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Vibration control systems: A review of their application to historical unreinforced masonry buildings

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ABSTRACT

Unreinforced masonry buildings generally present poor seismic performance given the low shear and tensile strength of the material. In the last decades, researchers have been exploring alternatives to overcome the limitations of traditional strengthening techniques, obtaining promising results in the application of vibration control systems, i.e., energy dissipation devices and base isolation that can add damping capacity to the structure or decouple it from the ground. This review focuses on the implementation of passive vibration control systems in historical buildings, namely in unreinforced masonry structures. The application of vibration control systems to masonry structures and the design of energy dissipation systems that satisfy the conservation criteria remain open issues.

1. Introduction

Disasters caused by natural hazards lead to important economic impacts [1], deaths and irrecoverable losses. In this matter, earthquakes have a significant contribution, for example, from 2000 to 2019, the total fatalities worldwide caused by earthquakes is nearly 810 000 [2]. The recent seismic events caused severe damage and the collapse of a considerable number of masonry buildings, such as the earthquakes in Haiti (2010, 220 000 estimated death toll and US$ 7.804 billion of damage) [3], Nepal (2015, 8896 death toll and US$ 7 billion of damage), Italy (2009, 308 death toll and about €10 billion of damage) [4], and Mexico (2017, 369 causalities and losses amounted to US$ 6 billion) [5]. Thus, it is fundamental to mitigate the seismic risk, increasing the resilience of the urban areas, mainly by reducing the seismic vulnerability of the most vulnerable building typologies.

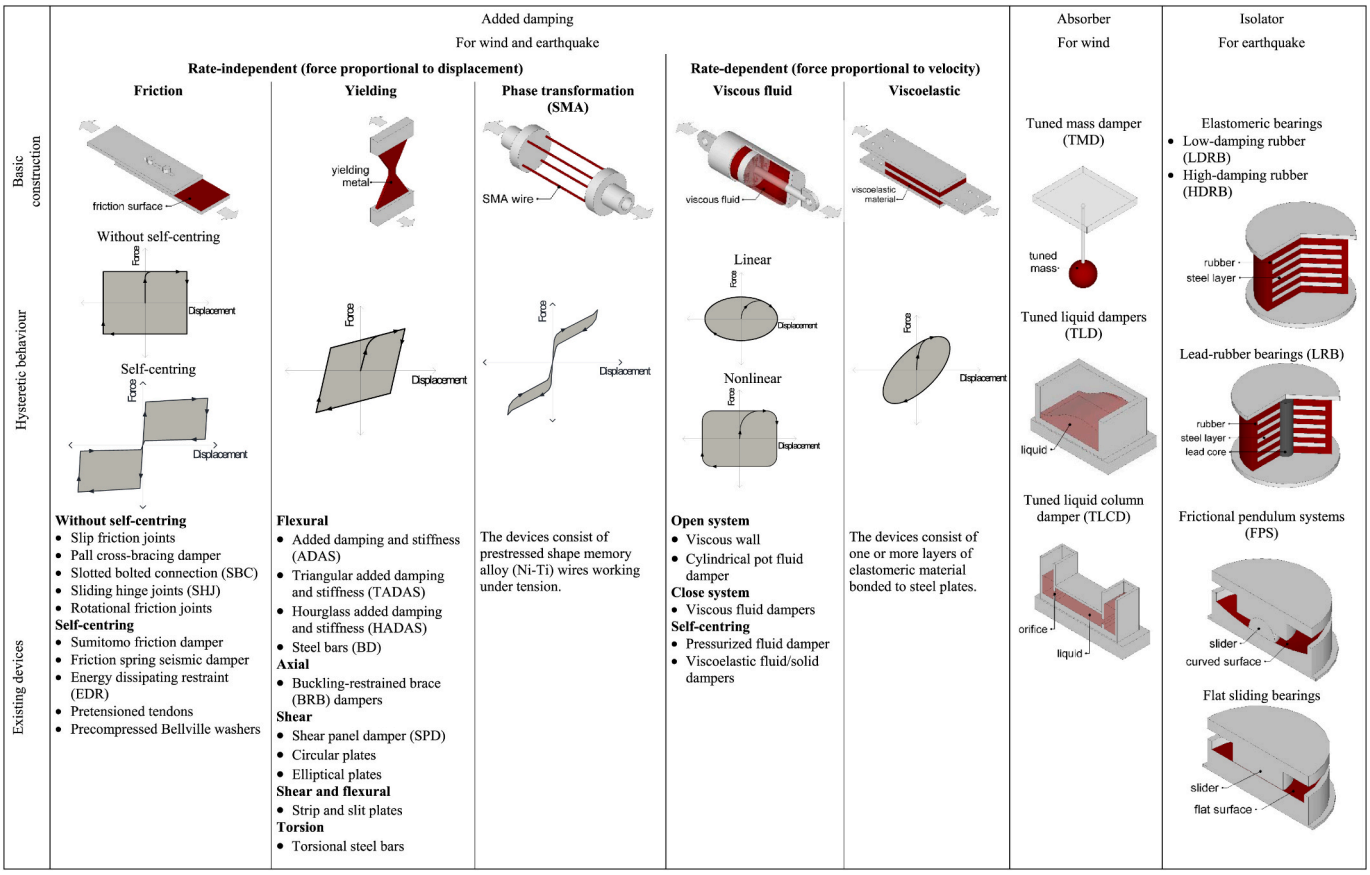
Conventional approaches for the seismic design of buildings rely on the combination of strength and ductility in such a way that the structure behaves within the elastic range for small and moderate earthquakes, whereas for stronger seismic events, the structure is ductile enough to yield and experience damage, developing plastic hinges without collapsing [6,7]. New structures depend on their stiffness and strength to resist seismic actions, and on their small damping capacity to dissipate dynamic energy. Nonetheless, the damage caused by a major earthquake may be so extensive and severe that the structure must be demolished. Increasing the strength and ductility capacity of a building to resist strong seismic excitations demands either the use of high-strength materials, which are expensive, or the dimensional enlargement of structural members, which increases the mass and inertial forces [8]. On the other hand, ancient masonry buildings generally present poor seismic performance because they lack ductility and have limited lateral resistance. Throughout history, a wide range of strategies has been developed by trial and error to strengthen them, including the use of metallic or timber tie rods, timber collar beams, buttresses, and in the last century, grout injections, use of steel bars, anchors, and the introduction of reinforced concrete members [9–12]. These traditional strengthening techniques aim at enhancing the mechanical properties of the construction materials, of certain units of the structural system (local strengthening), or the entire building (global strengthening). In general, global strengthening pursues the well-known box-behaviour, i.e., allowing the structural members to work together. However, the traditional techniques do not significantly improve the ductility since they are usually focused on enhancing the stiffness and strength. In addition, given the particular features of historical buildings, in many cases the seismic performance required by the codes (for example Part 3 of the Eurocode 8 [13]) cannot be attained, since the interventions can involve high costs and strong modifications to the original structural system [14].

The drawbacks of conventional strengthening approaches prompted

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Table 1
Passive vibration control systems (adapted from Ref. [17], with illustrations adapted from Ref. [16]).



the development of energy-based methods and techniques. These assume that the satisfactory performance of a structure is achieved when the energy demand during an earthquake is smaller than the energy stored and dissipated by the building [7]. An increment in the damping capacity can significantly reduce the dynamic response given its high ability to dissipate energy. The target can be accomplished by installing in the structure mechanical devices, known as vibration control systems, to supplement it with additional damping or decouple it from the ground, and thus, to increase its seismic- and wind-resistant capacity [6,8,15].

In terms of energy balance, the response of a structure (output energy) under seismic action (input energy) is given by:

$$E_{input} = E_k + E_p + E_{da} + E_{du} \quad [1]$$

where E_k is the kinetic energy of the building stored as motion, $E_p$is the potential energy stored as elastic deformation of the structure, $E_{da}$is the energy dissipated by the intrinsic damping through friction, heat and/or other similar losses, and E_{du} is the energy dissipated by damage of the structural and non-structural elements, i.e. the hysteretic behaviour (ductility). The kinetic and potential energies fluctuate during the excitation, storing and releasing part of the input energy. However, the input energy and the energy dissipated by damping and damage are cumulative. During the transformation of the potential energy into kinetic energy and vice versa, part of such energy is dissipated by damping effects. Since the potential energy is given by the elastic capacity, there is a limit upon which the energy is dissipated as damage at connections and structural elements [16,17].

