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Passive seismic protection systems with mechanical metamaterials: A current review

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Abstract. In this work, a review of mechanical metamaterials and seismic protection systems that use them is carried out, focusing on passive protection systems. During the last years, a wide variety of classical systems of seismic protection have demonstrated to be an effective and practical way of reducing the seismic vulnerability of buildings, maintaining their health and structural integrity. However, with the emergence of metamaterials, which allow obtaining uncommon mechanical properties, new procedures and devices with high performance have been developed, reducing the seismic risk through novel approaches such as: seismic shields and the redirection of seismic waves; the use of stop band gaps and the construction of buried mass resonators; the design of pentamodal base isolators. These ideas are impacting traditional areas of structural engineering such as the design and building of highly efficient base isolation systems. In this work, recent advances in new seismic protection technologies and researches that integrate mechanical metamaterials are presented. A complete bibliometric analysis was carried out to identify and classify relevant authors and works related with passive seismic protection system based on mechanical metamaterial (pSPSmMMs). Finally, possible future scenarios for study and development of seismic isolators based on mechanical metamaterials are shown, identifying the relevant topics that have not yet been explored, as well as those with the greatest potential for future application.

Keywords: mechanical metamaterials; passive systems; seismic isolators; seismic protection

1. Introduction

Seismic protection systems (SPS) are methods used in structural engineering to reduce the seismic risk of buildings (Soong and Spencer 2000, Spencer and Soong 1999). These systems are classified as passive (pS), active (aS), hybrid (hS) and semi-active (saS) (Forrai *et al.* 2001, Braz-César and Carneiro De Barros 2013, Datta 2003, Soong and Spencer 2000). All existing systems are embedded in the structure and aim to reduce its dynamic response using different strategies. pS are relatively simple devices designed without the need of external energy sources (Braz-César and Carneiro De Barros 2013, Spencer and Soong 1999). aS generate control forces to improve the performance of structure (Datta 2003, Soong and Spencer 2000). hS correspond to a combination of the pS and the aS, designed to enhance the structural control. Finally, the saS group includes systems that do not apply control forces, but can vary some of its internal properties (Soong and Spencer 2000, Spencer and Soong 1999).

In recent years, seismic protection devices (SPD), particularly passive ones (e.g., base isolators and damping devices), have become popular elements of SPS for buildings (Kitamura *et al*. 2004), due to their ease of installation in new (or old, usually historic heritage constructions) structures and their low cost. However, these classical passive seismic protection systems (CpSPS) have some shortcomings such as: problems of energy dissipation, and development of torsional modes (Braz-César and Carneiro De Barros 2013); its complex and expensive fabrication methods; the huge weight of the isolators (Calabrese 2019) and its high weakness to extreme temperatures during fire (Mazza 2017).

Mechanical metamaterials (mMMs) are carefully designed structures, based on periodic arrangements consisting of blocks or cells, which have functionalities and mechanical properties that differ from those of their constituent materials (Bertoldi *et al*. 2017, Florijn *et al*. 2014). In the last decade, metamaterials (MMs) have shown themselves as a promising and innovative line of research in material science (Florijn *et al*. 2014, Kadic *et al*. 2019a, Li and Gao 2016), which has allowed obtaining or controlling, in a convenient way, optical (Soukoulis and Wegener 2011), acoustic (Cummer *et al*. 2016), thermal (Schittny *et al*. 2013b), and mechanical (Yu *et al*. 2018) properties. Additionally, it has been possible to develop behaviors considered impossible, counter-intuitive or uncommon in

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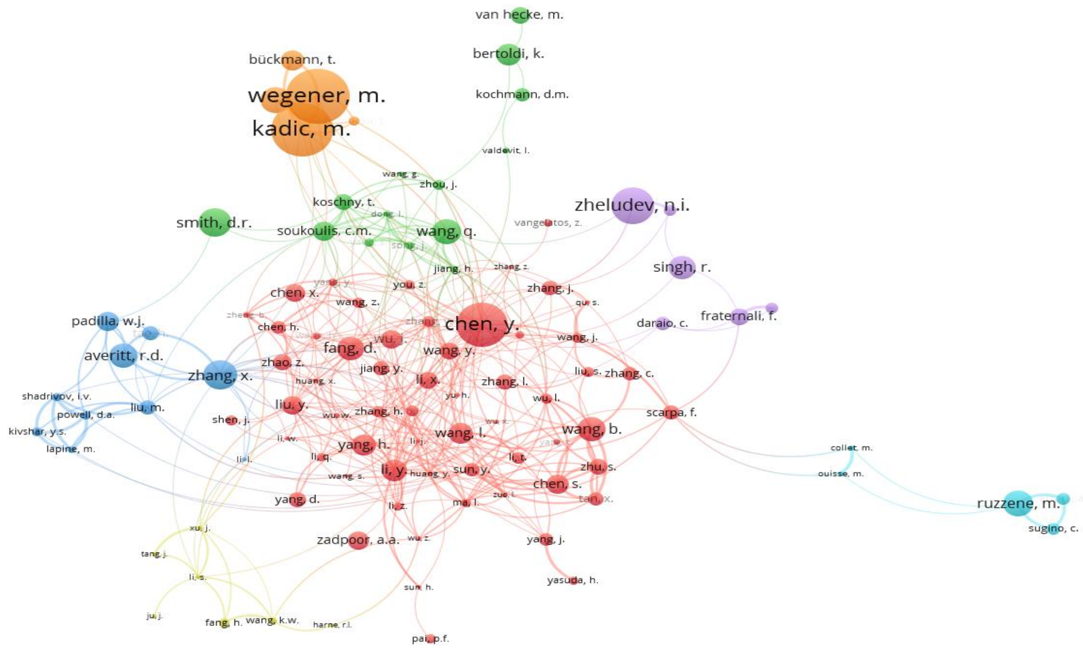

Fig. 1 Network analysis results with citation weight with VOSviewer (van Eck and Waltman 2010) for MMs

nature, such as: negative refractive indices (Smith *et al*. 2004); negative Poisson coefficients (D’Alessandro *et al*. 2018, Vogiatzis *et al*. 2017); and structures with a very low G/K ratio (similar to a fluid) (Kadic *et al*. 2012, Schittny *et al*. 2013a)

In this context, recent researches on passive seismic protection systems (pSPS) (Fabbrocino *et al*. 2015, Fraternali *et al*. 2015, 2018) have introduced a new approach to design and build base isolators using mechanical metamaterials (mMMs) and additive manufacturing techniques, which has shown itself to be a promising alternative for solving various shortcomings of CpSPS.

The recent application of mMMs in SPS for buildings has enabled the generation of new materials/devices and improvements in classical ones. For instance, the advances reported by Fabbrocino and Fraternali (Fabbrocino *et al*. 2015, Fraternali *et al*. 2015), with the development of seismic isolation units using pentamodal mMMs (pmMMS), or the generation of new passive protection devices (pPD) presented by Brûlé and others (Achaoui *et al*. 2016, 2017, Brûlé *et al*. 2013, 2017a, 2020, Ungureanu *et al*. 2015), which have focused on reducing the exposure of the structure to earthquakes, developing new mMMs to conform seismic shields that are not necessary attached to the building.

This work aims to show the current status of this novel and promising area of research, described here as passive seismic protection systems and devices based on mechanical metamaterials (pSPSmMMs) and it is organized as follows. In section 2, a bibliometric analysis carried out to detect the most recognized works and authors working in mMMS and pSPSmMMs are presented. Section 3 deals with mechanical metamaterials (mMMs), deepening in their classification and characteristics. Section 4 presents, in brief, classical passive seismic protection systems. Section 5 introduces the most relevant pSPSmMMs reported in the specialized literature. Section 6 offers future perspectives and finally, in section 7 the conclusions of the revision process are presented.

2. Bibliometric analysis-methodology

In this study, the bibliometric analysis was made using the *Scopus* database (27/07/2020) (Elsevier 2020) and the bibliometric analysis software VOSviewer (van Eck and Waltman 2010). Two explorations were made in the process. The first one focused on establishing the most relevant authors/papers in the topic of mMMs (see section 3) and the second one was oriented to identify highly recognized authors/works in the area of seismic metamaterials (SMMs). These works were the basis to section 5 of this review (pSPSmMMs).

The first search was made in *Scopus* (Elsevier 2020), using the terms "mechanical metamaterial" (mMMs), limiting the search to only journal articles and conferences, from 2000 to 2020. In the search, 1621 documents were obtained (see Fig. 1). From the results obtained, it was possible to find the most relevant authors working in mMMs and the relationships between them. This analysis facilitated the classification of the lines of research in mMMs that they develop. From better positioned authors such as Kadic or Wegener, among others, the compiled literature was filtered and authors of great importance, who were not captured initially but who contributed to the development of mMMs such as Milton (Milton 2016, Milton and Cherkaev 1995), Norris (Norris 2014) or Sigmund (Sigmund 1995) were incorporated.

