017**, *115*, 124–137. [CrossRef]
5. Fiorino, L.; Iuorio, O.; Macillo, V.; Terracciano, M.T.; Pali, T.; Landolfo, R. Seismic design method for CFS diagonal strap-braced stud walls: Experimental validation. *J. Struct. Eng.* **2016**, *142*, 04015154. [CrossRef]
6. Macillo, V.; Fiorino, L.; Landolfo, R. Seismic response of CFS shear walls sheathed with nailed gypsum panels: Experimental tests. *Thin Walled Struct.* **2017**, *120*, 161–171. [CrossRef]
7. Krawinkler, H.; Francisco, P.; Ibarra, L.; Ayoub, A.; Medina, R. *Development of a Testing Protocol for Woodframe Structures*; Publication No. W-02; CUREE: Richmond, CA, USA, 2001.
8. CEN. *EN 1993-1-3 Eurocode 3: Design of Steel Structures—Part 1–3: General Rules—Supplementary Rules for Cold-Formed Members and Sheeting*; European Committee for Standardization: Brussels, Belgium, 2006.
9. AISI. *S100-16 North American Specification for the Design of Cold-Formed Steel Structural Members*; American Iron and Steel Institute (AISI): Washington, DC, USA, 2016; ISBN 9781771391535.
10. Australia/New Zealand Standards. *AUS/NZS 4600. Cold-Formed Steel Structures*; Australia/New Zealand Standards: Sydney, NSW, Australia, 2005.
11. AISI. *S400-15 North American Standard for Seismic Design of Cold Formed Steel Structural Systems*; American Iron and Steel Institute (AISI): Washington, DC, USA, 2015.
12. SEI/ASCE. *ASCE 7-10 Minimim Design Loads for Buildings and other Structures*; American Society of Civil Engineers: Reston, VA, USA, 2010; ISBN 9780784410851.
13. NRCC. *National Building Code of Canada*; National Research Council of Canada (NRCC): Ottawa, ON, Canada, 2005.
14. CEN. *EN 1998-1 Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings*; European Committee for Standardization: Brussels, Belgium, 2004.

15. Liu, P.; Peterman, K.D.; Schafer, B.W. Impact of construction details on OSB-sheathed cold-formed steel framed shear walls. *J. Constr. Steel Res.* **2014**, *101*, 114–123. [CrossRef]
16. Yu, C. Shear resistance of cold-formed steel framed shear walls with 0.686 mm, 0.762 mm, and 0.838 mm steel sheet sheathing. *Eng. Struct.* **2010**, *32*, 1522–1529. [CrossRef]
17. Uang, C.-M.; Sato, A.; Hong, J.-K.; Wood, K. Cyclic testing and modeling of cold-formed steel special bolted moment frame connections. *J. Struct. Eng.* **2010**, *136*, 953–960. [CrossRef]
18. Adham, S.A.; Avanessian, V.; Hart, G.C.; Anderson, R.W.; Elmlinger, J.; Gregory, J. Shear wall resistance of lightgage steel stud wall systems. *Earthq. Spectra* **1990**, *6*, 1–14. [CrossRef]
19. Gad, E.F.; Duffield, C.F.; Hutchinson, G.L.; Mansell, D.S.; Stark, G. Lateral performance of cold-formed steel-framed domestic structures. *Eng. Struct.* **1999**, *21*, 83–95. [CrossRef]
20. Schafer, B.W.; Ayhan, D.; Leng, J.; Liu, P.; Padilla-Llano, D.; Peterman, K.D.; Stehman, M.; Buonopane, S.G.; Eatherton, M.; Madsen, R.; et al. Seismic response and engineering of cold-formed steel framed buildings. *Structures* **2016**, *8*, 197–212. [CrossRef]
21. Hoehler, M.S.; Smith, C.M.; Hutchinson, T.C.; Wang, X.; Meacham, B.J.; Kamath, P. Behavior of steel-sheathed shear walls subjected to seismic and fire loads. *Fire Saf. J.* **2017**, *91*, 524–531. [CrossRef] [PubMed]