Conventional strengthening techniques focus on increasing both the kinetic and potential energies to attain the required seismic safety level. However, there are other solutions to satisfy the energy balance. For example, the incoming energy E_{input} transferred from the ground into the structure can be minimized by isolating the base. An increment of dissipated energy can be accomplished by increasing the ductility E_{du} and/or the damping E_{da} of the structure itself, or with additional energy dissipation devices [18]. The technical solutions focused on dissipating energy can reduce displacements, inter-storey drifts, accelerations, shear base and, in some cases, concentrate damage in replaceable non-structural elements.

Vibration control systems can be sorted in four main groups: passive systems, semi-active systems, active systems, and hybrid systems. Passive systems are inert elements that do not require any source of power to control the dynamic response. The remaining systems require sensors, a control centre (computer), and an external power supply to operate. Semi-active systems can be considered as controllable passive devices, since the data provided by the sensors are only used to readjust their mechanical properties. Active systems generate a real-time force applied to the structure by means of electromechanical or electrohydraulic actuators, to cancel the external excitation. Hybrid systems combine passive systems with a semi-active or an active system. Although these techniques were initially intended for new constructions (mainly steel and reinforced concrete framed buildings and bridges), their implementation into historical masonry buildings and other similar structures with low ductility is being currently assessed. The present review addresses exclusively passive vibration control systems and their implementation in existing masonry structures, including monuments. For detailed information on semi-active, active and hybrid systems, the reader is referred to Refs. [8,19–22].

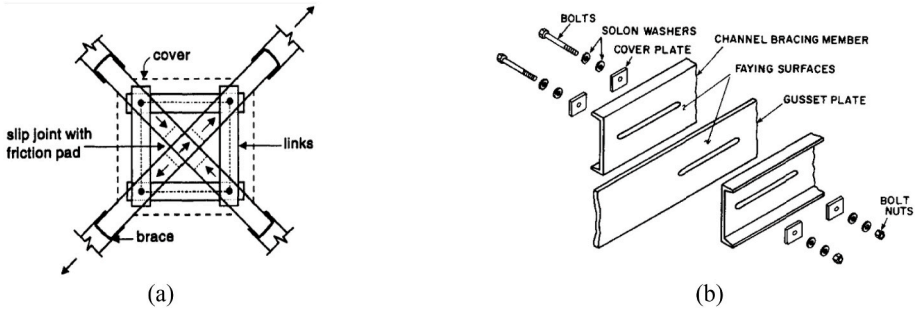


Fig. 1. Friction dampers: (a) Pall cross-bracing damper [27], (b) Slotted bolted connection [7].

2. Passive vibration control systems

Passive vibration control systems comprise a wide range of materials and configurations. When their main objective is to suppress vibrations by adding damping capacity (and sometimes stiffness), they are denominated as passive energy dissipation (PED) devices [8,14,15]. PEDs are inert components installed in buildings, that operate without an external power source. They use the forces and deformations produced by the kinetic energy of the own building, i.e., they react to the imposed load/displacement, generating a large damping force [8,12]. However, PEDs have limited control capacity, since their calibration is set to perform against specific dynamic actions. Therefore, they may exhibit an inefficient response when undergoing other types of vibration. Moreover, PEDs rely on relative structural displacements to trigger the dissipation mechanism, meaning that the dissipated energy is only related to the local response where the device is installed. On the other hand, PEDs are inherently stable and relatively easy to design and build [6,8]. Passive vibration control systems reduce displacements and/or accelerations by:

(1) Adding damping. PEDs can be rate-independent (the damping force is proportional to the relative displacement) or rate-dependent (the damping force is proportional to the relative velocity). Devices that use friction, yielding of metals, or phase transformation of metals to dissipate energy are rate-independent. Viscous fluids and viscoelastic devices are rate-dependent [17].
(2) Absorbing (redirecting) vibrations. The vibrations are reduced by transferring some of the dynamic energy to another mass [23]. They are often used to reduce vibration due to wind in medium- and high-rise structures.
(3) Reducing the seismic energy input. The base isolation systems introduce a layer that is often placed between the foundation and the structure, which is flexible in the horizontal direction and very stiff in the vertical direction. They change the vibration mode and lengthen the fundamental period of the structure, keeping it, in general, away from the main periods of the seismic load [6]. As a consequence of the decoupling, the devices distort and dissipate a large portion of the input energy before it arrives to the main structure.

Table 1 summarizes the passive vibration control systems based on the three groups above, and presents their basic construction, the idealized hysteretic behaviour, and lists the main existing examples. Some are already installed in historical buildings. In the following, the devices of groups 1 and 3 are discussed, since the techniques of group 2 have never been applied for the seismic upgrade of historical masonry buildings. The reader is referred to Refs. [15,24,25] for details regarding operation, materials, implementation, and applicable codes of passive devices for new buildings.

2.1. Friction devices

Friction devices, or friction dampers, dissipate energy when two solid bodies (with dry surfaces) slide relative to each other, the mechanical work being dissipated into heat [23,26]. Dampers are designed to slip when subjected to a certain force, either by uniaxial or rotational motion of its components, so that slippage occurs before damage develops in the main elements of the main structure. Since an activation threshold exists, the dampers add initial stiffness to the structure during normal service loads and moderate earthquakes. If the cyclic lateral force overcomes the threshold, the device deforms causing slippage of the surfaces, thus triggering the energy dissipation. However, the building may present permanent deformation after a strong earthquake if there is no restoring mechanism (self-centring) forcing the components to recover their original relative position within the damper [17]. The basic model that defines the response of friction dampers is the idealized Coulomb friction model, in which the frictional force F is proportional to the normal force N acting on the interface regardless of the contact area through the coefficient of friction μ, producing rectangular hysteretic loops with a significant amount of dissipated energy (Table 1) [6,17,23]:

$$F = \mu \mathrm{N} \quad [2]$$

Many solutions have been proposed for the development and implementation of this type of dampers. The most common include the Pall cross-bracing damper [27,28] (Fig. 1a), the slotted bolted connection (SBC) [29] (Fig. 1b), and the rotational friction joints [30]. More complex solutions with self-centring capacity include the Sumitomo friction damper [31], the energy dissipating restraint (EDR) and variants [32,33], and other similar devices (see Refs. [34–38]).

Laboratory tests have demonstrated that friction dampers reduce inter-storey drifts and accelerations, while the decrease of base shear is moderate. In addition, they are independent of frequency, amplitude, number of cycles, and temperature, showing a stable (predictable) hysteretic behaviour with high capacity of energy dissipation [6,7]. Nevertheless, the properties of the surfaces are difficult to maintain and may change throughout the life of the damper due to environmental factors that cause corrosion or decay of the sliding materials, affecting the response [15]. The normal force also may vary over the years, due to relaxation of the bolted system [21]. Furthermore, numerical solutions to predict the response of a building are computational demanding due to the high nonlinear behaviour of the friction dampers [39].

2.2. Yielding devices

The inelastic deformation of metals provides an effective mechanism of energy dissipation for structures undergoing cyclic loads such as earthquakes. Devices drawing on this property (hysteretic deformation) are called metallic yielding dampers and are typically designed to be incorporated into bracing systems of framed structures (reinforced concrete and steel) [23]. When a lateral load deforms the building, an

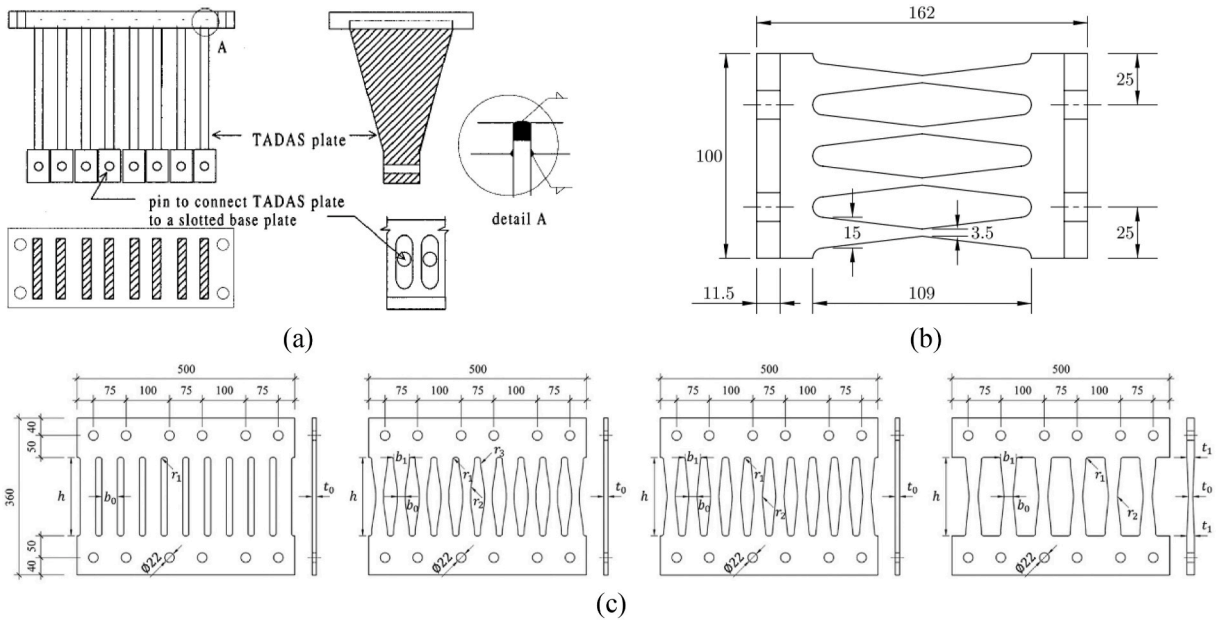


Fig. 2. Yielding devices: (a) TADAS [7], (b) Strip device proposed by Ghabraie et al. [46], (c) Strip device proposed by Lee et al. [41].