In the second search, the term “seismic metamaterials” (SMMs) was used under the same conditions, resulting in 145 documents (see Fig. 2). From Fig. 2 it was possible to

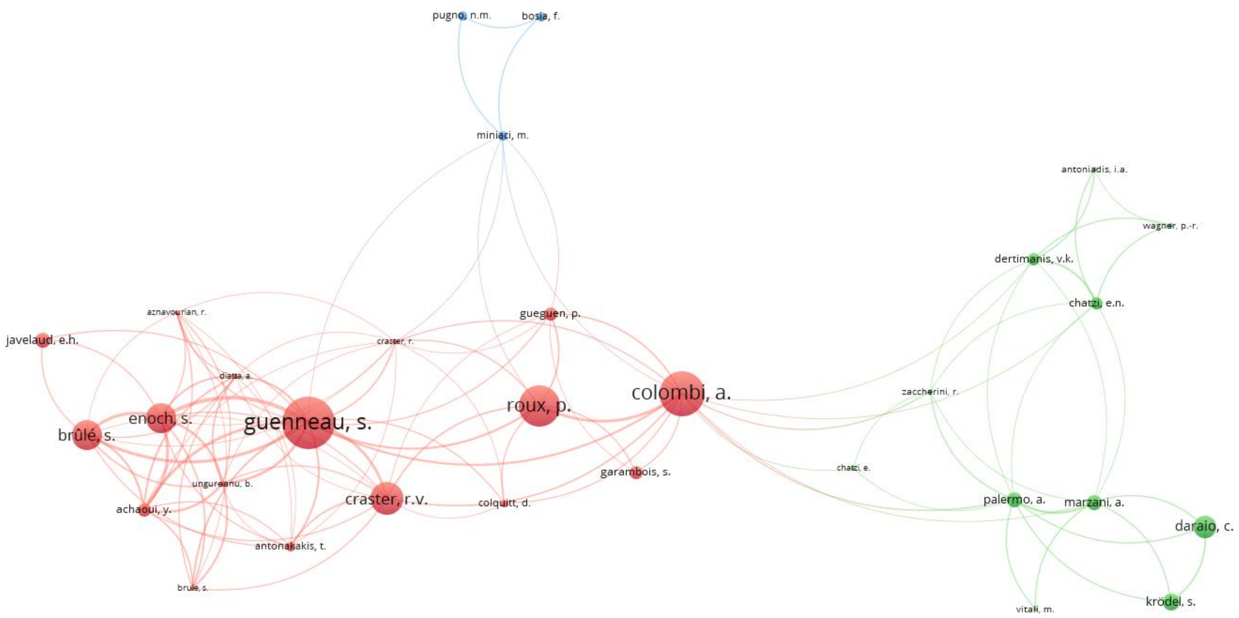

Fig. 2 Citation-weighted network analysis results with VOSviewer (van Eck and Waltman 2010) for SMMs

identify relevant authors like Brûlé and Guenneau and their works (see section 5 and References).

3. MMs and mMMs

As mentioned previously, MMs are artificial cellular structures designed and developed to show counter-intuitive or adaptive properties (i.e., optical, electrical, acoustic) which differ from the properties of the material that constitutes them (Bertoldi *et al*. 2017, Kadic *et al*. 2019b). The very particular behaviors that are developed in MMs are the product of the influence of their topology (or the pattern and shape of the periodically connected cells), where a particular distribution of the matter that forms the MMs or structure is sought in order to obtain the desired property (Bertoldi *et al*. 2017, Yu *et al*. 2018).

The first to venture into MMs was Bose (Bose 1898) in his classical work on refraction and polarization of electromagnetic waves. Later, Veselago (Veselago 1968) in the field of optics proposed a way to generate materials with negative refractive index, a concept that years later was studied in depth and developed by authors such as Smith (Smith *et al*. 2004) and Pendry (Pendry 2000). Subsequent research developed MMs in acoustics (Cummer *et al*. 2016, Dong *et al*. 2019, Maldovan 2013), mechanics (Muhlestein and Haberman 2016, Shim *et al*. 2013), nonlinear dynamic (Fabbrocino and Carpentieri 2017) and seismic (Fabbrocino *et al*. 2015, Fraternali *et al*. 2015, Zeng *et al*. 2020).

Based on the definition of metamaterial, a line of research that focuses solely on the manipulation of mechanical properties called mMMs was created (Bertoldi *et al*. 2017, Kadic *et al*. 2019b). In recent years, this line has been gaining strength, from authors such as Milton and others (Milton 2016, Milton and Cherkaev 1995), who demonstrated the possibility of modifying mechanical properties at will by proposing the following: if there exist only two materials, one sufficiently strong and the other weak, it is possible to generate, from them, a family of microstructures to obtain the desired elastic properties (Milton and Cherkaev 1995).

From publications by Milton and others (Milton 2016, Milton and Cherkaev 1995) new mMMs/structures with unusual mechanical properties were generated, e.g., structures with a null or negative Poisson modulus (Jiang and Li 2018, Milton 1992, Shim *et al*. 2013); structures with a null shear modulus (Bückmann *et al*. 2014b, Kadic *et al*. 2012); null or negative compressibility modulus (Xie *et al*. 2014); structural mMMs with reverse Saint-Venant edge effect (Karpov 2017) and the development of mMMs on a microscopic scale (Fleck *et al*. 2010a) and hyper light mMMs (Zheng *et al*. 2014).

In this context, according to the mMMs cell shape, its mechanical properties and distribution within the volume, Yu *et al*. (2018) and Bertoldi *et al*. (2017) developed a classification of mMMs corresponding to the mechanical properties and the pattern that follows. For the sake of clarity, the classification is shown in Fig. 3 and explained in the subsequent sections.

3.1 mMMs associated to Young's modulus (E)

According to Yu *et al*. (2018) (Fig. 3), the mMMs associated with Young's module, often related to light or ultralight structures, are classified into 5 categories: micro or nano networks; chiral; origami MMs; cellular origami, and finally transformation patterns. In order to complement the above classification, we included the tetrakis-like lattice mMMs (Babilio *et al*. 2017).

3.1.1 Micro/nano lattices

Consists of a cellular structure formed by lattice-type or beams elements, often formed by a considerably high number of elements, as illustrated in Fig. 4 (Fleck *et al*.

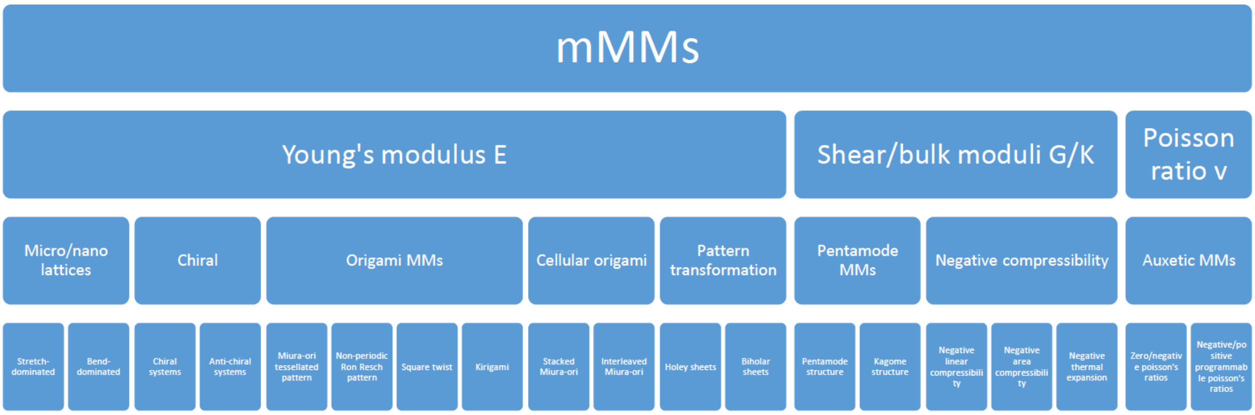

Fig. 3 Classification of mMMs - Source: adapted from Yu *et al*. (2018)

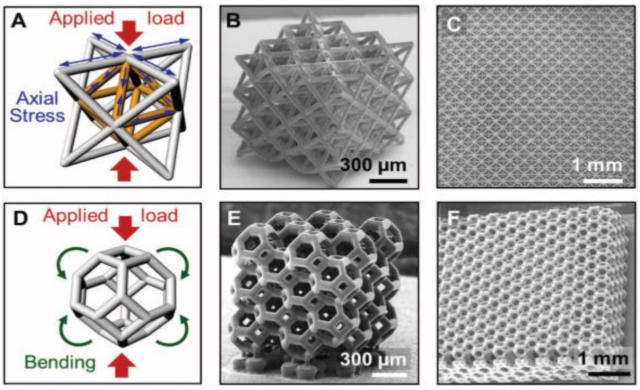

Fig. 4 Cells and Micro/nano lattice MMs - Source: Zheng *et al*. (2014)

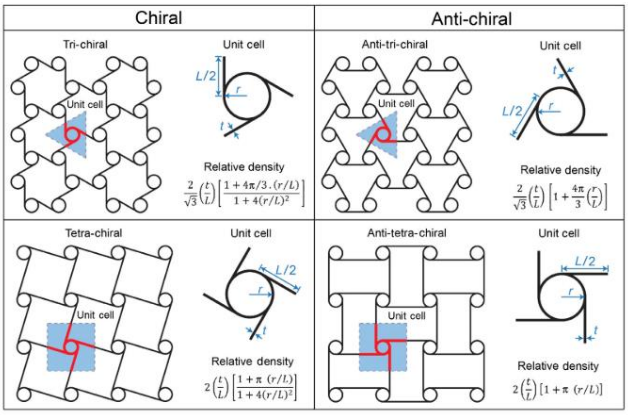

Fig. 5 Example of Chiral and Antichiral metamaterial - Source: Mousanezhad *et al*. (2016)

2010b). Due to the way these structures are arranged, they present formidably low densities in relation to its constituent material, being classified as ultra-light mMMs (Kadic *et al*. 2019b, Zheng *et al*. 2014).