22. Fiorino, L.; Macillo, V.; Landolfo, R. Shake table tests of a full-scale two-story sheathing-braced cold-formed steel building. *Eng. Struct.* **2017**, *151*, 633–647. [CrossRef]
23. Fiorino, L.; Bucciero, B.; Landolfo, R. Shake table tests of three storey cold-formed steel structures with strap-braced walls. *Bull. Earthq. Eng.* **2019**, *17*, 4217–4275. [CrossRef]
24. Peck, Q.; Rogers, N.; Serrette, R. Cold-formed steel framed gypsum shear walls: In-plane response. *J. Struct. Eng.* **2012**, *138*, 932–941. [CrossRef]
25. Velchev, K.; Comeau, G.; Balh, N.; Rogers, C.A. Evaluation of the AISI S213 seismic design procedures through testing of strap braced cold-formed steel walls. *Thin Walled Struct.* **2010**, *48*, 846–856. [CrossRef]
26. Mirzaei, A.; Sangree, R.H.; Velchev, K.; Comeau, G.; Balh, N.; Rogers, C.A.; Schafer, B.W. Seismic capacity-based design of narrow strap-braced cold-formed steel walls. *J. Constr. Steel Res.* **2015**, *115*, 81–91. [CrossRef]
27. Mohebbi, S.; Mirghaderi, S.R.; Farahbod, F.; Bagheri Sabbagh, A.; Torabian, S. Experiments on seismic behaviour of steel sheathed cold-formed steel shear walls cladded by gypsum and fiber cement boards. *Thin Walled Struct.* **2016**, *104*, 238–247. [CrossRef]
28. Accorti, M.; Baldassino, N.; Zandonini, R.; Scavazza, F.; Rogers, C.A. Response of CFS Sheathed Shear Walls. *Structures* **2016**, *7*, 100–112. [CrossRef]
29. Fiorino, L.; Terracciano, M.T.; Landolfo, R. Experimental investigation of seismic behaviour of low dissipative CFS strap-braced stud walls. *J. Constr. Steel Res.* **2016**, *127*, 92–107. [CrossRef]
30. Terracciano, M.T.; Vincenzo, M.; Pali, T.; Bucciero, B.; Luigi, F.; Landolfo, R. Seismic design and performance of low energy dissipative CFS strap-braced stud walls. *Bull. Earthq. Eng.* **2018**, *17*, 1075–1098. [CrossRef]
31. Ye, J.; Wang, X.; Jia, H.; Zhao, M. Cyclic performance of cold-formed steel shear walls sheathed with double-layer wallboards on both sides. *Thin Walled Struct.* **2015**, *92*, 146–159. [CrossRef]
32. Wang, X.; Ye, J. Reversed cyclic performance of cold-formed steel shear walls with reinforced end studs. *J. Constr. Steel Res.* **2015**, *113*, 28–42. [CrossRef]
33. Esmaeili Niari, S.; Rafezy, B.; Abedi, K. Seismic behavior of steel sheathed cold-formed steel shear wall: Experimental investigation and numerical modeling. *Thin Walled Struct.* **2015**, *96*, 337–347. [CrossRef]
34. Moghimi, H.; Ronagh, H.R. Performance of light-gauge cold-formed steel strap-braced stud walls subjected to cyclic loading. *Eng. Struct.* **2009**, *31*, 69–83. [CrossRef]
35. Latreille, P.; Nikolaidou, V.; Rogers, C.A.; Lignos, D.G. Characterization of cold-formed steel framed diaphragm response under in-plane loading and influence of non-structural gypsum panels. In Proceedings of the International Specialty Conference on Cold-Formed Steel Structures, St. Louis, MO, USA, 3–4 November 2010; p. 1.
36. Nikolaidou, V.; Latreille, P.; Rogers, C.A.; Lignos, D.G. Characterization of cold-formed steel framed/woodsheathed floor and roof diaphragm structures. In Proceedings of the 16th World Conference on Earthquake Engineering, 16WCEE, Santiago, Chile, 9–13 January 2017; p. 452.