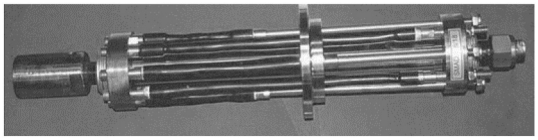


Fig. 3. SMA device with wires of Ni-Ti [61].

internal force develops at the connection where the device is fixed (normally between the top of the chevron bracing and the overlying beam of the frame). That force is used to cause the plastic deformation of the material by imposing either a pure or a combination of flexural, shear, axial, or torsional stress, depending on the design of the damper [15,17,26,40,41].

Flexural dampers are subjected to out-of-plane bending due to inter-storey drift, and normally use mild steel plates with different shapes. The most common are X shaped plates, denoted as ADAS (added damping and stiffness) and triangular shapes, known as TADAS (triangular added damping and stiffness) [17,26] (Fig. 2a). There are variations using bars, such as the HADAS [42] and the bar damper (BD) [43]. Other geometries involve slit and strip plates [44,45] subjected to in-plane deformation, which simultaneously develops bending moments and shear stresses. Several researchers optimized the shape of the strips in order to remove unnecessary material at the central part of the device [40,41,44,46,47] (Fig. 2b and c). Shear panel dampers (SPD) are normally composed of a thin plate of low yield steel, different solutions having been developed [48–55]. The devices activated by axial forces, dissipating energy under compression and tension, comprise buckling-restrained brace (BRB) dampers, which consist of a steel core with a cruciform cross-section surrounded by concrete, and a stiff steel tube [56]. The torsional deformation of a steel bar can also be used to dissipate energy, increasing the life of the material with respect to the fatigue effect [57–59].

The advantages of yielding devices include their stable hysteretic behaviour, long term reliability, comparative low cost, and relative insensitivity to environmental temperature [23]. Conversely, they allow a limited number of working cycles (low-cycle fatigue), have a nonlinear response [6], and need to be replaced when material yielding occurs. Moreover, although they reduce inter-storey drifts, they are less effective in decreasing accelerations and base shear [60].

2.3. Phase transformation devices

Shape memory alloys (SMA) are metallic materials able to undergo large deformations when a load is applied, and recover their initial shape once the load is removed and the material is heated [61]. Compared with normal steels, which have typical maximum elastic strains of less than 0.2%, shape memory alloys show superelasticity, with elastic strains up to 5%–7% [22,26]. SMA have been introduced in some passive devices in the form of wires subjected to constant tension [62] (Fig. 5). When the material deforms beyond a certain strain, yielding and energy dissipation occur, generating hysteresis loops like the ones shown in Table 1. SMAs recover their previous shape by applying heat, which changes the crystal structure from martensitic to austenitic [22]. SMA devices have self-centring capacity, are insensitive to environmental conditions (temperature and corrosion), and have a good fatigue resistance, dissipating large amounts of energy [6]. Although SMA with various compositions have been developed for numerous applications in different fields, the most used material is a nickel-titanium (Ni–Ti) alloy known as nitinol. The high cost of SMA materials is a constraint to the implementation in civil structures. In particular, the cost of the Ni–Ti is related to the difficulty of shaping the material into a specific form. In addition, small changes in the chemical composition and variations in the treatment during fabrication can cause significant modifications in the mechanical properties of the SMA [61].

2.4. Viscous fluid devices

Energy dissipation in viscous fluid (VF) devices draws on the resistance developed when a solid body moves within a VF. The former compresses and deforms the fluid, converting motion into heat. Under low frequency forces, VF devices increase the damping ratio of the structure without affecting the global stiffness [17,63]. The viscous forces generated during the excitation do not increase the base shear of the main structure, since they are out of phase in relation to the displacement dependent forces [63,64]. VF devices have been installed as a part of seismic base isolation systems, as well as components of bracing systems, to mitigate the effects of wind and earthquakes [15]. The most common configuration of a VF damper consists of a piston moving inside a closed cylindrical container full of a silicone compound

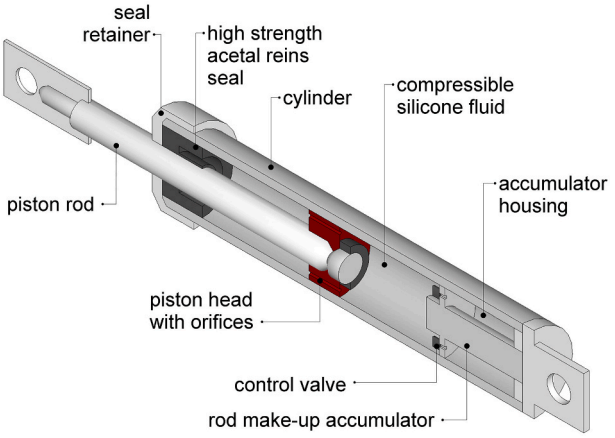


Fig. 4. VF damper with orifices (adapted from Ref. [65]).

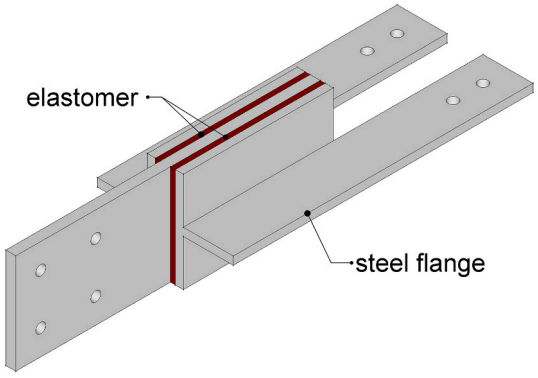


Fig. 5. Typical configuration of a VE damper (adapted from Ref. [31]).

(or a viscous oil with relatively low viscosity), which flows through the orifices drilled in the head of the piston from one side of the cylinder to the other [65] (Fig. 3). The classical Maxwell model is used as basis to describe both the linear and nonlinear dynamic behaviour of VF dampers [17,64]:

$$P(t) = C|\dot{u}(t)|^{\alpha} \quad [3]$$

where $P(t)$ is the force developed by the damper, $\dot{u}(t)$ is the relative velocity between the ends of the damper, C is the damping coefficient, and α is a value determined by the orifices at the head of the device. If α is equal to one, the force is linearly proportional to the velocity and the hysteresis loop has an elliptical shape (Table 1). In the case of nonlinear behaviour, the hysteresis loop approaches a rectangular shape as α tends to zero (Table 1).

The fluid can be pressurized to generate a constant restoring force inside the chamber and provide self-centring capacity [6]. Although the working principle of VF devices is straightforward, their actual design is complex to ensure a reliable response [15]. These dampers can be also relatively insensitive to temperature if the suitable mechanical components are integrated inside the damper. However, experimental tests have also demonstrated that VF devices have difficulty in reducing the effects of the dynamic force peak if this occurs in the early stages of the excitation [6].

2.5. Viscoelastic devices

Viscoelastic devices dissipate energy by shear deformation of solid viscoelastic (VE) materials, such as bitumen rubber, super-plastic silicone rubber, vulcanized and unvulcanized high damping rubber [6,23]. They are mostly used in framed structures to reduce the vibrations caused by wind and earthquakes. The typical VE device configuration consists of VE layers bonded to steel plates, as shown in Fig. 4. One end of the damper is connected to the main frame, while the other end is attached to the bracing system. When relative motion between ends occurs, the VE material distorts, behaving simultaneously as elastic solid and viscous fluid. In the process, thermal energy is generated due to the internal friction. After removing the load, the device recovers its original shape (self-centring capacity) [6,17,23].