In this kind of mMMs, the objective is to establish and properly distribute the elements of the cell and then distribute them in the volume (Fleck *et al*. 2010b).

Usually, the cells have two design philosophies, one in which the elements are distributed so that a large part of the loads are transmitted and distributed as axial loads along all the elements (lattice) or establish the cell so that the loads are distributed and can be supported as a result of the bending produced in the cell elements (beam) (Yu *et al*. 2018, Zheng *et al*. 2014), as presented in Fig. 4.

Additionally, the stiffens of this ultra-light mMMs depends mostly on the relative density and the cellular architecture, that is, the spatial configuration of the voids in the solid (Gibson and Ashby 1997, Lakes 1993). From a topological point of view, the configuration of the micro/nano lattices can be classified as open or closed cell structures (Gibson and Ashby 1997, Queheillalt and Wadley 2005), with an ordered or stochastic distribution (Torrents *et al*. 2012) that could present heterogeneous or regular microstructures.

3.1.2 Chiral mMMs

This metamaterial has a cellular configuration composed of chiral structures. The chiral cell consists of a central cylinder called node, with tangentially connected ligaments. Depending on their configuration they are classified as right-handed or left-handed (Grima *et al*. 2008, Mousanezhad *et al*. 2016).

Chiral mMMs were proposed by Wojciechowski (1989), later implemented and improved by Prall and Lakes (1997), Pozniak (2014). Chirality, in this context, describes the geometrical property of an object of not being superposable with its mirror image. Therefore, Chiral MMs can be divided into chiral and antichiral systems (Alderson *et al*. 2010, Grima *et al*. 2008, Lorato *et al*. 2010, Spadoni and Ruzzene 2012). Thus, cells connected to each other with nodes on the opposite side to the ligaments side constitute a chiral system and cells connected on the same side of the ligaments constitute an antichiral system (see Fig. 5) (Chen *et al*. 2013, Gatt *et al*. 2013).

Chiral or antichiral mMMs are named according to their nature and to the number of tangential ligaments connected (see Fig. 5). If each cylinder of the cell is connected to 3 or 4 tangential ligaments, it would be a tri-chiral or tetra-chiral metamaterial. Following the same logic, it is possible to obtain antichiral mMMs (or structures) of orders greater than 4.

The research carried out by Mousanezhad *et al*. (2016) have found that chirality (specifically antichiral configuration) is a highly effective way of developing auxetic properties, and it is currently the most commonly

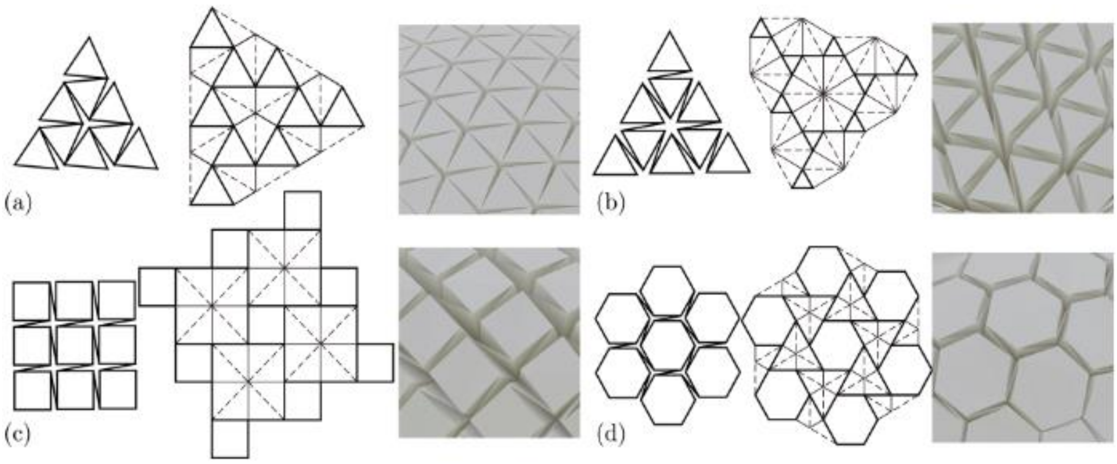

Fig. 6 Resch pattern. (a) Triangular pattern with regular 6-deg vertices. (b)-(d) Triangular, quadrangular, and hexagonal pattern with the insertion of diagons. - Source: Tachi (2013)

used structure for developing this type of mechanical behavior (Bertoldi *et al*. 2017, Grima *et al*. 2008, Mousanezhad *et al*. 2016, Shim *et al*. 2013, Spadoni and Ruzzene 2012).

Chiral mMMs have recently been successfully used in different applications. For instance, to develop a structure with negative thermal expansion behavior some authors used an anti-tetra-chiral cell (Gatt *et al*. 2013, Miller *et al*. 2010, Pozniak and Wojciechowski 2014). Finally, several interesting uses of hexa-chiral or tetra-chiral cells in acoustic applications were reported by Bacigalupo and Gambarotta (2016), Spadoni *et al.* (2009).

3.1.3 Origami mMMs

Origami and Kirigami are an art of Japanese origin consisting in the creation of decorative forms made from the folding (origami) or cutting (kirigami) of paper. This art is being used, beyond artistic purposes, to design ultra-light and customizable mMMs (Hanna *et al*. 2014, Lv *et al*. 2014, Schenk and Guest 2013, Silverberg *et al*. 2014, Song *et al*. 2012, Waitukaitis *et al*. 2015, Wei *et al*. 2013).

Origami mMMs seeks to manipulate and create complex structures from a two-dimensional material (e.g., paper) and is divided into 4 categories: the Miura-ori pattern; the Ron Resch pattern; the square turn pattern and finally, the metamaterial based on kirigami (Yu *et al*. 2018).

The pattern of Miura-ori (see Fig. 6), proposed by Miura (1975), and studied by Wei *et al*. (2013), Schenk and Guest (2013), Lv *et al.* (2014), corresponds to a mMMs based on a periodically folded structure in a herringbone pattern (Lv *et al*. 2014, Waitukaitis *et al*. 2015). The Miura-ori pattern has been used to obtain structures with auxetic behavior (Yasuda and Yang 2015).Multiple studies on mMMs based on Miura-ori revealed that the folded shell structure provides a negative Poisson ratio for deformations within the plane and a positive Poisson ratio for bending outside the plane (Schenk and Guest 2013, Wei *et al*. 2013). In addition, it has been possible to obtain structures based on the Miura-ori pattern with a wide range of thermal expansion coefficients (Boatti *et al*. 2017).

The structure consists of identical cells with convex and

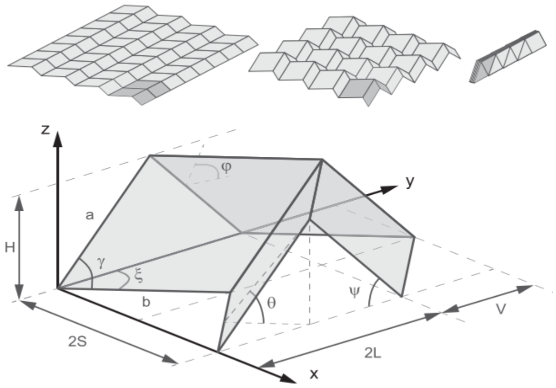

Fig. 7 Origami pattern from Miura-ori - Source: Schenk and Guest (2013)

concave folds with four coordinated ridges. The vertices are formed when four folds intersect, where the four adjacent vertices join to parallelepipeds that are arranged with inversion symmetry (Schenk and Guest 2013) (see Fig. 6).