37. Baldassino, N.; Bernardi, M.; Zandonini, R.; Zordan, M. Study of cold-formed steel floor systems under shear loadings. In Proceedings of the Eighth International Conference on Thin-Walled Structures (ICTWS 2018), Lisbon, Portugal, 24–27 July 2018.

38. Vieira, L.C.M.; Schafer, B.W. Lateral stiffness and strength of sheathing braced cold-formed steel stud walls. *Eng. Struct.* **2012**, *37*, 205–213. [CrossRef]
39. Peterman, K.D.; Nakata, N.; Schafer, B.W. Hysteretic characterization of cold-formed steel stud-to-sheathing connections. *J. Constr. Steel Res.* **2014**, *101*, 254–264. [CrossRef]
40. Swensen, S.; Deierlein, G.G.; Miranda, E. Behavior of screw and adhesive connections to gypsum wallboard in wood and cold-formed steel-framed wallettes. *J. Struct. Eng.* **2016**, *142*, E4015002. [CrossRef]
41. Ye, J.; Wang, X.; Zhao, M. Experimental study on shear behavior of screw connections in CFS sheathing. *J. Constr. Steel Res.* **2016**, *121*, 1–12. [CrossRef]
42. Fiorino, L.; Macillo, V.; Landolfo, R. Experimental characterization of quick mechanical connecting systems for cold-formed steel structures. *Adv. Struct. Eng.* **2017**, *20*, 1098–1110. [CrossRef]
43. Fiorino, L.; Pali, T.; Bucciero, B.; Macillo, V.; Teresa Terracciano, M.; Landolfo, R. Experimental study on screwed connections for sheathed CFS structures with gypsum or cement based panels. *Thin Walled Struct.* **2017**, *116*, 234–249. [CrossRef]
44. Serrette, R.; Nolan, D. Wood structural panel to cold-formed steel shear connections with pneumatically driven knurled steel pins. *Pract. Period. Struct. Des. Constr.* **2017**, *22*, 04017002. [CrossRef]
45. Shamim, I.; Rogers, C.A. Steel sheathed/CFS framed shear walls under dynamic loading: Numerical modelling and calibration. *Thin Walled Struct.* **2013**, *71*, 57–71. [CrossRef]
46. Nithyadharan, M.; Kalyanaraman, V. Modelling hysteretic behaviour of cold-formed steel wall panels. *Eng. Struct.* **2013**, *46*, 643–652. [CrossRef]
47. Kechidi, S.; Bourahla, N. Deteriorating hysteresis model for cold-formed steel shear wall panel based on its physical and mechanical characteristics. *Thin Walled Struct.* **2016**, *98*, 421–430. [CrossRef]
48. Fiorino, L.; Shakeel, S.; Macillo, V.; Landolfo, R. Seismic response of CFS shear walls sheathed with nailed gypsum panels: Numerical modelling. *Thin Walled Struct.* **2018**, *122*, 359–370. [CrossRef]
49. Macillo, V.; Shakeel, S.; Fiorino, L.; Landolfo, R. Development and calibration of a hysteretic model for CFS strap braced stud walls. *Adv. Steel Constr.* **2018**, *14*, 336–359.
50. Fiorino, L.; Shakeel, S.; Macillo, V.; Landolfo, R. Behaviour factor (q) evaluation the CFS braced structures according to FEMA P695. *J. Constr. Steel Res.* **2017**, *138*, 324–339. [CrossRef]
51. Shakeel, S.; Landolfo, R.; Fiorino, L. Behaviour factor evaluation of CFS shear walls with gypsum board sheathing according to FEMA P695 for Eurocodes. *Thin Walled Struct.* **2019**, *141*, 194–207. [CrossRef]
52. Martínez-Martínez, J.; Xu, L. Simplified nonlinear finite element analysis of buildings with CFS shear wall panels. *J. Constr. Steel Res.* **2011**, *67*, 565–575. [CrossRef]
53. Zhou, X.; He, Y.; Shi, Y.; Zhou, T.; Liu, Y. Experiment and FE analysis on shear resistance of cold-formed steel stud assembled wall in residential structure. *Adv. Steel Constr.* **2010**, *6*, 914–925.