Under certain conditions, the Kelvin-Voight model is capable of describing the dynamic response of these dampers [17]. This physical model is composed of a linear spring (proportional to the displacement) and a viscous dashpot (proportional to the velocity) in parallel:

$$P(t) = Ku(t) + C\dot{u}(t) \quad [4]$$

where K is the storage (elastic) stiffness, C is the damping coefficient, u and $\dot{u}$ are the relative displacement and velocity along the damper, respectively. The energy dissipated per cycle is represented by a hysteresis loop with inclined elliptical shape (Table 1). An increment in the ambient and/or internal temperature of the VE material can reduce stiffness and the dissipation energy capacity. Hence, more complex models have been developed to take into account the effects of internal and external temperature changes and other variables, such as frequency, amplitude and strain. These features can represent a disadvantage, since they complicate the analysis and design of damper systems [15,17,66,67]. Experiments have demonstrated that high damping rubber exhibits less dependency on temperature and frequency than other rubber materials [68].

Experimental campaigns on full scale steel and reinforced concrete structures subjected to seismic actions have proven that VE dampers reduce significantly the deformation and base shear [15]. Other advantages are the low cost and simple construction. Compared with other devices (yielding or friction), VE dampers also dissipate energy in small vibration amplitude. Compared with VF dampers, VE dampers supply additional stiffness to the structure due to the elastic component [69].

2.6. Base isolation

Base isolation systems are not a completely new concept. Several ancient temples, monasteries, and bridges in Greece, China, Italy, and other regions were isolated using different technologies such as granular materials (layers of sand, gravel, etc.) or wooden rollers under the foundation, among others [70]. The contemporary base isolation devices can be of various types. Elastomeric bearings alternate several horizontal layers of natural or synthetic rubber with steel shim plates to provide vertical stiffness (Table 1). This assemblage is placed between two thick steel plates at the top and the bottom, and then is covered with a rubber coating to protect the internal components from ambient factors [71]. These bearings can be fabricated with low-damping (natural or synthetic) rubber (LDRB) or high-damping rubber (HDRB), which can achieve equivalent damping ratios between 10% and 20%. This property is obtained by adding carbon black, oils, resins, or other fillers to the raw rubber [6,71]. LDRBs present an equivalent damping ratio up to 5% and exhibit a nearly linear shear stress-strain behaviour. To control the lateral displacements, LDRB are supplemented with other passive devices, such as yielding dampers or VF devices [21,71].

Lead-rubber bearings (LRB) consist of a low damping rubber bearing (LDRB) with a lead core casted or preferably press-fitted into a central hole in the bearing (Table 1) to guarantee its proper operation. The core provides damping and dissipates energy by yielding under low levels of pure shear stress, with stable hysteretic behaviour for a certain number of cycles. When the bearing undergoes lateral deformations, the interlocking with the steel shims causes shear in the lead along its whole volume. Lead behaves nearly as an elastic-plastic solid, and as it recrystallizes at ambient temperature (about 20 °C) repeated yielding does

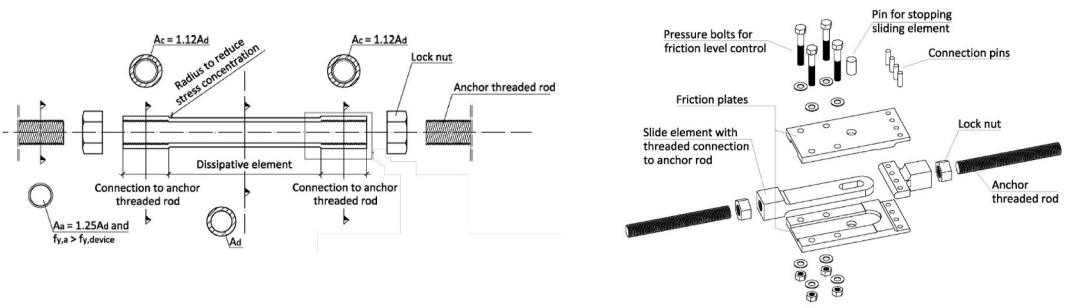


Fig. 6. (a) Geometry of hysteretic dissipative device, (b) Geometry of frictional device as patented by Cintec International Ltd and tested by Dâ€™Ayala and Paganoni [18].

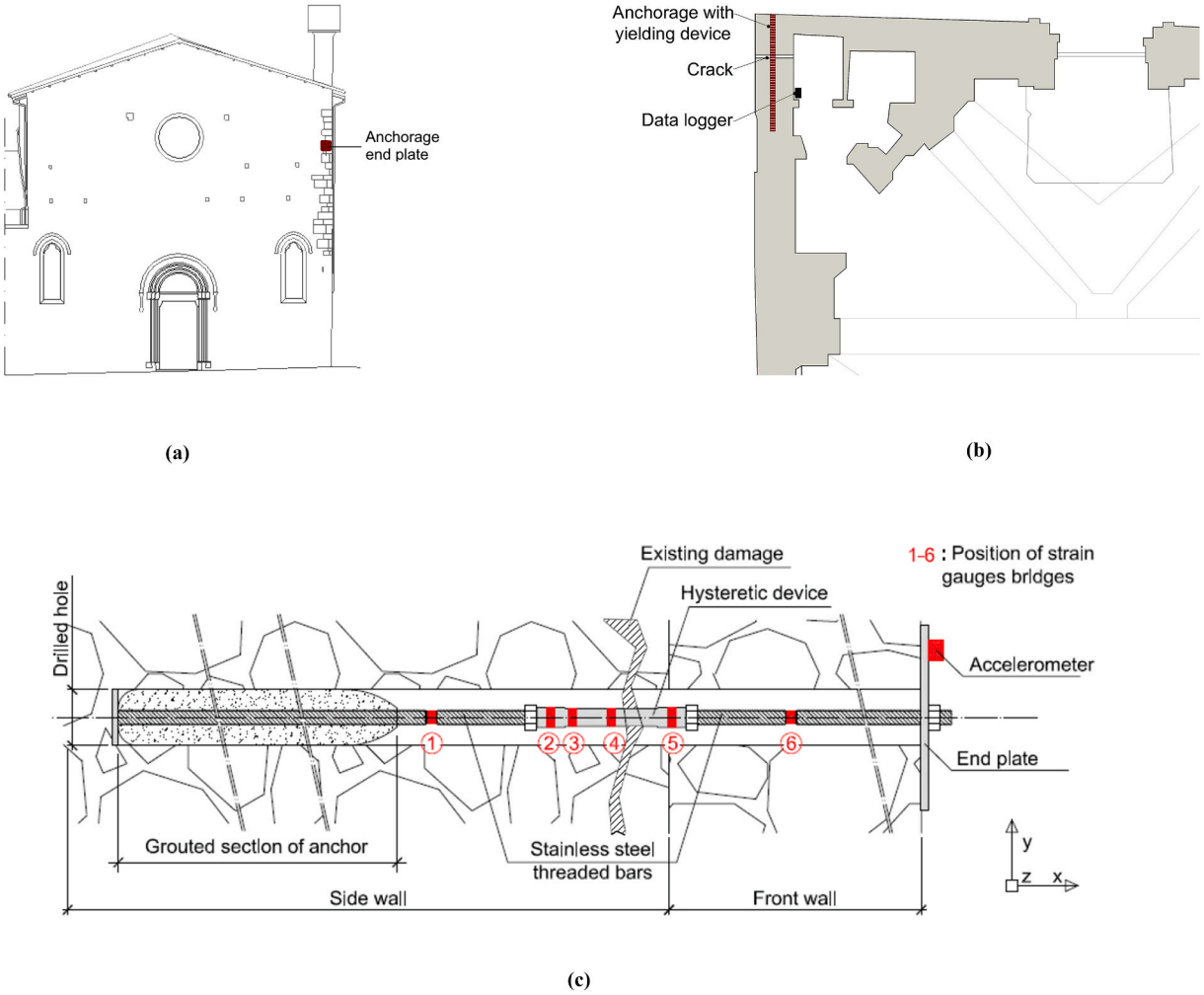


Fig. 7. (a) FaÃ§ade of the S. Giuseppe dei Minimi Oratory, Lâ€™Aquilla, Italy (b) Location of the yielding device, and (c) Installation detail of the yielding device (adapted from Ref. [18]).

not cause fatigue [6,21,71,72].