It is worth to mentioning the Ron Resch's pattern proposed by Resch between the 1960s and 1970s (Resch 1968, 1970, Resch and Christiansen 1970) and studied in depth by Tachi (2013), Lv *et al*. (2014) because this structure was developed based on a series of origami tessellations, by inserting a star-shaped fold (see Fig. 7) presenting a high compression load capacity. Several studies have revealed that higher order symmetries have an even higher load capacity (Lv *et al*. 2014). Additionally, potential applications have been shown in the development of energy absorption structures (Chen *et al*. 2019).

The square twist pattern is the least common of all origami mMMs. To develop the folding of the square twist pattern, it is necessary to consider two different modes of deformation, corresponding to folding and facet bending. In other words, the twist in this pattern cannot be developed with the fold alone, making this arrangement a bit conflicting compared to other Origami mMMs (Silverberg *et al*. 2014, 2015).

Finally, kirigami and origami based mMMs, stands out for its versatility in the generation of cells and complex

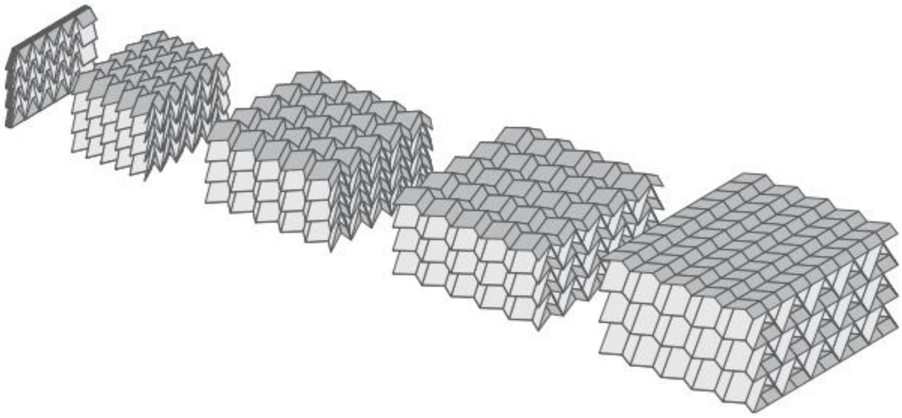

Fig. 8 Stacked Cellular Origami - Source: Schenk and Guest (2013)

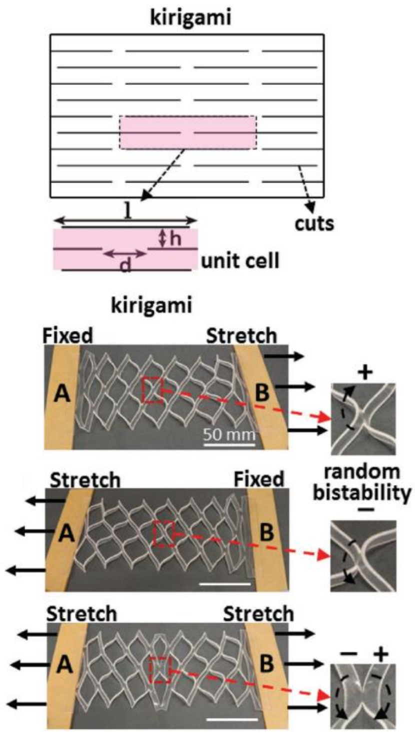

Fig. 9 Kirigami Metamaterial - Source: Tang *et al*. (2017)

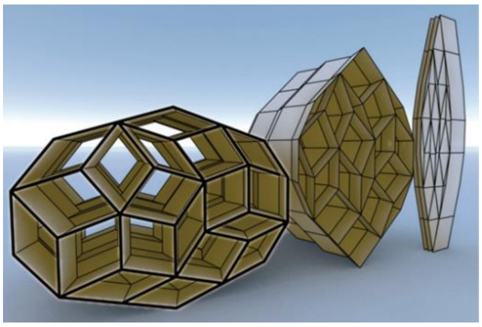

Fig. 10 Interleaved Cellular Origami - Source: Tachi and Miura (2012)

geometries (Neville *et al*. 2016) taking advantage of the effect of the structure´s configuration on its mechanical behavior (see Fig. 8). Possible uses of kirigami and origami mMMs as skin-energy savings in buildings, have been reported by Tang *et al*. (2017). Origami-based metamaterials are currelntly focused on the research of new patterns and the effect they have on the mechanical behavior.

Applications in optoelectronic instruments were proposed by Shyu (Shyu *et al*. 2015) and uses in wave control described in (Le *et al*. 2020, Zhu *et al*. 2018). In addition, authors such as Ishida *et al*. (2017) have extended origami-based metamaterials by developing applications in vibration isolation.

3.1.4 Cellular Origami mMMs

As a mMMs, cellular origami is mainly inspired by snapology, which corresponds to the creation of decorative figures on paper just like origami and kirigami, with the difference that the former is made from simpler figures (modules) that are distributed following a certain pattern (see Fig. 9).

Stacking pattern origami corresponds to a modular structure of layers (modules) assembled consecutively (see Fig. 9), usually made up of Miura-ori patterns (Schenk and Guest 2013). This metamaterial pattern has shown promising experimental results as a potential shock-absorbing device (Yuan *et al.* 2019). Additionally, as a result of its attractive aesthetics and its capability to develop structures with the possibility of folding, it has had a considerable reputation in the generation of domes, folding ceilings and multiple applications in architecture (Yang *et al*. 2019).

A cellular origami structure could be developed following two approaches: cellular origami with a uniform stacking pattern (Li and Wang 2015, Liu *et al*. 2016, Schenk and Guest 2013) or with an interleaved or variable pattern as shown in Fig. 10 (Filipov *et al*. 2015, Tachi and Miura 2012). This type of metamaterial has been used by authors such as Sadeghi and Li (2019) in the isolation of low frequency vibrations, obtaining promising results.

The interleaved, interlocking pattern, and in some texts called the tubular pattern, is a structure that combines the tessellations of origami with a certain pattern (see Fig. 10) (Cheung *et al*. 2014, Filipov *et al*. 2015, Tachi and Miura 2012). Because of its mechanical capabilities, possibility of folding and deformation modes, this pattern, has been of

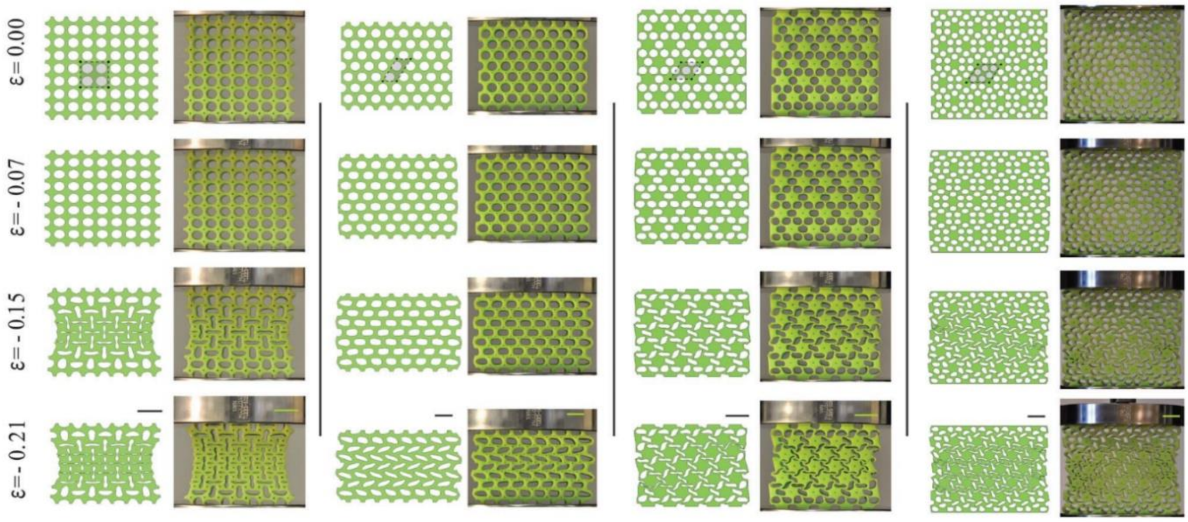

Fig. 11 Metamaterial with square, triangular, trihexagonal and rhomboid pattern – Source: Shim *et al.* (2013)

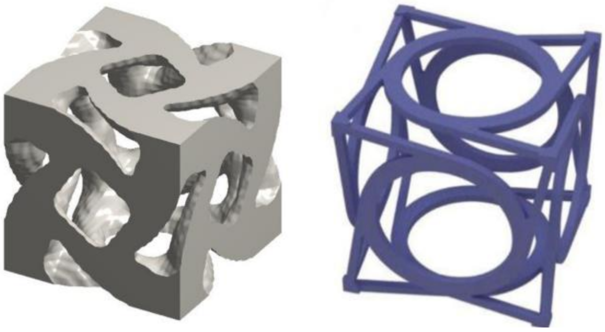

Fig. 12 Twist cell obtained with a topology optimization process - Source: Chen and Huang (2019), Frenzel *et al*. (2017)

great interest in architecture in the development of light structures (Filipov *et al*. 2015, Yang *et al*. 2019).