54. Hatami, S.; Rahmani, A.; Parvaneh, A.; Ronagh, H.R. A parametric study on seismic characteristics of cold-formed steel shear walls by finite element modeling. *Adv. Steel Constr.* **2014**, *10*, 53–71.
55. Buonopane, S.G.; Bian, G.; Tun, T.H.; Schafer, B.W. Computationally efficient fastener-based models of cold-formed steel shear walls with wood sheathing. *J. Constr. Steel Res.* **2015**, *110*, 137–148. [CrossRef]
56. Telue, Y.; Mahendran, M. Behaviour of cold-formed steel wall frames lined with plasterboard. *J. Constr. Steel Res.* **2001**, *57*, 435–452. [CrossRef]
57. ASCE. *41-13 Seismic Evaluation and Upgrade of Existing Buildings*; American Society of Civil Engineers: Reston, VA, USA, 2013.
58. Jenkins, C.; Soroushian, S.; Rahmanishamsi, E.; Maragakis, E. Experimental fragility analysis of cold-formed steel-framed partition wall systems. In Proceedings of the Structures Congress 2015, Portland, OR, USA, 23–25 April 2015; pp. 1760–1773.
59. Wang, X.; Pantoli, E.; Hutchinson, T.C.; Restrepo, J.I.; Wood, R.L.; Hoehler, M.S.; Grzesik, P.; Sesma, F.H. Seismic performance of cold-formed steel wall systems in a full-scale building. *J. Struct. Eng.* **2015**, *141*, 04015014. [CrossRef]
60. Magliulo, G.; Petrone, C.; Capozzi, V.; Maddaloni, G.; Lopez, P.; Manfredi, G. Seismic performance evaluation of plasterboard partitions via shake table tests. *Bull. Earthq. Eng.* **2014**, *12*, 1657–1677. [CrossRef]
61. Fiorino, L.; Bucciero, B.; Landolfo, R. Evaluation of seismic dynamic behaviour of drywall partitions, façades and ceilings through shake table testing. *Eng. Struct.* **2019**, *180*, 103–123. [CrossRef]
62. Badillo-Almaraz, H.; Whittaker, A.S.; Reinhorn, A.M. Seismic fragility of suspended ceiling systems. *Earthq. Spectra* **2007**, *23*, 21–40. [CrossRef]

63. Jenkins, C.; Soroushian, S.; Rahmanishamsi, E.; Maragakis, E.M. Experimental fragility analysis of cold-formed steel-framed partition wall systems. *Thin Walled Struct.* **2016**, *103*, 115–127. [CrossRef]
64. Restrepo, J.I.; Bersofsky, A.M. Performance characteristics of light gage steel stud partition walls. *Thin Walled Struct.* **2011**, *49*, 317–324. [CrossRef]
65. Retamales, R.; Davies, R.; Mosqueda, G.; Filiatrault, A. Experimental seismic fragility of cold-formed steel framed gypsum partition walls. *J. Struct. Eng.* **2013**, *139*, 1285–1293. [CrossRef]
66. Tasligedik, A.S.; Pampanin, S.; Palermo, A. Low damage seismic solutions for non-structural drywall partitions. *Bull. Earthq. Eng.* **2015**, *13*, 1029–1050. [CrossRef]
67. Petrone, C.; Magliulo, G.; Lopez, P.; Manfredi, G. Seismic fragility of plasterboard partitions via in-plane quasi-static tests. *Earthq. Eng. Struct. Dyn.* **2015**, *44*, 2589–2606. [CrossRef]
68. Pali, T.; Macillo, V.; Terracciano, M.T.; Buccieros, B.; Fiorino, L.; Landolfo, R. In-plane quasi-static cyclic tests of nonstructural lightweight steel drywall partitions for seismic performance evaluation. *Earthq. Eng. Struct. Dyn.* **2018**, *47*, 1566–1588. [CrossRef]
69. Fiorino, L.; Pali, T.; Landolfo, R. Out-of-plane seismic design by testing of non-structural lightweight steel drywall partition walls. *Thin Walled Struct.* **2018**, *130*, 213–230. [CrossRef]