Other base isolation systems use sliding components and friction interfaces. Flat sliding bearings consist of blocks that slip on plane horizontal stainless-steel plates. The use of Polytetrafluoroethylene (PTFE, trademark "Teflon") in the sliding blocks provides a low friction coefficient to the interface. Since the lateral stiffness of the bearing is quite low, horizontal components of the seismic action are barely transmitted to the uppermost structure. Due to their reduced lateral stiffness, other devices are used in combination with flat sliding bearings to control the horizontal displacements and provide self-centring mechanisms [21,72]. Base isolation also can rely on geometrical factors such as rolling surfaces or pendular motion [72]. For example, the frictional pendulum systems (FPS) operate using an articulated slider on a spherical sliding surface coated with a polished stainless-steel layer (Table 1). When the ground undergoes a lateral displacement, the spherical plate moves relatively to the articulated slider. The energy is dissipated by friction while restoring forces (self-centring capacity) are generated by gravity when the structure rises out of the equilibrium

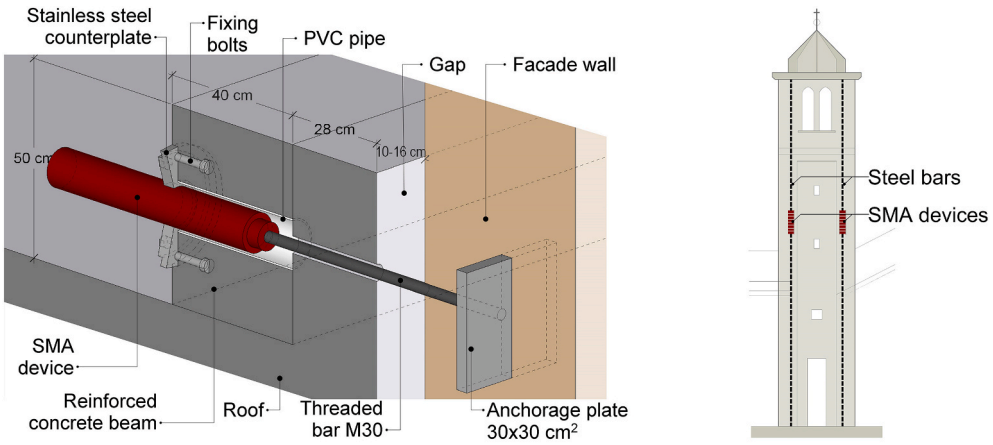


Fig. 8. (a) Installation of SMA dampers in the San Francesco Basilica, Assisi, Italy (adapted from Ref. [84]), (b)Schematic application of SMA dampers at the bell tower of San Giorgio church, Trignano, Italy (adapted from Ref. [86]).

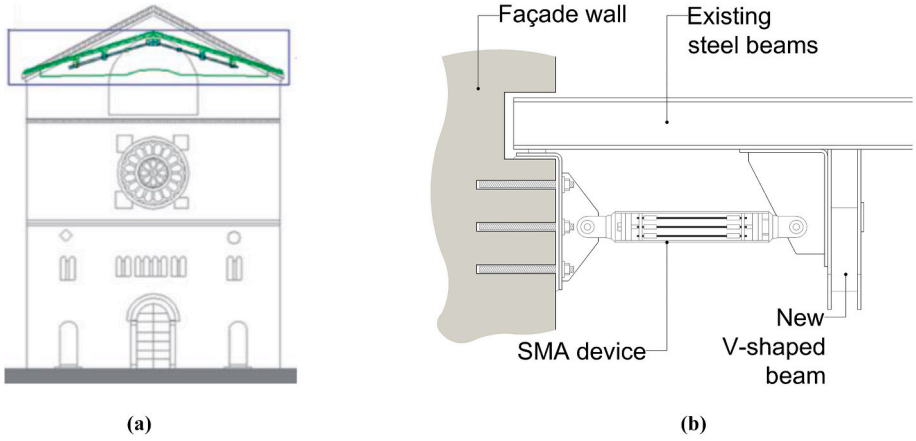


Fig. 9. (a) FaÃ§ade of San Feliciano Cathedral, Foligno, Italy [84], (b) Installation of the SMA dampers (adapted from Ref. [84]).

position along the spherical surface [21]. For a more detailed review about base isolation systems, the reader is referred to Ref. [73].

3. Application of passive vibration control systems to existing masonry structures

Only a few examples of implementation of energy dissipation devices and base isolation in existing masonry buildings, including monuments, can be found in the available literature. Base isolation, yielding and friction devices, as well as VF and phase transformation devices, have been proposed to reduce the vulnerability of existing masonry structures. The most representative examples of installation in real buildings are mainly located in the United States of America (USA) and Italy. In other cases, the devices were either only tested in laboratory or are still under experimental validation. The application of passive devices has been also proposed and assessed through numerical modelling of case studies, but never implemented in the actual buildings. Furthermore, since the 1990s, different Italian organizations have worked in collaboration for the research, development and implementation of innovative strengthening techniques applied to the seismic protection of historical buildings [74].

3.1. Friction and yielding devices

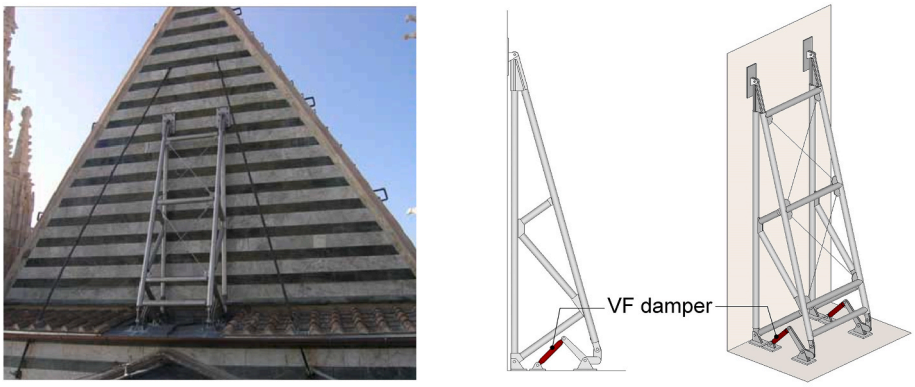
Lockrem et al. [75] developed and tested a diaphragm-to-wall connector that dissipates energy by friction. The system consists of connectors (placed at the floor/roof level) linked to vertical post-tension rods installed in the core of the walls, from the foundation until the top. The relative horizontal displacements between the wall and the floor/-roof produce a sliding motion of the wedges inside the connector. On the other hand, the proposal developed by Preti et al. [76] draws on the in-plane deformation of the roof when the building is subjected to seismic excitations. The horizontal diaphragm is divided in three parts; the central section, made of plywood, is considerably rigid, whereas the ends, built with wooden strips, are flexible. All the diaphragms should be properly anchored to the walls. Special dissipative friction devices are fixed to neighbouring strips, so that they are active when relative sliding of the adjacent wooden pieces occurs. The device is made of one steel plate clamping another one, obtaining a friction coefficient of 0.31. An experimental campaign was carried out on a dissipative flexible diaphragm and numerical models were calibrated based on the results. The diaphragm presented a stable dissipative behaviour, and the models showed a reduction in terms of drift, shear, and acceleration.

In 2000, the Santa Maria di Collemaggio Basilica, in L'Aquila, was supplied with horizontal steel braces along the nave and aisles, at the roof height. There was a yielding device consisting of a flexible frame (4 bars fixed to four stiff corners) at the centre of the braces located at the ends of the nave. Dynamic identification tests before and after the intervention demonstrated that the stiffness of the nave increased [77]. Consequently, the transept (including the dome, the triumphal arch, and



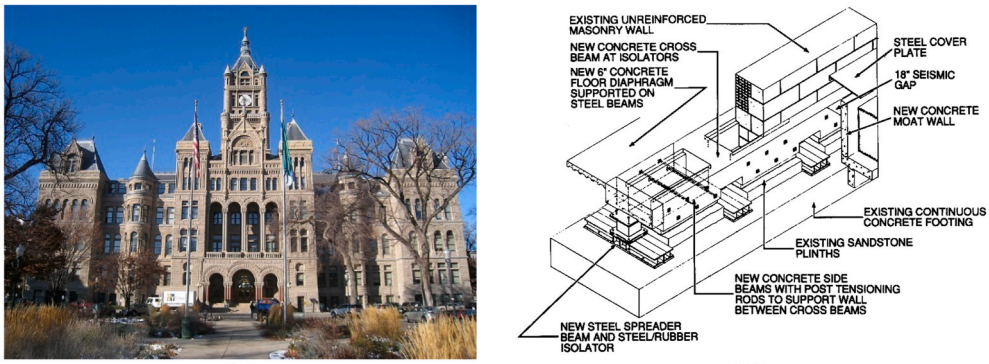
(a) (b)

Fig. 10. (a) Metallic roof and VF dampers of the San Giovanni Battista Church, Carife, Italy and (b) VF damper of the Library of Federico II University of Naples, Italy [88,89].



(a) **(b)**

Fig. 11. Implementation of VF dampers in the main faÃ§ade of the Cathedral of Siena, Italy (adapted from Ref. [92]).