Origami mMMs has been studied by Ye *et al*. (2019) focusing on their the energy dissipation capabilities, but additional advancements in modelling, to account for its nonlinear dynamic behaviour and energy absotion/dissipation and fatigue properties must be carried out to make available applications in sP (Xiang *et al*. 2020, Yasuda *et al*. 2019). Although several applications of origami mMMs have been reported, the work presented by Zhou *et al*. (2016) demonstrates that origami crash boxes outperform conventional tubes in terms of energy absorption showing that the complete diamond failure mode is extremely efficient in this case. Based on the aforementioned results, the authors anticipate that novel works reporting analysis and uses of origami and kirigami mMMs in pSPSmMMs would appear in the next few years.

3.1.5 Transformation patterns mMMs

This metamaterial has a relatively simple cell, which is replicated spatially in order to fill a determined volume, in a homogeneous or variable way, with the purpose of obtain a solid with customizable mechanical properties that depend on the mechanical forces applied (Yu *et al*. 2018). Structures with auxetic behavior have been reported by Vogiatzis *et al*. (2017), with zero or negative compressibility by Xie *et al*. (2014) and with a tunable strain-stress relationship by (Bertoldi *et al*. 2017, Shim *et al*. 2013).

Transformation patterns mMMS (see Fig. 11) are highly sensitive to the shape and distribution of the cells in the volume. Usually, hollow cells (see Fig. 12) are allocated in a simple pattern to obtain structures with instabilities such as snapping, buckling or to conform linear or non-linear mechanisms with large deformations (Bertoldi *et al*. 2017, Florijn *et al*. 2014, Shan *et al*. 2014, Shim *et al*. 2013, Yu et al. 2018). The above characteristics, could be strategically used in pSPS. However, to develop more complex performances, multiple authors had used topology optimization processes, originally established by Bendsøe and Kikuchi (Bendsøe and Kikuchi 1988), in order to find the most convenient cell shape and its allocation.

In this context, the following results are worth mentioning: the twist cells (Ai and Gao 2019, Chen and Huang 2019); the generation of transformation patterns mMMs with auxetic behaviors (Ai and Gao 2019, Gao *et al*. 2019, Zhang and Khandelwal 2019) and chiral structures of the twist type (Chen and Huang 2019).

3.1.6 Tetrakis-like lattice mMMs

A new type of network based on tetrakis like lattice (isotropic and anisotropic) in 2D was studied theoretical and experimentally by Babilio (Babilio *et al*. 2017). This mMMS present a highly young modulus vs density relation and, according to the authors, these results will permit the future development of optimal anisotropic lattice with pre-defined mechanical properties in selected directions.

3.2 mMMs associated to Shear modulus (G) and bulk modulus (K)

Pentamode and negative compressibility mMMs are presented in this section. The first has the particularity of developing a very low G/K ratio, which some authors call a disappearing shear modulus or *metafluid* metamaterial (Yu

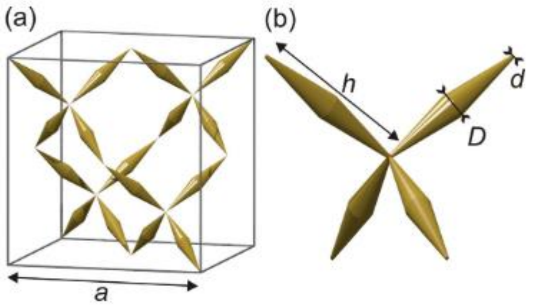

Fig. 13 (a) Milton and Cherkaev pentamodal cell (b) Pentamode cell presented by Wegener - Source: Kadic *et al*. (2012)

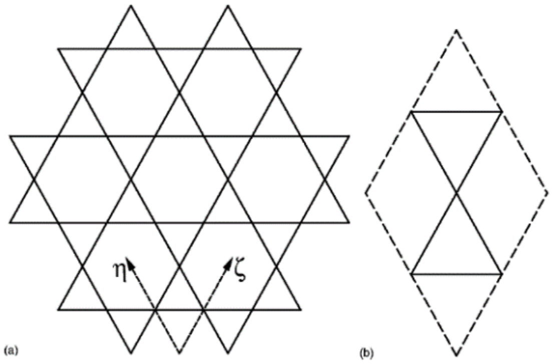

Fig. 14 (a) Kagome-type truss (b) Kagome-type cell - Source: Wicks and Hutchinson (2004)

et al. 2018). This characteristic corresponds to having a very low effective shear modulus, compared to the compressibility modulus. Finally, structures conformed by mMMs with negative compressibility when subjected to hydrostatic pressure, expand in the opposite direction of pressure application.

3.2.1 Pentamodal mMMs - pmMMS

pmMMs were introduced by Milton (Milton *et al*. 2006, Milton and Cherkaev 1995) and Sigmund (Sigmund 1995), and improved by authors such as Gurtner, Wegener and Norris (Gurtner and Durand 2014, Kadic *et al*. 2012, Norris 2014). The pentamodal metamaterial is an extreme material (Yu *et al*. 2018) with a diamond-like structure in which four links meet at one point (Milton and Cherkaev 1995, Norris 2014, Sigmund 1995).

The first experimental studies and manufacture of this metamaterial only took place until early 2012 by authors such as Wegener, Bückmann and coworkers (Bückmann, *et al.* 2015, Bückmann *et al*. 2014, Kadic *et al*. 2013, Martin *et al*. 2012). Those authors proposed a new pentamodal cell model and used additive manufacturing techniques to obtain test specimens. The model presented by Wegener and others differs from the classical model of Milton and Cherkaev (1995) in the geometry of the cone where the new one has a diameter (d) in the connection zone (see Fig. 13).

Successfully application of pmMMs in passive SPS (seismic isolation) has been reported by Fraternalli, Amendola and others (Fabbrocino *et al*. 2015, Fraternali *et al*. 2015), obtaining interesting results when comparing its stress-strain behavior with commercial lead rubber bearing (LRB) seismic isolation devices.

The Kagome metamaterial discovered by the complex material theory group-Princeton (Wicks and Hutchinson 2004) is also classified as pmMMs (see Fig. 14) and corresponds to a lattice-type structure (Hyun and Torquato 2002, Wills *et al*. 2002) associated with the Kagome network (Hyun and Torquato 2002) and other periodic isostatic networks (Chen *et al*. 2014, Mao *et al*. 2015, Mao and Lubensky 2011).

Authors like Vitelli (2012), Paulose *et al.* (2015), Kane and Lubensky (2013), have obtained noteworthy results of mechanical behavior by studying the possibility that two-dimensional geometries could be extrapolated to get mMMs in three dimensions, with characteristics that resemble an ideal fluid.

3.2.2 Negative compressibility mMMs-NCmMMs

Negative compressibility behavior is associated only with the compressibility module. This module corresponds to the quotient of the relative volume change of a solid (or fluid) with respect to a change in pressure (hydrostatic) (Xie *et al*. 2014). *NCmMMs* are subdivided into 3 types: negative linear compressibility; negative area compressibility; and negative thermal expansion (Yu *et al*. 2018).

It its worth mentioning that, *NCmMMs* comprises materials/structures that develop an expansion or compression, in the opposite direction of the pressure (Baughman *et al*. 1998, Nicolaou and Motter 2012), this behavior has only been obtained in structures of the Honeycomb and foam type (Baughman *et al*. 1998). *NCmMMs* with negative area compressibility have a rare property that consist in developing bi-directional contraction when under unidirectional structural stress (Cai *et al*. 2015). Finally, *NCmMMs* with negative thermal expansion, correspond to a structure that, when heated, will contract in one or more directions, instead of expanding, making the structure, in general, present a counter-intuitive performance, but the material that constitutes it does not (Goodwin *et al*. 2008, Lakes 1993, Lakes and Wojciechowski 2008, Munn 1972).

3.3 mMMs associated to Poisson's ratio (v)

This classification contains the auxetic mMMs (AmMMs), which group the structures with a negative or zero Poisson coefficient. AmMMs correspond to materials which, due to their geometric configuration or the topology of their cells, develop a negative Poisson ratio (Kadic *et al*. 2019b, Wojciechowski 1989, Yu *et al*. 2018). Within this category, two classifications could be established. The first one, corresponds to the development of a mMMs with a negative or zero Poisson coefficient, which is homogeneous throughout the solid and does not present variation, and a second class, where the coefficient can be manipulated at convenience in the volume of the solid, typically developing a strategy similar to that of mMMs with transformation patterns (see sec 3.1.5).