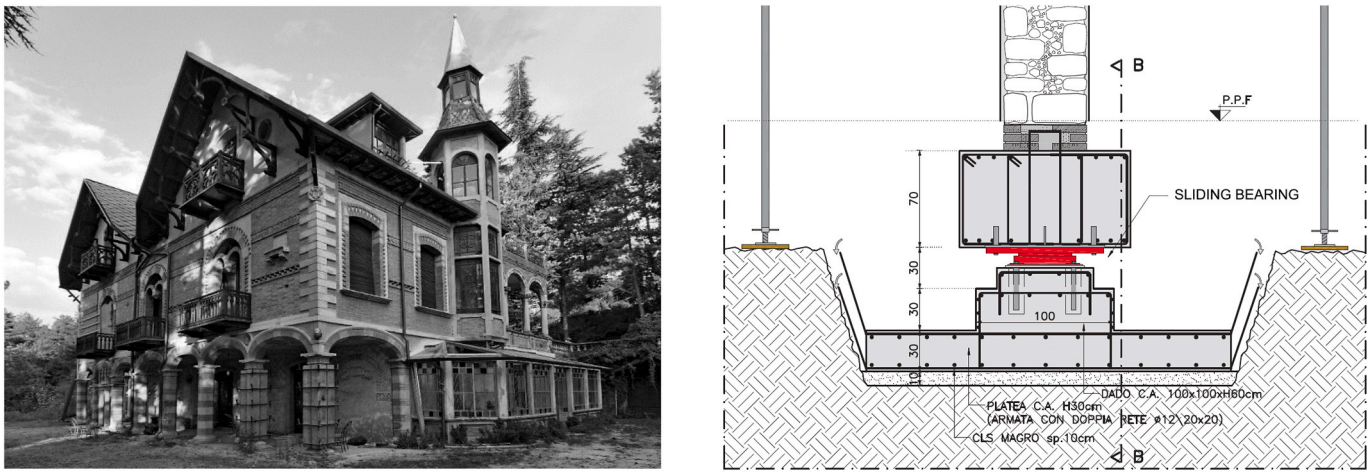
(a) (b)

Fig. 12. (a) City and County Building in Salt Lake City, Utah, USA [www.wikipedia.com 2021], (b) Base isolation system [97].

some pillars) collapsed in the 2009 L'Aquila earthquake due to a torsional effect produced by the eccentricity between the mass centre and stiffness centre. According to Ref. [78], the yielding devices were ineffective. Based on the post-earthquake survey, they failed given the poor design and bad execution: the rods of the braces were not always under tension and buckling occurred, the devices were not activated since small relative displacement developed at their location, and the slippage of the anchors between the bracing system and the roof.

D'Ayala and Paganoni [18,79,80] proposed and evaluated the implementation of friction and yielding devices as part of stainless steel anchors to improve the connection between orthogonal masonry walls. The aim was to prevent the out-of-plane collapse and to limit the cracking of the masonry. Thus, the devices were designed to control the relative displacements and accelerations, increase the ductility and dissipate energy.

The yielding device consists of a hollow stainless-steel rod narrowed at the centre. The ends are thicker and threaded to be screwed to the anchor. Since the device was designed to work under axial forces, it yields in the central part when subjected to tension and prevents buckling (Fig. 8a). The friction device is composed of one steel element that slides between two external plates. Four bolts keep the external plates together and adjust the compression level. The whole damper is made of stainless steel and the friction interfaces do not present any friction coating. The ends are fixed to the anchor through a threaded connection (Fig. 8b). Both devices underwent an experimental campaign to assess their behaviour for cyclic actions and maximum strength



(a) (b)

Fig. 13. (a) "La Silvestrella", L'Aquilla, Italy (b) Base isolation system (adapted from Ref. [109]).

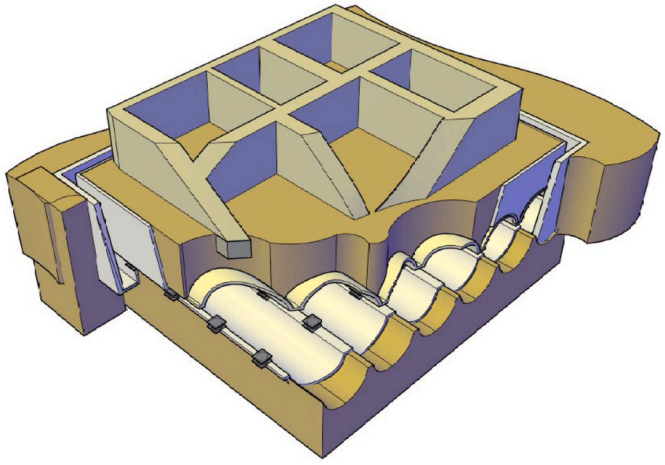


Fig. 14. (a) Seismic isolation structure for existing buildings (SISEB) [70].

capacity. They presented stable and repeatable hysteretic loops for a certain number of cycles [18,79,80]. Further numerical analyses showed that the installation of the friction device increases the capacity of the anchoring system, dissipates energy, and reduces the damage propagation in the surrounding material [81].

The S. Giuseppe dei Minimi Oratory, in L'Aquilla, Italy, was adopted as case study in the framework of the NIKER project, to validate a prototype of the yielding device developed by D'Ayala and Paganoni [18]. It was installed in a damaged wall, namely at the connection between the south lateral wall and the main façade (Fig. 9), where a vertical crack developed by the activation of the out-of-plane mechanism during the 2009 L'Aquila earthquake. After one year of monitoring, the performance of the devices could not be evaluated under real seismic actions, since the expected small to moderate intensity earthquake did not occur.

Another experimental campaign was carried out by Gonçalves et al. [82], who performed a set of experimental tests to characterize the cyclic behaviour of walls known as "*frontal*" (wall perpendicular to the façade) of 18th century Portuguese *Pombalino* buildings. The specimens included four Saint Andrew's cross timber modules with brick infill. Two walls were reinforced using a diagonal brace that included a yielding damper composed of a thin steel rod and lateral restraint to prevent buckling. The results showed that the device had a good performance in tension, but instability in compression. Moreover, the system is difficult to implement in rehabilitations.

3.2. Phase transformation devices

The first strengthening interventions with SMA devices on existing masonry structures were carried out within the framework of the ISTECH project [83]. Two buildings in Italy were selected for the pilot application, namely the San Francesco Basilica in Assisi [84,85] and the tower of the San Giorgio church, in Trignano [86]. The San Francesco Basilica, built in the 13th century, suffered damage during an earthquake in September 1997, developing large cracks, permanent deformation, and even collapses of vaults and tympana. The retrofitting included the use of 47 SMA devices to connect the two tympana of the transept to the existing reinforced concrete roof, as shown in Fig. 12a. Based on their location, the SMA devices were designed to withstand maximum displacements between 8 and 25 mm. Additionally, VF dampers were installed along the perimeter of the building to connect the sections of a metallic truss used to strengthen the walls. Under normal service conditions, the truss and walls behave independently, whereas during an earthquake the devices become stiff, hence walls and truss work together [85].

The bell tower of San Giorgio church is 18.5 m high, with a square plan ($3 \times 3\ m^2$). It is composed of four masonry piers with non-structural masonry walls between them. During the earthquake of October 15th, 1996, several horizontal cracks developed at the piers and walls due to oscillation and torsional motion of the top. The first stage of the strengthening intervention comprised the consolidation of the cracked masonry and the reconstruction of the floors. The second phase aimed at increasing the overall flexural resistance by placing four vertical prestressing steel tie bars at the tower internal corners (Fig. 12b). Each tie bar consists of six tight-screwing segments and one SMA device made of 60 Ni–Ti wires (1 mm diameter and 300 mm length). The tie bars were prestressed to 20 kN each, to guarantee a full compression state of the masonry elements even during bending and attain the maximum energy dissipation. Thermal deformation of the steel was also considered in the design of the system. After an earthquake on June 18th, 2000, the bell tower did not show any sign of damage, validating the efficiency of the SMA devices [86].

Other applications of SMA devices can be found also in Italy, in the San Feliciano Cathedral, in Foligno, and in the San Serafino church, in Montegranaro [84]. In the first case, the main façade detached (8 cm displacement) due to an earthquake that occurred in 1997. Traditional steel bars placed at 15 m height improved the connection between lateral walls and façade. This connection was made using nine SMA

Table 2
Passive vibration control systems applied or developed for masonry buildings.