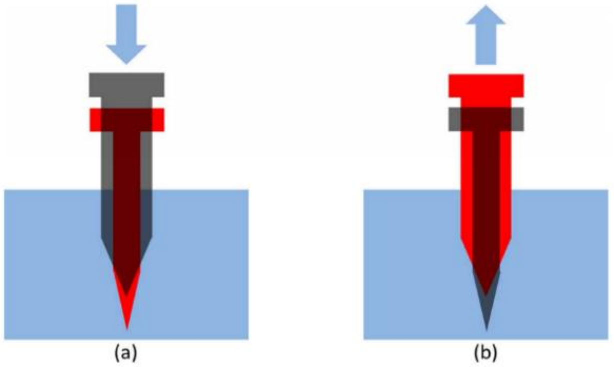

Fig. 15 Application of auxetic MMs in the design of anchors (a) penetrated anchor (b) extracted anchor - Fuente: Ren *et al*. (2018)

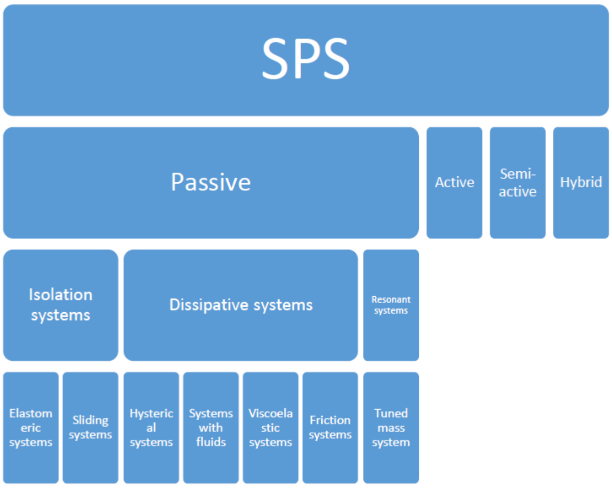

Fig. 16 Breakdown of passive SPS- Source: adapted from Braz-César and Carneiro De Barros (2013)

AmMMs are often related to antichiral mMMs, since it corresponds to the most common structure to obtain a cell with a negative Poisson coefficient (see Fig. 15). However, it has been possible to develop an equivalent cell using origami (Yasuda and Yang 2015), Honeycomb (Zhang and Khandelwal 2019), or in much more complete structures such as those developed by Bückmann and others (Bückmann *et al*. 2014a).

4. Classical Seismic Protection Systems (SPS)

Since their origins, classical SPS (see Fig. 16) have been established as a necessary tool for the control and reduction of the seismic risk of the different civil structures. The following sub-sections contains a brief account of classic SPS.

4.1 Classical passive seismic protection systems-CpSPS

CpSPS are devices that seek to increase the capability of the structure to withstand a seismic event (Braz-César and Carneiro De Barros 2013, Datta 2003, Jung *et al*. 2004,

Fig. 17 (a) elastomeric system (b) friction pendulum - Source: De Luca and Guidi (2019)

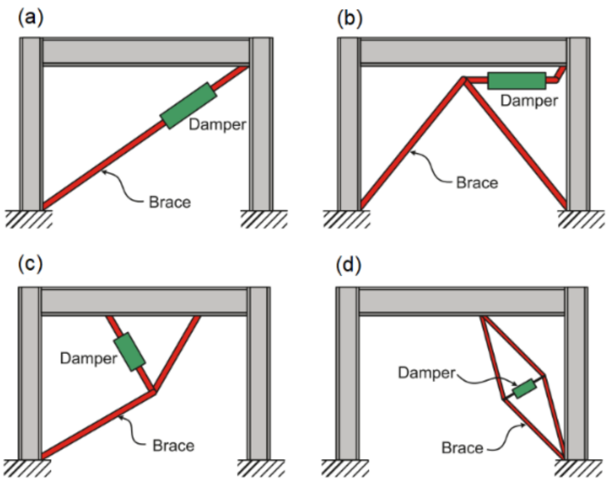

Fig. 18 (a) diagonal; (b) V or Chevron type; (c) Toggle system; (d) scissor-jack - Source: Choi and Kim (2010)

Soong and Spencer 2000). CpSPS correspond to fairly simple devices installed in the structure to reduce its seismic response. Fig. 17 and Fig. 20 presents three classical devices widely used: friction pendulums, elastomeric isolators and tuned mass dampers.

Within SPS (see Fig. 16), CpSPS have enjoyed great popularity and interest (Kitamura *et al*. 2004), being one of the simplest, most practical and economical alternatives. CpSPS could be grouped in 3 types: Seismic isolation systems (SIS); the energy dissipation devices (EDD) and the resonant systems (RS).

SIS are devices that seek to decouple the structure from its foundation, in order to reduce the interaction between the soil and the structure and therefore its response to earthquakes (Calvi and Calvi 2018, Chen *et al*. 2006, De Luca and Guidi 2019, Ng and Xu 2006).

Within the SIS the most popular are: the friction pendulum (FSP) and the elastomeric devices which in turn are subdivided into Laminated Rubber Bearing (LRB) and

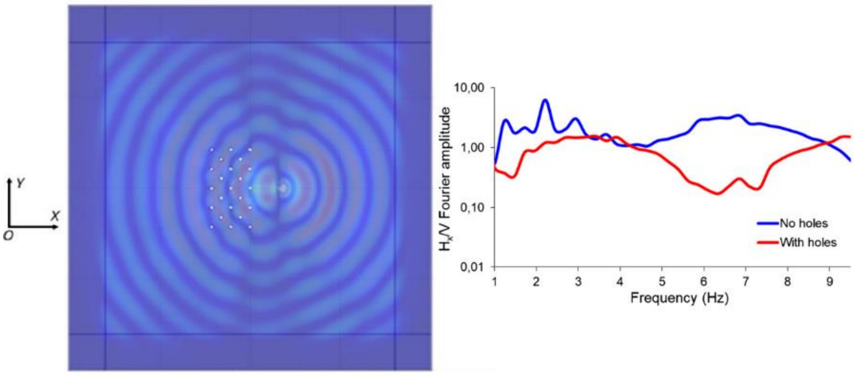

Fig. 19 Effect of seismic soil mMMs - Source: adapted from Brûlé *et al*. (2020)

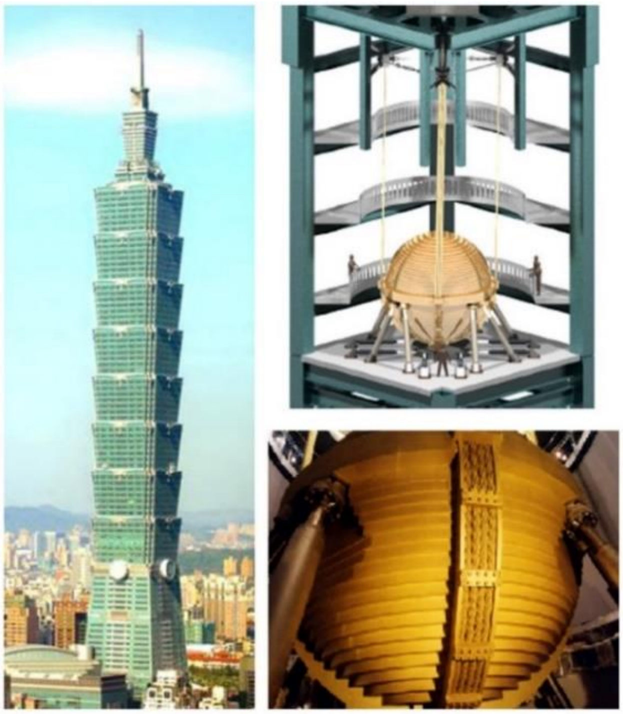

Fig. 20 Taipéi 101 Tuned Mass System – Source: Bekdaş and Nigdeli (2011)

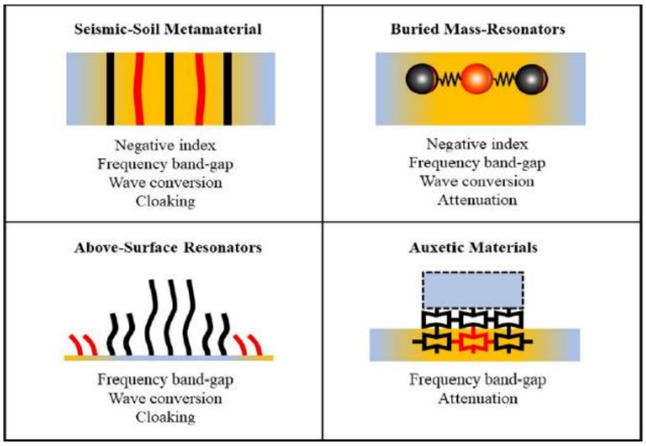

Fig. 21 Current SPS with mMMs - Source: Brûlé *et al*. (2020)

High Damping Rubber Bearing (HDRB) (see Fig. 17).