Type of passive vibration devices	Country	Building/Research	Structural system	Status
Friction devices	United States of America	Development of diaphragm-to-wall connectors [75]	Unreinforced masonry	Testing
Friction devices	Italy	Dissipative Roof Diaphragm [76]	Unreinforced masonry	Testing and numerical analysis
Friction devices	United Kingdom	Frictional device (Cintec International Ltd) [18,79,80]	Unreinforced masonry	Testing and numerical analysis
Yielding devices	Italy	S. Giuseppe dei Minimi Oratory [18]	Unreinforced masonry	Application
Yielding devices	Italy	Santa Maria di Collemaggio basilica [77,78]	Unreinforced masonry	Unsuccessful application
Yielding devices	Portugal	Testing campaign on wallettes [82]	Pombalino's walls	Testing
SMA devices	Italy	San Francesco Basilica in Assisi [84,85]	Unreinforced masonry	Application
SMA devices	Italy	Bell tower of San Giorgio church in Trignano [86]	Unreinforced masonry	Application
SMA devices	Italy	San Feliciano Cathedral in Foligno [84]	Unreinforced masonry	Application
SMA devices	Italy	San Serafino church in Montegranaro [84]	Unreinforced masonry	Application
SMA devices	Portugal	Testing campaign wallettes [87]	*Pombalino*'s walls	Testing
Viscous fluid devices	Italy	San Giovanni Battista church [88,89]	Unreinforced masonry	Application
Viscous fluid devices	Italy	Federico II Library, University of Naples [88,89]	Unreinforced masonry	Application
Viscous fluid devices	Italy	Industrial masonry building [90]	Unreinforced masonry	Application
Viscous fluid devices	Italy	Cathedral of Siena [91]	Unreinforced masonry	Application
Viscous fluid devices	Italy	Bell tower of San Zenone in Fermo [95]	Unreinforced masonry	Numerical analysis
Viscous fluid devices	Italy	LICORD device [93]	Unreinforced masonry	Testing
Viscous fluid devices	Portugal	"*Gaioleiro*" building in Lisbon [94]	*Gaioleiro*	Numerical analysis
Viscous fluid devices	Cyprus	Agios Ioannis Prodromos church [96]	Unreinforced masonry	Numerical analysis
Base isolation	United States of America	City and County Building in Salt Lake City [97]	Unreinforced masonry	Application
Base isolation	United States of America	Salt Lake Temple in Salt Lake City [105]	Unreinforced masonry	Application
Base isolation	United States of America	Mackay School of Mines, University of Nevada [98]	Unreinforced masonry	Application
Base isolation	United States of America	Los Angeles City Hall [99]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	Oakland City Hall [70,99]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	Pasadena City Hall [101]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	San Francisco City Hall [70,99]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	Utah State Capitol [101]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	U.S. Court of Appeals in San Francisco [102,103]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	United States of America	San Francisco Asian Art Museum [101]	Steel frames combined with unreinforced masonry walls	Application
Base isolation	New Zealand	New Zealand Parliament (including Parliament House and Parliamentary Library) [103,104]	Unreinforced masonry	Application
Base isolation	New Zealand	Wellington Maritime Museum [113]	Unreinforced masonry	Application
Base isolation	New Zealand	BNZ Building [113]	Unreinforced masonry	Application
Base isolation	Italy	La Silvestrella [109]	Unreinforced masonry	Application
Base isolation	Italy	Palazzo Ciuffini-Cricchi-Volpi [114]	Unreinforced masonry	Application
Base isolation	Italy	Emiciclo building [114]	Unreinforced masonry	Application
Base isolation	Italy	San Giovanni Battista church in Apagni [74,110]	Unreinforced masonry	Proposal
Base isolation	Italy	Santa Croce church, near Nocera Umbra [74,110]	Unreinforced masonry	Proposal
Base isolation	Italy	Seismic Isolation Structure for Existing Buildings (SISEB) [70,112]	Unreinforced masonry	Proposal
Base isolation	Mexico	San Francisco de Asis church in Olinalá, Guerrero [111]	Unreinforced masonry	Application
Base isolation	Republic of Macedonia	Mock-up of the St. Nikita church [106,107]	Unreinforced masonry	Testing
Base isolation	Republic of Macedonia	ALSC system (Almost lifted structure concept) [108]	Unreinforced masonry	Testing
Base isolation	Turkey	Ulu mosque [115]	Unreinforced masonry	Numerical analysis
Base isolation	Romania	Iasi City Hall [116,117]	Unreinforced masonry	Application
Base isolation	Romania	Bucharest City Hall [118]	Unreinforced masonry	Application
Base isolation	Romania	Victor Slavescu building [118]	Unreinforced masonry	Application
Base isolation	Romania	Arch of Triumph [118]	Unreinforced masonry	Application
Base isolation	Romania	ST. Nicolae Aroneanu church [119]	Unreinforced masonry	Application
Base isolation	Armenia	School in Vanadzor [116]	Unreinforced masonry	Application

devices, each having one end attached to a new steel beam added to the existing metallic structure, while the other end was fixed to a plate anchored to the masonry (Fig. 13). In the San Serafino church, damaged by the Umbria-Marche earthquake in 1997, two SMA devices were installed to prevent the out-of-plane collapse of the main façade. The devices are coupled to steel ties that connect the top of the tympanum to the lateral walls.

Branco et al. [87] performed a series of quasi-dynamic tests on ten "*frontal*" walls (walls of *Pombalinos* buildings, from the 18th century) to compare their in-plane behaviour for different strengthening

techniques, including SMA devices. The devices, made of NiTi wires, were connected diagonally to the corners of the panels. It was concluded that although an increase in the energy dissipation was detected when installing the SMA devices, the application did not significantly change the walls response.

3.3. Viscous fluid devices

The intervention project on the San Giovanni Battista church in Carife, Italy (1990), consisted in the replacement of the roof by a rigid metallic structure, aiming at providing the church with a box-behaviour. The new roof was connected to reinforced concrete ring beams (casted on the top of the walls) using VF dampers (Fig. 10a). The adaptive restraint properties of the devices allow the free dilatation of the metallic members due to thermal changes (slow movements), but it constitutes a very stiff connection when the relative velocities between the ends of the devices exceed a threshold due to dynamic actions. It should be noted that such devices only add stiffness and do not dissipate energy, since there is no motion of the pistons during an earthquake. A similar solution was adopted in the retrofitting of the Federico II Library of the University of Naples, Italy, in 1997 (Fig. 10b) [88,89], and in an old industrial masonry building with large span and absence of intermediate walls, combining VF devices with yielding dampers [90]. In the Cathedral of Siena, Italy, the thin tympanum of the main façade was attached to a rigid metallic structure that was built behind it. Then, two VF dampers were installed at the base of the metallic frame, in such a way that the overturning motion of the tympanum triggers the response of the devices, dissipating energy and, consequently, improving the out-of-plane behaviour of the tympanum (Fig. 11) [91].

Recently, Giresini et al. [93] developed and tested a device named Linear Controller Rocking Device (LICORD) that restraints the out-of-plane response of masonry walls for medium to high velocities during earthquakes. The device is composed of one or more VF dampers and springs installed in parallel between two plates. VF dampers dissipate the kinetic energy by adjusting the flow through the holes, whereas the springs provide self-centring capacity. A traditional steel tie rod is then connected to one plate of the device, while the other plate is embedded into the wall, so that when the latter starts the out-of-plane rocking the tie pulls one plate against the other, compressing the springs and dampers. The device was tested for free vibration on two masonry walls of different dimensions, changing the flow of the dampers. Although the device only works when the tie is under tension, the results showed that when it is properly calibrated, there is a reduction of displacement amplitude (between 63 and 72%), a decrease of the number of impacts between the base of the walls and the foundation, and an increment of the vibration frequency. This represents an increase of the equivalent damping, i.e., from 4% (unrestrained wall) to 20% (using the device).

Numerical analyses have also been carried out to assess the performance of VF dampers applied to some historical buildings. For example, Branco and Guerreiro [94] compared different strengthening systems applied to a model of a "*gaioleiro*" building in Lisbon, Portugal. The study encompassed the construction of reinforced concrete walls, the installation of base isolation, and the use of VF dampers. The walls of the building shaft (interior patio) were attached to a stiff auxiliary structure made of steel frames, which were connected to braces using VF dampers. The numerical analyses demonstrated that VF devices, whose application is less invasive, presented the best performance in terms of stress at the foundation, and a similar response to that of the reinforced concrete walls in terms of displacements. Pavia et al. [95] presented a similar procedure for a bell tower of San Zenone in Fermo, Italy, a building damaged by several earthquakes between 2016 and 2017. The proposed strengthening technique consisted of the connection of the masonry enveloped to a flexible inner tower made of steel frames where the VF devices were placed on each frame using a scissor-jack configuration. The proposal was assessed through nonlinear dynamic analyses using a finite element model. The results showed that there was a decrease of 55% of the displacements and a considerable reduction of the drift and stress levels.