EDD includes all devices that have the function of increase the structural damping and reducing its response to the earthquake (Oviedo and Duque 2009, Pong and Tsai 1995, Symans *et al*. 2008). In practice, this type of passive system consists of the installation of a system of dampers that are mounted with support elements as shown in Fig. 18. Within this approach, the most commonly used dampers are: viscous fluid dampers, viscoelastic solid dampers, metal dampers and friction dampers.

RS correspond to a set of devices with a considerably high mass, that is tuned in order that it vibrates at the same fundamental natural frequency as the structure, so that, at the moment of the earthquake, it generates a force opposite to the excitation (see. Fig. 20), reducing the response of the structure to the earthquake (Jabary and Madabhushi 2015, Jangid 1995). The RS are subdivided into tuned mass dampers (TMD), tuned liquid dampers (TLD) and tuned liquid column dampers (TLCD) (Braz-César and Carneiro De Barros 2013).

During the las 50 years, TMD, TLD and TLCD have been extensively studied and applied by the scientific and civil engineering communities, resulting in more sub-systems that are intended to improve their overall performance. However, the recently development of seismic protection systems based on mechanical metamaterials (SPSmMMs) has been gaining momentum, because them could solve problems of CpSPS like: energy dissipation; development of torsional modes; complex and expensive fabrication methods; huge weight of the devices and high weakness to extreme temperatures during fire (Braz-César and Carneiro De Barros 2013, Calabrese *et al*. 2019, Mazza 2017). These new approaches are discussed in the following sections.

5. pSPSmMMs

In this section, pSPSmMMs identified by some authors as seismic MMs (SMMs) are examined. pSPSmMMs correspond to the novel application of mMMs in the seismic protection of buildings (Brûlé *et al*. 2020). SPSmMMs are passive devices that seek to manipulate the propagation of the waves and its impact on the structure, directly intervening the soil or the foundation.

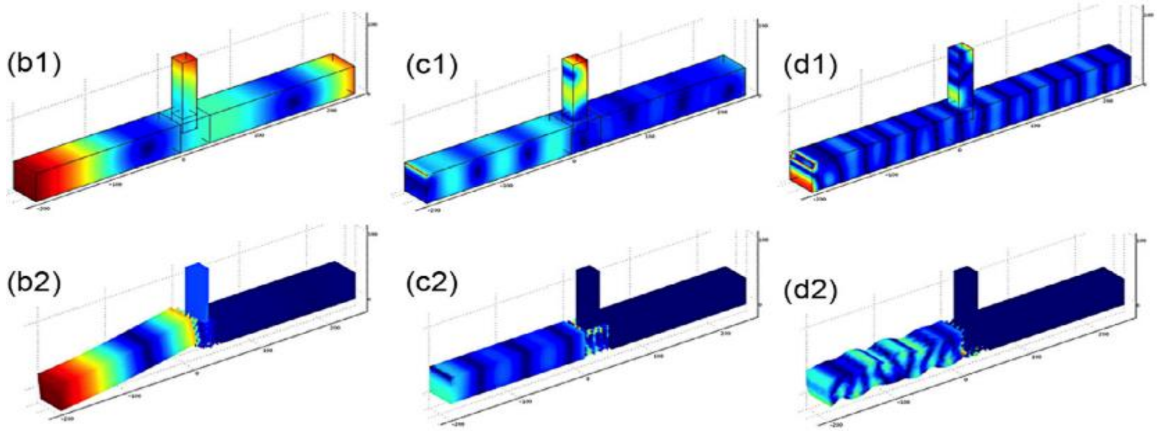

Fig. 22 seismic wave propagation in structural system with and without seismic protection with AmMMs - Source: adapted from Ungureanu *et al*. (2015)

According Brûlé *et al*. (Brûlé *et al*. 2020) SPSmMMs can be classified into 4 types: soil seismic mMMs (SSmMMs); surface resonators (SR); buried mass resonators (BMR) and auxetic seismic mMMs (ASmMMs) as presented in Fig. 21. Taking into account its relevance, the new *pmMMS* base isolator (pmMMsBI), recently introduced by Fabbrocino *et al*. (Fabbrocino *et al*. 2015; Fraternali *et al*. 2015) is also discussed. Finally, novel composed foundations with resonant mMMs are addressed (Brûlé *et al*. 2017b, 2020, Huang *et al*. 2017).

5.1 SSmMMs

SSmMMs consists of a series of cylindrical elements (although they exist with a different cross section than a circular one (Achaoui *et al*. 2017) with a hollow or solid section (Brûlé *et al*. 2013, 2017a) that are introduced into the ground. These devices are intended to alter the propagation of the seismic waves through principles such as Bragg's Law (Achaoui *et al*. 2017, Brûlé *et al*. 2017a). SSmMMs exhibit the behavior proposed and analyzed in the classical studies of Veselago (Veselago 1968) and Pendry (Pendry 2000, Smith *et al*. 2004), where the phase of the output group wave is controlled, as well as the transmitted and reflected waves.

SSmMMs develop amplitude reductions in a high frequency range of the Fourier spectrum (an interesting feature for uses in low height buildings) and amplification reductions in the elastic response spectrum according to a full-scale experiment developed by the Menard company (Brûlé *et al*. 2013, 2017c) (see Fig. 21) in which total reflection (Bragg effect) was developed, allowing wave path control by the specially designed anisotropy and attenuation via energy dissipation.

5.2 SR

Like the previous one, SR corresponds to a series of (frequently) cylindrical elements, which are arranged on the surface in a similar way to a forest as illustrated in Fig. 23, and act as a seismic barrier (Brûlé *et al*. 2020, Colombi *et al*. 2016b).

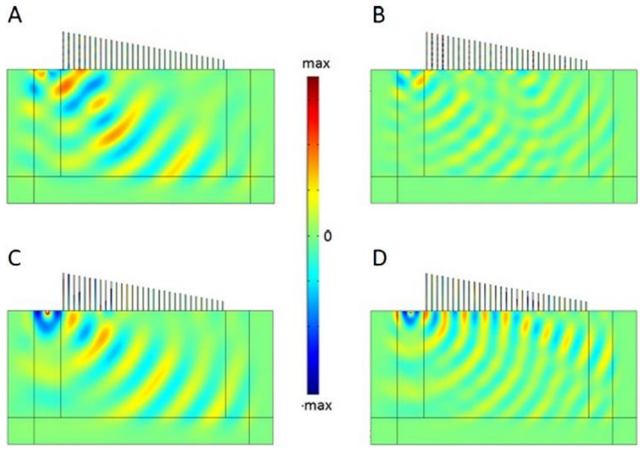

Fig. 23 Two-dimensional simulation for surface metamaterial resonators with decreasing height (from 14 m to 4 m) and diameter of 0.3 m, for a Rayleigh wave of frequency 70 Hz (figures A and C) and 120 Hz (figures B and D) - Source: Brûlé *et al*. (2020)

The distribution of these elements, results in a conversion of surface Rayleigh waves, to massive shear waves or to surface wave filters with band gaps, but with a higher frequency (Brûlé *et al*. 2020, Colombi *et al*. 2016a). SR has obtained promising results (Zeng *et al*. 2020), but caution is needed with its implementation since, depending on the incidence of the incoming wave, it could be harmful to neighborhood buildings of the array (Colombi *et al*. 2016a, 2016b, Palermo and Marzani 2018).

5.3 BMR

Unlike passive TMD, BMR are buried mass resonators that do not form part of the structure, as shown in Fig. 24. In general terms, both mechanisms work under the same physical concept.

BMR are distributed as an array (see Fig. 24) that is tuned for a particular frequency. When this system is stimulated, the masses will resonate in the opposite direction to the seismic excitation and counteract the excitation by inertial forces. Although BMR are appealing,

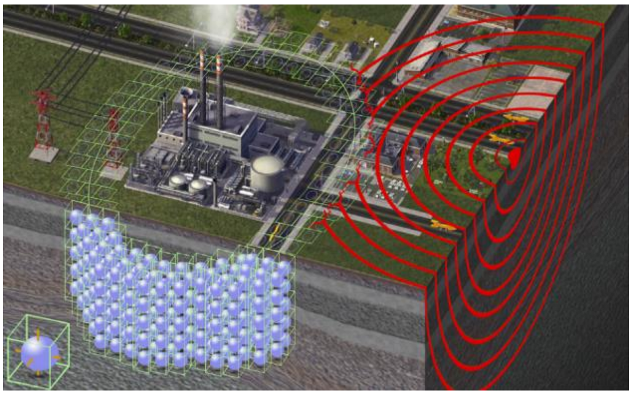

Fig. 24 Buried Mass Resonators - Source: Achaoui *et al*. (2016)

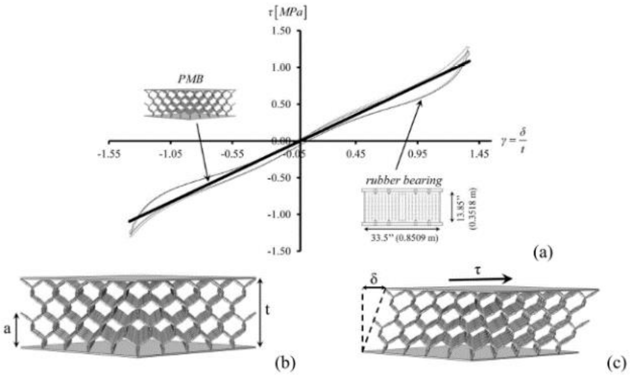

Fig. 25 Comparison between the shear stress vs. shear strain responses of the pentamode bearings and a low-damping rubber bearing - Source: Fabbrocino *et al*. (2015)

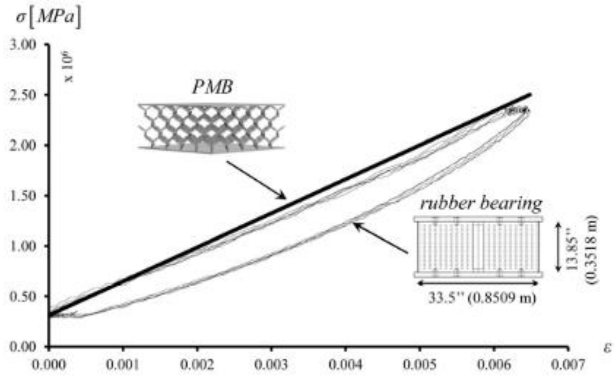

Fig. 26 Comparison between the axial stress vs. axial strain responses of the pentamode bearings and a low-damping rubber bearing - Source: Fabbrocino *et al*. (2015)

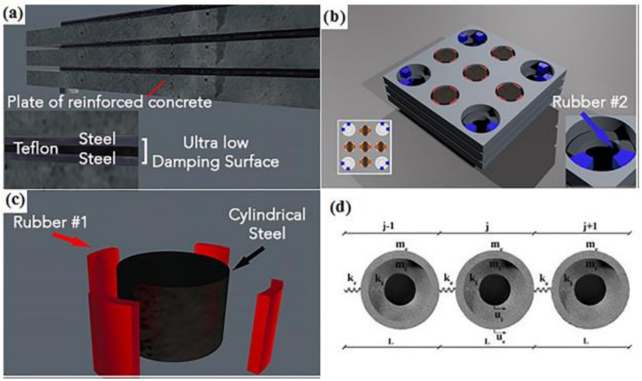

Fig. 27 Schematics of composite foundation - Source: Casablanca *et al*. (2018)

its uses are limited by its high costs, the scales in which it is handled (for manufacturing) and finally, it is still challenging to obtain efficient stop bands (Achaoui *et al*. 2016, Brûlé *et al*. 2020).

5.4 ASmMMs

Structures that due to their topology develop a negative Poisson module are called auxetic. With the use of ASmMMs it is possible to develop stop band gaps that are compatible with seismic waves. In this regard, Ungureanu *et al.* (2015) have discovered, that a ASmMMs foundation of a building allows suppression of wave transmission (in elastic conditions) in the interval from 1 to 100 Hz (see Fig. 22).

5.5 pmMMsBI

In addition to the systems classified by Brûlé *et al*. (Brûlé *et al*. 2020), in recent years, the application of mMMs in SPS and the development of different construction techniques such as additive manufacturing has made it possible to build structures with complex geometries and to develop new pSPS based on the classic systems. In this case, authors such as Fabroccino *et al*. (Fabbrocino *et al*. 2015, Fraternali *et al*. 2015), began by perfecting the classic systems, with the application of mMMs (pentamodal) for the development of a pmMMsBI (see Figs. 25 and 26).

Although it is necessary to submit pmMMsBI devices to further testing before making an actual use, the results obtained so far have been encouraging, where systems with pmMMs could be an alternative with outstanding performance compared to a traditional elastomeric seismic isolation system (Fabbrocino *et al*. 2015). One of the main advantages of this approach is the fact that the mechanical properties of pmMMsBI are controlled in high degree by its geometry (configuration of the internal network) and not by its chemical composition (Fabbrocino and Amendola 2017).

5.6 Composite foundations with resonant mMMs-CFRmMMs

An alternative way of applying mMMs in seismic isolation is by creating composite structures based on multiple layers of soil (Brûlé *et al*. 2017b, 2020, Huang *et al*. 2017). This idea was later formulated as composite foundations (Mu *et al*. 2020, Witarto *et al*. 2018) as presented in Fig. 27.

CFrmMMs developed by Witardo *et al*. (2018) have shown the effective development of stop bands in a one-dimensional (1D) periodic foundation and isolation system. In this context, Casablanca *et al*. (2018), have improved *CFrmMMs* adding resonant mMMs (Casablanca *et al*. 2018, Finocchio *et al*. 2014) (see Fig. 27) by developing effective P and S wave filters.

6. Future perspectives

Multiple studies of the use of mMMs are focused on architecture and urban planning of cities, and the idea of seismically efficient cities has even been put forward (Brûlé *et al*. 2017d, 2020). In addition, Mitchell *et al*. (2014) have centered their works on building materials, seeking to improve the dynamic performance of structures with a meta-concrete and Wang *et al*. (2020) have implemented the use of mMMs in the development of a aSPS.

Specifically, new kinds of mMMs would be incorporated into SPS. This could improve the control of the dynamic response of isolators and therefore of buildings. Among mMMs that show promising applications are mMMs with snapping (Yang 2020), which allow high energy dissipation in an elastic way. Another possible evolution of isolators could be found combining them with variable Poisson coefficient mMMs, so that undesirable deformations in them could be avoided.

A high potential is also observed in alternating stiffness or mass mMMs, which allow control of transmitted and reflected seismic waves. mMMs with controlled deformation paths, that redirect the internal forces in the structure and permit control of the transmissivity functions, making possible to reduce the reaction forces in desired directions. Finally, mMMs with imperfections or irregularities in its periodic pattern let a redirection of the wave propagation path, that eventually could have real life applications in pSPSmMMs. In this context, potential uses of mMMs to improve other classical SPS e.g., active, semi-active and hybrid, are expected in the next few years.

7. Conclusions

In this work, 1621 papers and conference papers relevant to mMMS and pSPSmMMs were filtered and analyzed. From these, it was possible to carried out a complete classification of pSPSmMMs.

To the author’s best knowledge, applications of origami in pPSmMMs have not been reported yet.

Research into mMMs and its applications is a crucial scientific subject, in which, up to the date, noteworthy developments of new pSPSMMs based on topological optimization and additive manufacturing have been reported.

pSPSMMs have shown encouraging outcomes, which allowed the development of new alternative approaches and solutions, like CFrmMMs and ASmMMs, to pursue effective reduction of the structure exposure to earthquakes.

The application of mMMs has allowed the development of alternative SPS, such as the seismic mMMs (mentioned in previous sections) widely studied by Colombi, Guenneau and Brûlé. In addition, with the introduction and blend of mMMs with CpSPS, alternative systems (pmMMsBI) using pentamodal cells have been obtained by Fabbrocino *et al*. (2015), Fraternali *et al*. (Fraternali 2016, Fraternali *et al*. 2015, 2018).

Although Harmonic response and stop band gaps are a promising approach to seismic protection, they are no consolidated as a tool for pSPSmMMs design.

In summary, pSPSmMMs is a line of research that apply different approaches to the classical ones like SsmMMs, BMR and SR, could impact structural engineering, allowing the development of alternative pS inspired by classical devices or the evolution of new highly efficient devices.

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CC

Abbreviations

Seismic protection systems (**SPS**)

- passive (**pS**),
- active (**aS**),
- hybrid (**hS**)
- semi-active (**saS**)

classical passive seismic protection systems (**CpSPS**)
seismic protection devices (**SPD**)
mechanical metamaterials (**mMMs**)
metamaterials (**MMs**)
seismic metamaterial (**SmMMs**)
pentamodal mechanical metamaterial mMMs (**pmMMS**)
passive protection devices (**pPD**)
passive seismic protection systems and devices based on mechanical metamaterials (**pSPSmMMs**)
Negative compressibility mechanical metamaterials (**NCmMMs**)
Auxetic mechanical metamaterials (**AmMMs**)
Seismic isolation systems (**SIS**)
Energy dissipation devices (**EDD**)
Resonant systems (**RS**)
seismic protection systems based on mechanical metamaterials (**SPSmMMs**)
soil seismic mMMs (**SSmMMs**)
surface resonators (**SR**)
buried mass resonators (**BMR**)
auxetic seismic mMMs (**ASmMMs**)
pentamodal mechanical metamaterial base isolator (**pmMMsBI**)
composed foundations with resonant mMMs (**CFRmMMs**)