The Agios Ioannis Prodromos church in Askas, Cyprus, was selected to study the application of innovative strengthening techniques in the framework of the INCO-MED project [96]. The building has three naves with a timber roof, and the walls were built with rubble stone, mud, and brick to fill the gaps between stones. The seismic response of the church with VF dampers was assessed using a numerical model that was calibrated based on the modal properties estimated from dynamic identification tests. Then, a set of parametrical dynamic analyses changing the position, quantity, and damping properties of the devices allowed to estimate the best cost-effective configuration in terms of drifts (0.1% as maximum acceptable value). The results showed that there was a significant reduction of the base shear and displacements in all the cases. The final solution consisted of 96 devices placed at the roof level of the lateral naves. With this arrangement, the base shear stress decreases around 57% and the inter-storey drifts are within the range of the predefined limit.

3.4. Base isolation

The City and County Building in Salt Lake City (Utah, USA) is considered to be the first historical building where a vibration control system was applied (in the mid-1980s) [97]. It is a five-storey structure completed in 1894, whose bearing walls are made of unreinforced masonry and stone. The plan dimensions of the whole building are 40×80 m, and the highest element is the clock tower, with 76 m height. Studies performed since 1970s strongly recommended to retrofit the structure against the seismic hazard. However, the application of traditional strengthening techniques to comply with the codes of that time implied high costs and the replacement of the whole interior bearing structure, i.e., the construction of a new debuilding inside the original exterior façades. Engineers assessed different retrofitting solutions and concluded that the best option was the implementation of a base isolation system, to shift the fundamental period of vibration of the whole building, avoiding amplifications and high dynamic forces. The isolation system consists of 443 lead-rubber bearings installed between the structure and the existing foundation. A new reinforced concrete secondary structure was built under the ground level. It consists of beams on each side of the walls, to withstand the structure and transfer the load to the isolation bearings (Fig. 6). Furthermore, a trench with a 30 cm gap was built around the building, so that it could freely move horizontally during a seismic event.

This application set the basis for other retrofitting operations in historical buildings. In 1992, a system of high-damping rubber bearing combined with slide elements was installed in the Mackay School of Mines, at the University of Nevada, USA (a building made of unreinforced brick masonry) [98]. Also in the USA, lead-rubber bearings were used for seismic risk mitigation of historical structures built with steel frames in combination with unreinforced masonry walls in the City Halls in Los Angeles, Oakland, Pasadena, and San Francisco, as well as in San Francisco Asian Art Museum and Utah State Capitol [70,99–101]. A frictional pendulum isolation system was implemented for the seismic retrofit of the U.S. Court of Appeals building, in San Francisco, also in the USA [102]. The intervention consisted of 256 bearings of 1880 mm radius, composed of a concave stainless steel surface supported on an articulated slider coated with PTFE [103]. The New Zealand Parliament, a complex that consists of three main buildings, including the Parliament House and the Parliamentary Library, was isolated using a combination of 145 lead-rubber bearings, 230 high-damping rubber bearings, and 42 sliding bearings [103,104]. In 2019, the renovation of the Salt Lake Temple, in Salt Lake City, USA, started and is scheduled to be completed in 2024. The intervention includes a deep and complex base isolation system as part of its seismic upgrade [105].

Between 1990 and 2000, Byzantine churches in the Republic of

Macedonia were analysed, aiming at developing a methodology for the application of base isolation systems. After the study of the different systems, rubber bearings combined with yielding devices and "stopper elements" were selected as a solution for historical constructions [106]. This set was tested on a shake table using a scaled model of a representative building, the St. Nikita church in Banjani. The mock-up was subjected to several levels of accelerations obtaining a high performance of the base isolation system even under strong intensities (0.63 g) [107]. Within the framework of the PROHITECH project, Tashkov et al. [108] performed shake table tests on a scaled model of another Byzantine church in 2008. The mock-up was supplied with a sliding system called ALSC (Almost Lifted Structure Concept) that presents a low friction coefficient (0.05–0.10). In this system, a pressurized fluid is introduced between the upper (sliding) and lower (fixed) plates. Springs surrounding the sliding plate provide self-centring capacity and restrain excessive horizontal displacements. The sliding forces can be controlled by varying the fluid pressure. The mock-up was subjected to accelerations up to 1.5 g without presenting damage, demonstrating the effectiveness of the system since the sliding plate allows the structure to behave as a rigid body.

In Italy, the mansion known as "La Silvestrella" was severely damaged by the L'Aquila earthquake in 2009. This masonry building dates from early 1900 and maintains its original configuration. Thus, given its unique architectural features and the damage severity, a traditional strengthening intervention presented many shortcomings due to the high level of invasion. The solution was the implementation of a base isolation system, consisting of a new foundation, 25 elastomeric bearings, 23 sliding devices and a very stiff grid of reinforced concrete beams to transfer the load from the walls to the base isolation bearings [109] (Fig. 7). Within the framework of the PROSEESM project, base isolation systems were proposed to improve the dynamic behaviour of the San Giovanni Battista church, in Apagni, and the Santa Croce church, near Nocera Umbra, both in Italy, and both damaged by two earthquakes in 1997 and 1998 [74,110].

The base isolation executed for a small church in Mexico differs from all the previous applications. The upper part of the bell tower of the San Francisco de Asis church in Olinalá was destroyed by an earthquake in 2017. For its reconstruction, the base isolation system was installed at 12.00 m height over the ground, between the lower part of the tower and the new belfry, approximately at the same high of the nave roof [111].

ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) and Politecnico of Torino patented the Seismic Isolation Structure for Existing Buildings (SISEB), which consisted of an isolated platform under the foundation of the building without the direct intervention to the structure. The decoupling is produced by the introduction of halved horizontal pipes (of at least 2 m diameter), where the bearings are placed between the lower and upper parts (Fig. 14). The building is then separated from the surrounding soil by a trench [70]. This system was considered by Clemente and De Stefano [112] for the retrofitting of the Margherita Palace and the Civic Tower in L'Aquila.

Table 2 summarizes the passive vibration control devices proposed and installed in historical buildings. It also includes the experimental campaigns and the numerical analyses performed to validate the application in unreinforced masonry structures.

4. Conclusions

Conventional methods and structural codes addressed to design modern buildings may be difficult to implement, or are even inapplicable to historical buildings, as they can result in extremely invasive interventions. Additionally, traditional techniques meant to provide a box-behaviour in buildings work as rigid elements and may have some limitations to achieve suitable and reliable safety levels. They barely profit from the energy dissipation involved during the cyclic seismic action to dampen vibrations. Hence, based on energetic criteria, the implementation of strengthening techniques that can deal with and dissipate the excess of input energy supplied by an earthquake can overcome the shortcomings of traditional solutions.

Vibration control systems were applied for the first time in the 1960s to new reinforced concrete and steel structures. They have demonstrated their effectiveness for improving the dynamic response of buildings when subjected to wind and ground motions. In general, they consist of passive mechanisms or devices that are installed along the structure to increase its damping coefficient. However, the implementation of vibration control systems in historical buildings, namely in unreinforced masonry constructions, has been barely explored. Base isolation is currently the most used system for historical buildings after the first implementation in the United States of America in the 1980s. Although their efficiency for reducing the seismic vulnerability has been proved, this technique implies high levels of intervention and high costs, which restricts its application to a few constructions of high relevance.

To overcome this issue, researchers have adjusted existing passive dampers (VF dampers) and developed new devices (friction, yielding and SMA devices) since the end of the 1990s. Some of them are still being tested and validated, such as the LICORD device. On the other hand, the efficiency of VE dampers on these buildings has not been studied. Furthermore, the available literature does not provide a design method for the implementation of dampers in historical masonry buildings. Monuments are the only buildings with real applications, whereas their implementation into minor architecture, such as dwellings, have been barely studied. Conservation criteria must be accounted for in the design and implementation of dissipative systems in existing masonry buildings. Factors like size, shape, and location can affect the aesthetics of the building. Additionally, the mechanical properties of masonry (low tension strength, brittleness, and heterogeneity), the efficiency of the connections between construction elements, and the dynamic behaviour of the buildings, should be also considered. The application of energy dissipation devices in existing masonry buildings is a relatively new field for engineers and researchers, where there are many open issues that should be evaluated and improved. Since energy dissipation devices rely on relative deformation, their current application to historical buildings is generally limited, mainly due to the low ductility of the unreinforced masonry, which may collapse before the activation of the devices. In this regard, future research should address the compatibility of commercial systems, their modification and adaptability, or even the development of new low-cost devices considering the properties of the structural elements (masonry walls and timber floors and roof) and the combination with other strengthening techniques. Additionally, limit states must be defined for masonry buildings strengthened using energy dissipation devices, in which some level of damage under strong earthquakes can be acceptable. Therefore, minor and repairable damage can be admissible if low-cost energy dissipation systems prevent local or global collapses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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